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1 Acknowledgments

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2 Executive summary

As the populations of Pacific Island Countries (PICs) grow and climate change accelerates, food and nutrition security are coming under increasing pressure. Climate science worldwide has projected an increase in global temperatures of 1.5^{o}C by mid-century at a minimum. Coral reefs worldwide are projected to decline by a further 70-90% at this level of warming, creating a potential tipping point for the collapse of these ecosystems and the livelihoods and industries that depend on them. Such collapse will have far-reaching consequences for PICs because many coastal communities are highly dependent on reef fisheries. In addition, sea level rise is causing inundation and erosion of productive coastal agricultural land and mangroves. Consequently, there is an urgent need to identify and implement solutions that will transform coastal food production in the most vulnerable areas to improve food and nutrition security in ways that will be achievable and sustainable despite the severe climate change impacts expected in the coming decades.

This SRA contributed to the growing need to understand future food systems change in the Pacific region, by exploring two major concepts in sustainability science – transformation and circular bio-economies (CBE) – that are potentially central to achieving the step-change necessary in coastal food systems. The SRA drew on the multi-disciplinary expertise and experience of 19 scientists from five organisations to build a shared understanding of and capacity to enable transformations of food systems: Australia's CSIRO; the Pacific Community (SPC); the Cawthron Institute, New Zealand; AgResearch New Zealand, and the University of Technology Sydney. The results and tools developed by the SRA have formed the foundation for the forthcoming CLIM/2020/178 *Transformation pathways for Pacific coastal food systems* project.

The objectives of the SRA were to:

1. Develop a 'Hot Spot' analysis of coastal food systems in the Pacific where transformation is most necessary, focussing on the Solomon Islands and Kiribati;
2. Scope capacities required to transform food systems in the Solomon Islands and Kiribati;
3. Scope potential integrated food production options based on CBE and other novel technologies, and assess their ability to close the food and nutrition gap in the Solomon Islands and Kiribati;
4. Establish effective partnerships between the project partners for CLIM/2020/178*,* focussing on pilot sites in the Solomon Islands and Kiribati.

A method was developed to identify Hot Spots, where the combination of business-as-usual climate change and population growth projections indicate the greatest magnitude of change may occur between the present day and mid-century. The analysis was tested and conducted at the sub-national scale for the Solomon Islands and Kiribati, the focal PICs for CLIM/2020/178. Results indicated that there are regional variations within these countries. In the Solomon Islands, Guadalcanal Province is likely to experience the greatest changes, largely due to intrinsic population growth, exacerbated by possible in-migration and urbanisation from other regions. Central Province and Malaita Provinces may experience less extreme change. In Kiribati the Phoenix Islands group are most at risk due to a combination of sea level rise and population growth, followed by the Gilbert Islands. These results provide important information with which to guide ongoing government, donor and aid responses, and have informed the scaling-out strategy for the CLIM/2020/178 project. They also highlight the 'multiplier effect' of population growth when combined with climate change.

Potential futures for food systems in the Solomon Islands and Kiribati were also explored more qualitatively, by identifying current drivers and their trends, including climate change, population, socio-economic and nutritional aspects, and projecting these forward in time.

Indicators to measure intentional transformative capacity were also collated from the literature, and adapted to food system contexts in the Pacific, which to date has not been attempted.

Using a typology of coastal food systems for coral atolls (e.g. Kiribati) and volcanic islands (e.g. Solomon Islands), the team investigated potential CBE opportunities where waste from one form of production could act as an input to another. For coral atolls, the use of tuna waste as fertiliser for agriculture was ranked the most feasible, followed by small-scale livestock production where waste can be used as fertiliser and to generate biogas. Integrated multi-trophic aquaculture, open ocean farming of algae, and small indigenous fishery species also provide opportunities. For volcanic islands, tuna and coconut waste could be combined to fertilise gardens, followed by integrated urban backyard systems incorporating aquaponics and biosolids from human waste. Most of the material flows involved marine-terrestrial transfer, rather than vice versa, particularly for the coral atolls.

Applying downscaled business-as-usual climate and population projections collated by the Hot Spots analysis, the climate change-compatibility of these production options was assessed. Using the Assets Drivers Wellbeing Interaction Matrix tool (ADWIM), the impacts on the current and future components of food production in the proposed Kiribati and Solomon Islands pilot sites (Makin Island and Ghizo Island, respectively) were assessed. In both cases, the use of marine fish waste as an input to agriculture was the most climate change-compatible, while for coral atolls land-based elements were highly exposed to inundation due to sea level rise. An additional emphasis for volcanic islands was the opportunity to enhance backyard food production in urban areas, which is relatively immune to climate change or population impacts.

A draft indicator framework was developed to test the potential benefits of alternative options, including productivity, CBE principles, environmental sustainability, livelihoods, nutrition, resilience to shocks, social equity and culture. Testing the framework against the tuna waste opportunity showed that not all indicators would be relevant for all production systems or locations, and that social and cultural aspects would have to be adapted to local contexts and priorities. Indicators could also be weighted according to local priorities.

The results of the Hot Spots analysis, the transformative capacity indicators, alternative production options and their climate change compatibility, and assessment indicators have been incorporated into the design of CLIM/2020/178. The background data collated on food system status, trends and potential futures will also be applied in the project, along with the communication products. However, the draft indicators and alternative production system opportunities will be refined through the participatory activities that will take place in CLIM/2020/178.

From this SRA, four recommendations are made:

Recommendation 1: Within the Solomon Islands and Kiribati, food system transformational efforts need to be targeted at the Hot Spots of Guadalcanal Province and the Phoenix Islands, followed by Central and Malaita Provinces and the Gilbert Islands.

Recommendation 2: The Hot Spots method should be applied to other PICs, and could be applied at a sub-province level if data resolution and resources allow.

Recommendation 3: Refine and test the transformative capacity and alternative production opportunities with PICs stakeholders, using the two indicator frameworks as an initial starting point.

Recommendation 4: Ground test the biophysical feasibility and potential of the alternative production options, particularly those involving CBE principles. A priority should be those options for the Solomon Islands and Kiribati pilot sites which are likely to be most climate change-compatible.

3 Background

As the populations of Pacific Island Countries (PICs) grow and climate change accelerates, food and nutrition security are coming under increasing pressure. Climate science worldwide has projected an increase in global temperatures of 1.5^{o}C by mid-century at a minimum, and the United Nations is currently warning that such an increase may actually be experienced within the next decade. The Intergovernmental Panel on Climate Change has advised that coral reefs worldwide are projected to decline by a further 70-90% at this level of warming, creating a potential tipping point for the collapse of these ecosystems and the livelihoods and industries that depend on them. Such collapse will have far-reaching consequences for PICs because many coastal communities are highly dependent on reef fisheries. In addition, sea level rise is causing inundation and erosion of productive coastal agricultural land and mangroves.

These reef fishery impacts will exacerbate existing nutritional and health problems, including the ongoing epidemic of non-communicable diseases, by further limiting the availability of protein and micro-nutrients. The current COVID-19 pandemic is also revealing the vulnerability of many rural coastal areas due to their reliance on imported foods and fragile supply chains, and the necessity to secure or rebuild local food resources to increase resilience during such crises. COVID-19 has also caused emigration of people from urban areas back to home villages, placing unprecedented pressure on local food resources. Consequently, there is an urgent need to identify and implement solutions that will transform coastal food production in the most vulnerable areas to improve food and nutrition security in ways that will be achievable and sustainable despite the severe climate change impacts expected in the coming decades.

In 2015 the Pacific Community (SPC) published *A New Song for Coastal Fisheries Pathways to Change* which estimated that due to population growth and declining fish biomass and habitat, there would be an annual fish supply deficit (or ‘food gap’) of 115,000 tonnes by 2030. A key recommendation of the New Song was for integration of the multiplicity of existing initiatives, scaling up of community-based fisheries management, and political engagement to acknowledge the gravity of the problem and promote coordinated responses. There was also recognition that closing the food gap will require alternative and diversified sources of protein and livelihoods, a holistic approach that engages all elements of food systems and acknowledges multiple pressures and drivers of change that interact with climate change (e.g. population growth, unsustainable fishing, land use change, urbanisation, tourism and pandemics). This requires an integrated systems approach which links communities with government sectors (e.g. fisheries, agriculture, health and education), and also the private sector, NGOs, regional bodies and donors to generate collective and rapid action.

Much ACIAR research has explored potential technical innovations that could increase coastal food production and diversify livelihood opportunities in the Pacific. In addition, the SPC has piloted various aquaculture technologies including aquaponics in Fiji and the Marshall Islands, and inland integrated aquaculture using tilapia, chickens and ducks in Fiji and Vanuatu. Most recently, in 2019-2020 SPC initiated the *Food Systems for Health and Nutrition Integrated Program* to better coordinate, partner and resource food systems-thinking across SPC’s activities with Pacific Governments. This program has various objectives and implementation modalities, one of which is the piloting of novel research that supports integration of marine and land-based production systems. Another relevant and emerging area of research is ‘circular bio-economy’ principles that would involve recycling of organic materials to enhance more efficient input and waste use, nutrient cycling and productivity. The New Zealand Government’s Ministry for the Environment and AgResearch New Zealand have established a Circular Bio-economy Group to examine these opportunities, but so far not from the perspective of transforming food systems in PICs.

With the exception of the SPC's current *Food Systems for Health and Nutrition Integrated Program* and the ongoing ACIAR project *Agriculture and fisheries for improved nutrition: integrated agri-food system analyses for the Pacific region* (FIS/2018/155), there have been few research initiatives that apply a systems approach to analysing the growing food crisis in coastal regions of the Pacific, and which aim to integrate technological innovations with cultural, social and political perspectives. In addition, only the *Climate change and Pacific food systems: decision-making for transformational change* (WAC-2019-148; Butler et al. 2021) has explored participatory multi-stakeholder action research that can identify appropriate solutions and generate transformative capacities. The current COVID-19 crisis has emphasised this necessity and also provides a potential window of opportunity to explore and trigger transformational change. Furthermore, while climate change is often noted as a rationale for why these projects are worthwhile, few if any have explicitly considered the risks of fishery collapse, suitable alternatives to complement or replace fisheries, and thus the need for innovations that boost coastal food production.

This SRA contributed to the growing need to understand future food systems change in the Pacific region. The SRA explored two major concepts in sustainability science – transformation and circular bio-economies – that are potentially central to achieving the step-change necessary in coastal food systems.

3.1 Key concepts

3.1.1 Food system transformations

The term 'transformation' has many different applications and interpretations in the sustainability discourse (Park et al. 2012, Feola 2015). At its broadest, it implies a radical shift to something fundamentally different, rather than marginal or 'incremental' improvements and technological fixes to existing practice and behaviour. Ultimately, a transformation requires fundamental changes to the structure, function, relationality, and cognitive aspects of social, technical, and ecological systems, and leads to new patterns of interaction and behaviour (Patterson et al., 2017).

Scoones et al. (2020) refine the term's use into three categories. First, *structural transformation*, which is concerned with politics, economy and society, and can involve revolutionary shifts in power and control at key moments. These may be proactively induced or occur unexpectedly. Second, *systemic transformation* where a bounded social-ecological system or socio-technical system shifts to a new configuration or identity following changes in controlling variables, whereby thresholds are passed that cannot be easily reversed. Third are *enabling approaches* which take a more activist and intentional stance, focussing on building the capacity of actors to achieve structural or systemic change that delivers more desirable outcomes.

In terms of agriculture and climate change, transformation is often viewed through the systemic lens described by Scoones et al. (2020). It is invoked when incremental adaptations are not sufficient to maintain the current form of food production, and an alternative must be found (Walker et al. 2010, Kates et al. 2012, Park et al. 2012, Rickards and Howden 2012, Vermeulen et al. 2018; and see Fig. 1). The World Resources Institute (Carter et al. 2018, p. 3) extends this approach to *transformative pathways,* which are 'coordinated sequences of short- and medium-term actions or projects that enable shifting agricultural production systems through significant, widespread changes to become more resilient to longer term projected future climate impacts'. Notably, these conceptualisations only consider food production rather than food systems, which are defined as "all the elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities that relate to the production, processing, distribution, preparation and consumption of food, and the output of these activities, including socioeconomic and environmental outcomes" (HLPE, 2020, p. 11).

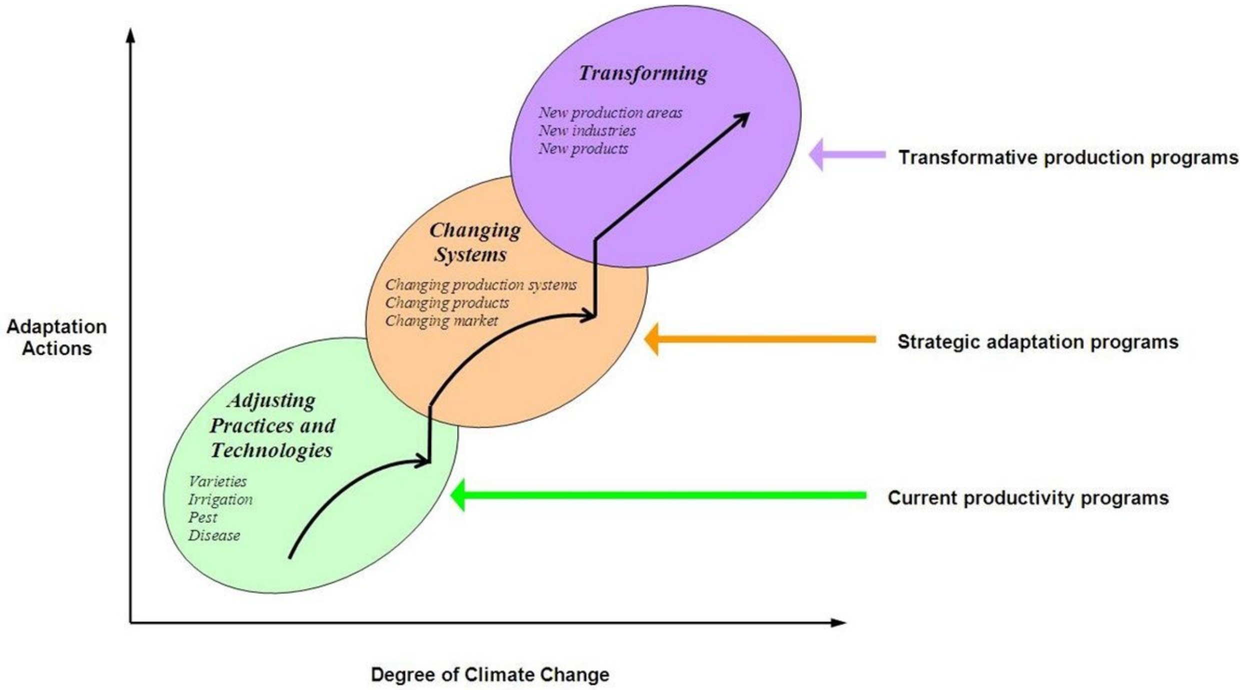


Figure 1. Food production and food systems may have to shift from current to more transformative production systems (from Howden et al. 2010)

Rapid transformations are necessary for food systems if they are to become more sustainable, equitable, and healthier (Slater et al., 2022). While there is growing literature on food systems transformations, the focus has remained on 'what' needs to be transformed (such as technologies), and less on exploring the processes entrained in 'how' to enable a transformation. A focus on process proactively builds enabling capacity that can tackle the underlying structure of political and social-ecological systems (Vogel and O'Brien, 2021), thereby intentionally changing rather than passively waiting for it to occur. Such proactive, process-based transformational effort has the additional benefit of building stakeholder capacity to anticipate and navigate future uncertainty (Leventon et al., 2021).

The concept of transformative capacity (Wolfram, 2016) has so far only been theorised and not tested empirically in the field of food systems transformations. Instead, research and policy on food systems transformations continues to focus on macro-scale changes in trade and diets (Slater et al., 2022), yet calls for transformations continue to ignore the rural poor and their agency in any transformational process (Davis et al., 2022). Hence the role of power, social relations and agency in transformative capacity has yet to be considered.

3.1.2 Circular bio-economies

A circular bio-economy (CBE) considers the intersection between the technosphere and the biosphere, where biological ecosystems interact with inputs, society and technology. It consists of primary resources (e.g. soil, pastures, rain, biodiversity, solar radiation, fresh and marine water bodies, natural reserves), carriers (e.g. electricity, fuels, animals, water), end uses (e.g. food, fibre, materials) and wastes (heat, emissions, excreta, degraded water, pollutants). Fundamentally a circular bio-economy is based on the principles of reducing waste and pollution by keeping products and materials in use, and regenerating natural systems (EMF, 2015), therefore posing a sustainable alternative to the conventional linear economy of 'take-make-dispose'.

This alternative approach is readily applicable to food systems, where it can mitigate greenhouse gas emissions by (re)utilising waste and generating self-sufficiency, therefore building resilience to supply chain shocks, as recently experienced globally by the COVID-19 pandemic. Such disruptions to input supplies raise the cost of on-farm production, consequently increasing food prices in value chains downstream. This is especially true for low-medium income countries that struggle to purchase inputs for agricultural production. However, very little attention is given to circular bio-economy opportunities in many low-income and medium-income countries whose food systems are potentially more exposed to climate or other shocks.

PICs depend on agriculture and fisheries for their economic development and livelihoods, both in terms of exported commodities and subsistence. Food system value chains are also fragmented and highly diverse across the Pacific. According to Robins et al. (2020), Fiji and Samoa have more than 60% of their total protein intake derived from imported products, while Kiribati, Vanuatu and Solomon Islands import 30-40%. At the same time, Pacific countries have many food resources that are either unutilised and wasted or used inefficiently (Glatz, 2012).

Combined with the growing pressure of climate change on food security, plus burgeoning non-communicable disease prevalence, these characteristics suggest that there are significant opportunities for CBE principles to contribute to a systemic transformation of Pacific coastal food systems. Being generally small and bounded, islands provide potentially discreet locations within which circularity can be explored and trialled. In particular, the integration and recycling of organic wastes as inputs to food production could be practicable. In some cases, historical practices which have been abandoned due to the influx of imported foods may provide sources of knowledge on which to revitalise local food production, stimulating waste reduction and contributing to improved diets in the process.

4 Objectives

This Small Research Activity (SRA) aimed to build a conceptual and technical foundation for a larger ACIAR-funded project (CLIM/2020/178 *Transformation pathways for Pacific coastal food systems*) that will test and implement tools and processes to build transformational capacity, with a focus on pilot sites in the Solomon Islands and Kiribati. The SRA drew on the multi-disciplinary expertise of 19 scientists from five organisations to build a shared understanding of and capacity to enable transformations of food systems:

- CSIRO: CSIRO has been undertaking research for development across the Pacific region for more than 25 years, focussing on food systems, agriculture, aquaculture and fisheries, nutrition, climate adaptation and mitigation, and decision-support processes for transformation.
- SPC Land Resources Division, Strategy, Planning, and Learning Division, and Fisheries, Aquaculture and Marine Ecosystems Division: These divisions are leading the *Food systems for health and nutrition integrated programme*. This SRA worked with SPC to identify priority locations and novel production systems that could augment the emerging program, supporting their cross-divisional work and potential future case studies.
- Cawthron Institute, New Zealand: The Cawthron Institute provides expertise in state-of-the-art aquaculture technology, food safety, fisheries and coastal governance research, plus existing relationships with government officials in Kiribati in the development of community-based aquaculture.
- AgResearch New Zealand: AgResearch NZ brought multi-disciplinary skill sets in agricultural and food systems, nutrient cycling, and CBE research and practice.
- University of Technology Sydney (UTS): UTS has been supporting SPC's *Food systems for health and nutrition integrated programme*, and also led the PICs component of the recently completed ACIAR project CS/2020/146 *Assessment of food system security, resilience and emerging risks in the Indo-Pacific in the context of COVID-19*.

The objectives of this SRA were to:

1. Develop a 'Hot Spot' analysis of coastal food systems in the Pacific where transformation is most necessary, focussing on the Solomon Islands and Kiribati;
2. Scope capacities required to transform food systems in the Solomon Islands and Kiribati;
3. Scope potential integrated food production options based on CBE and other novel technologies, and assess their ability to close the food and nutrition gap in the Solomon Islands and Kiribati;
4. Establish effective partnerships between the project partners for CLIM/2020/178 *Transformation pathways for Pacific coastal food systems,* focussing on pilot sites in the Solomon Islands and Kiribati.

Consequently, the research questions posed by this SRA were:

Question 1: Which Hot Spot sub-national regions in the Solomon Islands and Kiribati face the greatest future food and protein deficits due to climate change and other drivers?

Question 2: How can the transformational capacity of these Hot Spots be measured?

Question 3: Which integrated or CBE technologies could be applied to transform coastal food production in the Solomon Islands and Kiribati?

Question 4: How can feasibility and sustainability outcomes from these options be assessed?

5 Methodology

5.1 Island typologies

There are various ways of organising analysis into the diversity of climatological, hydrological, cultural, and agricultural systems of the Pacific. The PICs are generally organised around three sub-regions: Melanesia, Polynesia, and Micronesia. Melanesia has the largest of islands, with weather, freshwater, and land conditions suitable for agriculture and forestry. Polynesian islands are smaller in size but their characteristics vary greatly, with some favourable for agricultural production. Atolls are found throughout all three regions, and are low-lying reef islands with sandy soils and limited freshwater. Some nations are comprised exclusively of atolls islands, such as Tuvalu and Kiribati. Coastal fishing is common across the entire Pacific, contributing to the primary or secondary source of income for up to 50% of households (SPC, 2015).

For the analysis in this study, we followed the typology of islands used in ACIAR's CS/2020/146 *Assessment of food system security, resilience and emerging risks in the Indo-Pacific in the context of COVID-19* (Robins et al., 2020). The typology, originally developed by Taylor et al. (2016), organised food production systems into the following three island types:

> **Group 1**: relatively large PICs of Melanesia (Papua New Guinea, Fiji, Solomon Islands, New Caledonia and Vanuatu).
> **Group 2**: middle-sized PICs of Polynesia (Samoa, Tonga and French Polynesia).
> **Group 3**: land-poor micro-states that are predominantly atolls (e.g. Kiribati, Niue, Tokelau, Tuvalu, Wallis and Futuna, Guam, Nauru, Cook Islands).

The above typology guided our initial design into understanding the types of climate futures that might exist in the region under business-as-usual scenarios. As the study progressed, we focused on the Solomon Islands (Group 1) and Kiribati (Group 3) as examples of the diversity of geological, cultural and food system characteristics that exist in the region, and to inform the development of the larger ACIAR project CLIM/2020/178.

5.2 Current and future food system trends and drivers of change

To understand qualitative and quantitative trends in food systems and their drivers of change in the region, we first searched databases for Pacific and food security related scientific and grey literature, including terms related to climate change, fisheries, agriculture, nutrition, and development. The search was initially undertaken for four PICs to cover the three island types: Tonga, Vanuatu, Solomon Islands, and Kiribati.

A total of 471 references were imported into Endnote, and screened by abstract to determine their suitability in providing projections of future food systems. The resulting short-list informed our characterisation of the biophysical, socio-economic and food security conditions of the four countries. While acknowledging the multiple facets of complex food systems, these three variables allowed us to assess interactions between the primary human and environmental aspects of food systems, and their status and trends.

The drafting of the Hot Spots analysis for the Solomon Islands and Kiribati (see 5.3 below) was complemented with a futuring activity undertaken by the research team to hypothesise an 'imagined' future vision for the country after an 'inflection point' in the system (Merrie et al., 2018). Inflections points trigger changes that require a system to either transform, or fall back into a state of balance. An example would be frequent or permanent inundation of villages due to sea level rise that result in change in ecology, technology, governance and culture, affecting the dynamic interaction of people with their environment.

5.3 Hot Spots analysis

The Hot Spots analysis focussed on two primary drivers of change identified in the literature review above: climate change and population growth. Quantitative data were collated for the present and for business-as-usual projections for near-future dates, determined by data availability (2050 scenario for the Solomon Islands and Kiribati). Projections of food and nutrition security variables were also important, but despite the impacts of climate change being identified as a high priority in the region, none were available. While statistics exist for the current status of food consumption and nutrition, few studies have forecasted food security outcomes and how they will be influenced by changing climates and socio-economic patterns (Westerveld et al., 2021). Hence developing a method for generating food insecurity scenarios for PICs under different socio-economic and biophysical conditions is an important area of future research.

Data were sourced for appropriate sub-national spatial units, which were determined to be provinces for the Solomon Islands and island groups for Kiribati. The Hot Spot prioritisation was based on calculations of absolute changes between the present and future scenarios (Figure 2). The method assumed that future impacts on food systems and production will be greatest if changes (increases or decreases) are higher. The first step of the method involved the calculation of the absolute value of the percentage change for each of the variables used in the model ($var_{a,b,...}$) investigated:

$$\Delta var_{a,b,...} = |(a_{2030} - a_{2020})/a_{2020}|$$

The second step was to rank (1 is lowest rank, i.e. minimal change) the changes in each variable compared to one another. For example, changes in rainfall were ranked at the scale of provinces in the Solomon Islands (eight provinces, ranking 1-8) and island groups (Gilbert, Phoenix and Line Islands) in Kiribati (ranking 1-3).

The third step was to calculate the overall mean value of the rank for each spatial unit. The higher the rank value, the higher the priority (1 lowest, 8 highest). In the example shown in Figure 2, Province C has the highest priority (mean rank 2.3), followed by Province A (mean rank 2) and Province B (mean rank 1.7). Appendix 1 provides the climate change and population projection data and data sources used to calculate the rankings for the Solomon Islands and Kiribati.

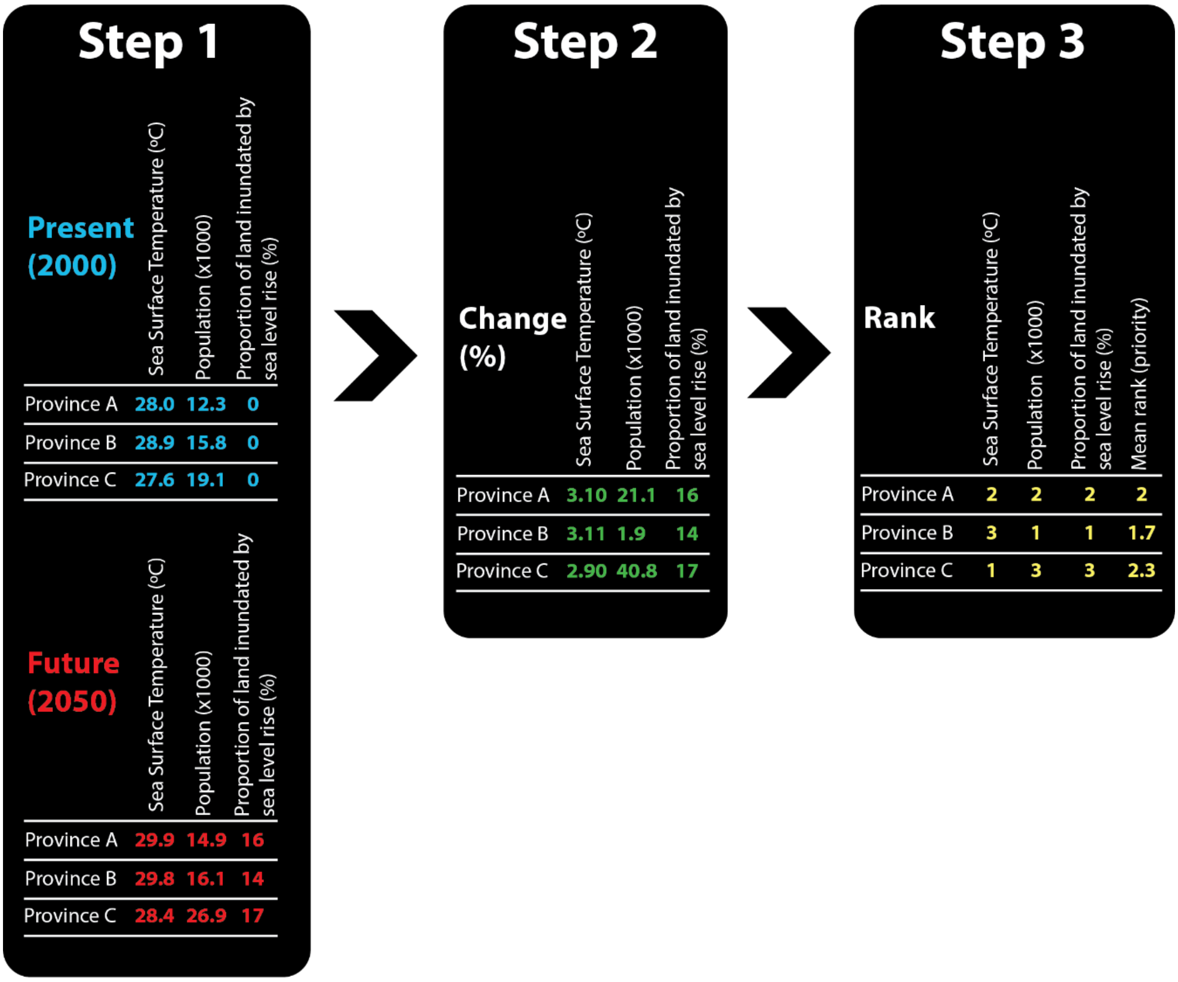


Figure 2: Summary of Hot Spot prioritisation method with fictional examples to demonstrate how climate change and population projection data were used to calculate prioritisation rankings.

The priority data was visualised spatially using heat maps which colour-coded spatial units with their respective priority ranks. For example, in Kiribati the highest rank was colour-coded in red, medium priority yellow and low priority green. It is important to note that the colours are not normative (i.e. good or bad change). Rather, they illustrate the expected magnitude of change. Also, the input data have related uncertainties and confidence limits, and for climate change assumed a 'business-as-usual' global emissions trajectory. Hence the rankings only provided a guide about anticipated changes by 2030 based on business-as-usual climate and population models.

5.4 'Futuring' Pacific food systems

The growing field of futures literacy focuses on the utility of using imaginations of the future to trigger actions in the present. Developing futures literacy is an important component of planning for uncertain futures (Mangnus et al., 2021; Pouru-Mikkola and Wilenius, 2021), as it creates options for challenging current systems and identifying strategies for building alternative futures.

To envisage a transformed food system for the Solomon Islands and Kiribati, we undertook a desktop 'futuring' exercise that drew from the trends and thematic issues identified in the literature review (see section 5.1). To avoid thinking about current interventions as necessarily transformative (for example, scaling-up and scaling-out of modifications to existing farming practice; see Figure 1), we imagined socio-economic and biophysical conditions that may exist in 2100 (i.e. beyond a potential inflection point). To develop future food system imaginaries, we adapted Spijkers et al. (2021) to create narrative scenarios which built on the underlying drivers derived from the literature under four themes: environmental, political, social and economic (Figure 3).

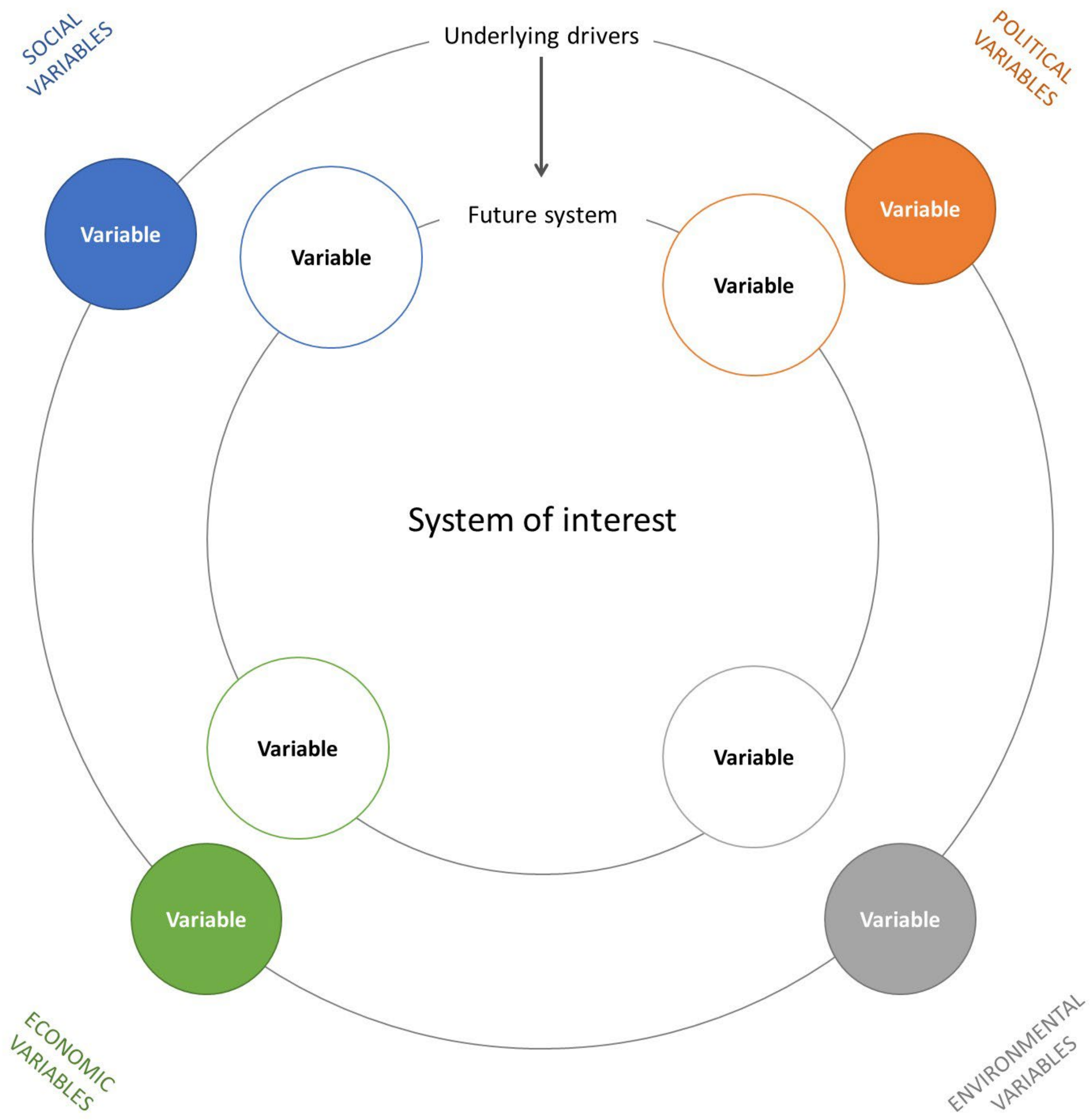


Figure 3: Futures framework used for narrative development (adapted from Spijkers et al. (2021).

5.5 Transformative capacity indicators

To develop an assessment framework for evaluating intentional transformative capacity, we drew on three theoretical building blocks – transformative adaptation, transformations, and adaptive capacity – all of which have seen accelerated growth in scholarship, albeit to a lesser extent with respect to food systems. These three themes provide complementary foci which are necessary to support the analysis of social-ecological systems and their responses to rapid global environmental change. This theoretical foundation was used to critically examine the most comprehensive set of indicators for transformative capacity developed to date, by Wolfram (2016). We adapted these into a set of draft indicators that could be tested and refined empirically in the forthcoming CLIM/2020/178 *Transformation pathways for Pacific coastal food systems* project, and to develop activities in the project that may build intentional transformational capacity.

5.6 Options for transformed food production

To identify possible options for transformed coastal food production, we 1) undertook an exercise to understand and categorise current coastal food production systems in the Pacific, 2) explored how these systems may be integrated or improved to encourage transformation, and 3) assessed the future climate compatibility of these options.

5.6.1 Characterisation of food production for two Pacific island types

The Pacific island typology used in section 5.1 was further simplified to represent predominant food production systems. While there are several ways to classify Pacific islands based on lithology and altitude (Nunn et al., 2016), we opted to draw a distinction between *coral atolls* (with reference to Kiribati as a pilot site for CLIM/2020/178) and *volcanic islands* (with reference to the Solomon Islands as a pilot site).

Led by the SPC experts within the team and their broad knowledge of agriculture and fisheries in the Pacific, we conducted a high-level exploration of the range of coastal food production systems typical to each island type by searching databases for terms related to major production categories including fisheries, aquaculture, crops, agroforestry, household livestock and farming systems. These production categories were then classified into sub-categories, each with its own brief contextual summary and description of the main production inputs, outputs and waste streams.

5.6.2 Exploring alternative food production options

During on-line workshops, the team examined the list of food production systems typical to coral atolls and volcanic islands, and explored how these systems could be integrated or enhanced. This process involved 1) examining and discussing opportunities to integrate wastes from production systems as inputs to other production systems, 2) listing the potential impacts of such integration (with particular reference to scale of impact), 3) listing the possible limitations of integration and 4) highlighting information gaps. The analysis also suggested any new food production opportunities that did not necessarily require integration but would complement the alternative options.

A matrix was then created to score the potential for the use of waste from one production component to become an input to another. Simple scoring criteria were used to assess integration potential (0 = not possible, 1 = possible but limited feasibility, 2 = average, needs lots of scoping, 3 = looks promising, 4 = excellent opportunity). This was repeated for both island typologies. The output from this process was a prioritisation of proposed alternative food production for the two island types based on either a high integration potential and/or new opportunities for producing food. Selected examples were then transposed into flow diagrams, and posters were produced as communication aids for use in the forthcoming CLIM/2020/178 project.

5.6.3 Assessing climate change compatibility of alternative food production options

To assess the compatibility of the proposed alternative production options with anticipated climate change, the team undertook an analysis of future climate projections for the proposed pilot study locations in the Solomon Islands (Sagheraghi, Ghizo Island, Western Province) and Kiribati (Makin Island, Gilbert Islands). An inventory of current food production species (which would form components of potentially transformed production systems) was made, and climate change impacts on each assessed. Using the team's cross-disciplinary expertise, an on-line workshop was then held to consider the implications of the impact assessments for the feasibility of alternative production options.

Future climate change impacts on food production species

Our analysis was based on a preliminary assessment of future business-as-usual climate change impacts on current production species for each site using the Asset Driver, Well-being Interaction Matrix (ADWIM) tool (Skewes et al., 2016). The inventory of key production species was compiled from a literature review of each pilot site, and through conversations with SPC team members with local in-country expertise. Priority species were identified based on their local value, cultural importance, and relevance to the alternative production options, covering both terrestrial and aquatic environments.

As well as allowing stakeholders to semi-quantitatively value the ecosystem goods and services (EGS) that they utilise, ADWIM models the impacts from climate change and population change on these EGS, based on their exposure and sensitivity to these drivers, and ultimately the potential impact on human well-being (Figure 4). Potential impacts (i.e. the sum of exposure and sensitivity) on specific EGS are derived from relevant scientific literature or expert knowledge which is stored in a library within the ADWIM tool. Outputs are provided as the sum of potential future impacts (+ or -) resulting from changes in each driver and related stressors (e.g. for climate change: sea level rise, sea surface temperature, ocean acidification) on each EGS. Data and data sources used in this ADWIM analysis are presented in Appendix 2.

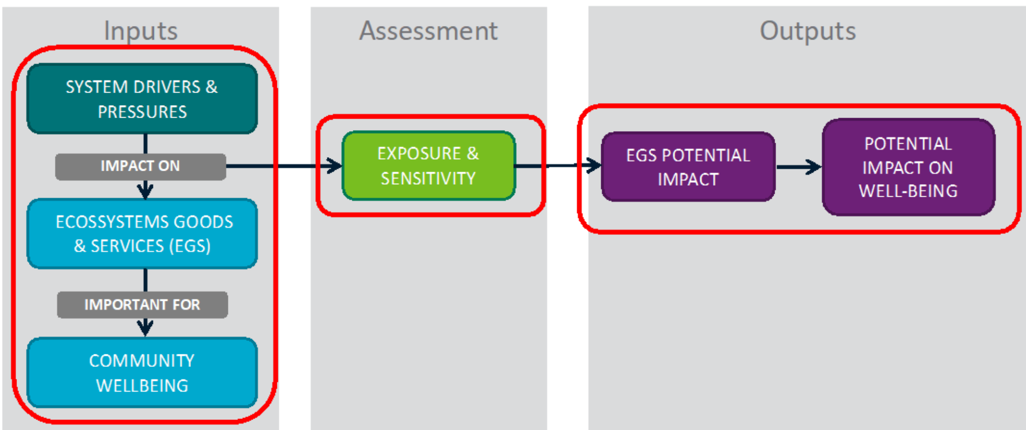


Figure 4: Overview of the Asset Driver, Well-being Interaction Matrix (ADWIM) tool used to assess the impacts of climate and population changes on key food production species.

Assessing climate compatibility of production options

An on-line workshop was held to discuss the climate compatibility and feasibility of the proposed alternative food production options for the two pilot sites. Applying the ADWIM analysis for both locations, the team discussed the ecological viability (i.e. climate impacts on the key production species) and the physical viability (i.e. the impact of climate extremes on production and infrastructure) of each of the proposed options for the pilot site. The workshop also examined any site-specific opportunities or modifications to the proposed options that had not been captured at the island type level. Finally, each alternative production system was given a simple colour-coded overall climate compatibility assessment based on their ecological and physical feasibility.

5.7 Developing a preliminary assessment framework

To develop an assessment framework to measure and communicate the feasibility and relative benefits of proposed alternative production options in terms of sustainability and social outcomes, the team undertook a literature review to scope the range of potential food system performance indicators. We targeted literature relating to food 'systems assessment frameworks', 'Pacific food systems', 'Sustainable Development Goals', and 'food security goals'. Where possible, we made an effort to prioritise literature related to the Pacific region. We also drew on the experience of our multi-disciplinary team members to provide specialised insights on food production relating to nutrition, productivity, social equity, cultural acceptability, BCE and resilience.

We referenced over 70 bibliographical sources to create a list of performance indicators. Two on-line workshops were held to discuss the inclusion of potential indicators, the description of each indicator and possible scoring criteria for each. Care was taken to ensure that indicators included social, cultural, ecological, and economic assessments of food production options. Scoring criteria were typically simplified to three options (e.g., good, medium, bad), each with its own explanation.

Consideration was also given to existing data sources for each indicator, data gaps (i.e. data needed to enable the use of the indicator), 'explainability' of each indicator to affected Pacific island communities, and how best to weight each indicator given the changing contexts of different food production systems and locations. A simple weighting test was performed by scoring the relevance of each indicator against one of the proposed food production options. This relevancy weighting test would eventually need to be performed more systematically and ground-truthed within a local participatory context.

6 Achievements against activities and outputs/milestones

Objective 1: Develop analysis of 'Hot Spot' coastal food systems in the Pacific where transformation is most necessary, focussing on the Solomon Islands and Kiribati

no.	activity	outputs/ milestones	completion date	comments
1.1	Hot Spot analytical framework	Island typology, downscaled climate change and population growth driver data collation	November 2020	
1.2	Hot Spot analysis	Maps of Solomon Islands (provinces) and Kiribati (island groups) Hot Spots	November 2020	

Objective 2: Scope capacities required to transform food systems in the Solomon Islands and Kiribati

no.	activity	outputs/ milestones	completion date	comments
2.1	Futures narratives for transformed food systems	Futures narratives for Solomon Islands and Kiribati	January 2021	
2.2	Transformative capacity indicators	Draft indicators of transformative capacity	January 2022	

Objective 3: Scope potential integrated food production options based on CBE and other novel technologies, and assess their ability to close the food and nutrition gap in the Solomon Islands and Kiribati

no.	activity	outputs/ milestones	completion date	comments
3.1	Categorisation of coastal food production systems for island typologies	Collation of primary inputs and waste streams of production systems for volcanic islands and coral atolls	November 2020	
3.2	Identification of CBE opportunities in food production systems	Opportunities for integration and novel food production options in volcanic islands and coral atolls	March 2021	
3.3	Climate compatibility of production options for Solomon Islands and Kiribati pilot sites	ADWIM analysis of climate impacts and feasibility of production options	May 2022	

3.1	Preliminary assessment framework for alternative production options	Indicators of relative sustainability and social benefits of alternative production options	May 2022	

Objective 4: Establish effective partnerships between the project partners for CLIM/2020/178 Transformation pathways for Pacific coastal food systems

no.	activity	outputs/ milestones	completion date	comments
4.1	Agreed project design for CLIM/2020/178, budget and coordination between partners	Approved project design, plan and budget	August 2022	

7 Key results and discussion

The following sections present integrated results for research Question 1, focusing on Hot Spot analyses and food system futures.

7.1 Kiribati: Hot Spots and food system futures

Kiribati is composed of 32 coral atolls and one ‘raised’ island, which are home to approximately 120,000 people. Of these, 45% are rural, spread out across the three island groups: Gilbert Islands, Phoenix Islands and Line Islands. While land area is very limited at 811 km^2, the total Exclusive Economic Zone is larger than the continental USA at 3.4 million km^2 (Figure 5). Unlike many of its Pacific neighbours, Kiribati sits outside the cyclone belt, avoiding the extreme weather events typical of other Western Pacific nations which threaten infrastructure and livelihoods. Culturally, it is largely Micronesian, but Polynesian influences and presence exist throughout the archipelago. The country is young, and with a vast ocean resource, has tremendous potential for a radically transformed ocean-based and technology-driven food system – but this system will be dependent on the recovery and reproduction of marine habitats in light of projected ocean acidification and sea surface temperature rises. More broadly, food systems in Kiribati are rapidly changing due to the intersection of population health profiles, a young population, and increasing impacts of sea level rise.

Figure 5: Kiribati and its Exclusive Economic Zone

7.1.1 Food and nutrition context

Kiribati currently is living in an obesogenic food environment, where a combination of trade and shifts in food availability and consumption are influencing population health. Indigenous traditional diets characterised by the consumption of fresh fish, tubers, fruit and green leafy vegetables, legumes and meat have transitioned to Westernised diets mostly based on fatty and processed food, oils and confectionary (Eme et al., 2019a;

Farmery et al., 2020). Fish and brown coconut are the main contributors to dietary energy produced domestically – however, only 12% of total energy intake comes from home production. The remoteness and poor soils of the islands make access and regular consumption of fruit and vegetables difficult – in Kiribati the daily per capita intake is only 130 grams, well under the 400 grams recommended by the World Health Organisation (WHO). Poverty is a major driver of food insecurity, with 22% of the population living below the poverty line and 41% experiencing moderate to severe levels of food insecurity. Food and nutrition security is not on track to meet Sustainable Development Goal 2 Zero Hunger by 2030. Over 60% of food is purchased, and of this, cereals contribute 59% of total energy intake. Household incomes are increasingly being used to access imported non-traditional foods – over 50% of income is used to access food, and imported foods make up 72% of the diet (Sievert et al., 2019).

Healthy diets are challenging to sustain in Kiribati, with the majority (61%) of adults from South Tarawa reported to consume no more than four food groups (Eme et al., 2019b). Protein and sodium intakes are considered high among this population, but calcium and potassium intakes are low. High sodium intakes were also reported in a study of householders in urban South Tarawa and rural Butaritari (Eme et al., 2020). The same households had low intakes of vitamin A, calcium, iron and zinc, which may be a reflection of their low diet diversity, consisting mostly of non-traditional and refined foods (Eme et al., 2020). Thiamine deficiency has also been reported among women in the Kuria atoll in South Tarawa which may be due to diets consisting mostly of rice, sugar and small amounts of fortified flour. Poor dietary habits have also been reported by the Global School-Based Student Health Survey among adolescents, in particular a low consumption of fruit and vegetables (85.4%), and moderate consumption of fast food (43.7%) and soft drinks (22.4%).

Nutrition-related diseases, such as Type 2 diabetes, are becoming more prevalent in Kiribati (WHO, 2021). The Global Nutrition Report indicates some progress towards stunting targets, yet they remain high at 15.2%. The prevalence of overweight children under 5 is 2.1%. Obesity and diabetes prevalence is considerably higher than the Solomon Islands, with more than half of women (53.7%) and less than half (45.4%) of men being obese, and approximately one-quarter of women (26.2%) and men (24.8%) living with diabetes (Global Nutrition Report, 2021). Anaemia prevalence (32.6%) among women is similar to that reported in the Solomon Islands (Global Nutrition Report, 2021). A study of 10 islands found higher rates of stunting (23.6%), lower rates of anaemia (21.9%) and similar rates of obesity (46.4%) compared to that reported in the Global Nutrition Report. Approximately 10% were underweight. Moderate rates of anaemia were also reported among children under 5 years of age (34.2%) and wasting was reported among almost 7% of children under 5 years of age.

Under a business-as-usual scenario, diets are expected to continue to change as a result of urbanisation, further increasing demand for marine resources and imported processed food (Farmery et al., 2020).

7.1.2 Climate context

The climate in Kiribati is tropical, warm and humid, where air temperatures are regulated by the temperature of the oceans. Rainfall is highly variable from year to year and across the three island groups (FAO, 2019a). The climate is strongly influenced by the El Niño Southern Oscillation (ENSO), which moves warm ocean waters from the west to the east of the Pacific Ocean, bringing wetter and warmer conditions to Kiribati in the years it occurs (World Health Organization, 2018). During La Niña years the climate is characterised by droughts, negatively affecting crops and water security. Freshwater supply is an important consideration in Kiribati because most of its population rely on groundwater (generally within 2 m of the surface) or rainwater for primary or secondary purposes (Pacific Community, 2020; SOPAC, 2007). Currently, storm surges, droughts and over-extraction of groundwater are causing seawater intrusion into fresh groundwater sources and sea level rise will further increase this problem (SOPAC, 2007). Owing to high inter-annual variation, it is unclear whether rainfall will increase or decrease in the future (BoM and CSIRO, 2014c). Nevertheless, climate change will intensify El Niño events, resulting in more severe droughts in the years they occur, reducing agricultural productivity (Lee et al., 2018), as happened during the 2014 droughts.

Ocean acidification is likely to increase with rising atmospheric carbon dioxide levels. Although adult reef fish have not been shown to be directly vulnerable to ocean acidification, their immediate coral reef habitats are at high risk. Coral reefs are considered to be the most vulnerable marine habitat in the tropical Pacific region, with reductions expected in reef-building calcification rates and structural integrity (Johnson et al., 2015). Ocean acidification may threaten commercially important commodities such as molluscs and crustaceans. A recent study (Bednaršek et al., 2020) demonstrated conclusively that increasing ocean acidity is impacting the shells of crab larvae, making them more vulnerable to predation as well as weakening support structures for muscles and possibly leading to loss of important sensory and behavioural functions. While fish don't have shells, the lower pH in the surrounding water and the constant exposure of their cells to this water will impact the pH of the fish's blood – a condition called acidosis[1].

Climate change is already affecting food production in Kiribati. Sea level rise, increases in seasonal and annual temperatures, ocean acidification, and changes in rainfall patterns have been observed (BoM and CSIRO, 2014a). As a result of climate change, crop production, fisheries and freshwater supply are in decline (FAO, 2019a). For example, sea level rise has caused inundation of turtle nesting sites (World Health Organization, 2018), and changes in rainfall are affecting crops. Warmer waters have caused extensive coral bleaching and mortality (Carilli et al., 2012; Magel et al., 2020; Mangubhai et al., 2014; Obura and Mangubhai, 2011), which resulted in a >50% decline in the abundance and biomass of reef fish (Magel et al., 2020). The synergistic effects of climate drivers, such as temperature and ocean acidification can amplify negative impacts on ecosystems such as coral reefs, affecting fish productivity (Dutra et al., 2021).

Sea level rise will be one of the largest disruptors to food production and the urbanisation trend. The most recent predictions suggest that seas will rise by 1.35 m by 2100 (Grinsted and Christensen, 2021), an increase of 25 cm from previous Intergovernmental Panel on Climate Change (IPCC) projections (IPCC, 2019b). This is because climate is changing more quickly than initially thought (Duffy et al., 2021). Higher sea levels will exacerbate current pressures on land resources. At the initial stages of rise in sea level, coastal erosion and flooding will bring saltwater intrusion, negatively affecting fresh groundwater, crops and reducing the amount of land available for housing and agriculture. Crops, like giant swamp taro can tolerate relatively high levels of salinity and are more resilient to sea level rise and salinisation impacts than other crops (Rao et al., 2013). There may be some opportunities as well. For example, vertical reef accretion in response to rising seas may prevent increase in shoreline wave energy and mitigate effects from waves on the shoreline (Beetham et al., 2017).

Although year on year and decadal variability in temperature will still occur, more warmer years and decades are expected in the future (BoM and CSIRO, 2014a). Air and sea temperatures will continue to rise impacting crops and fish, both directly and indirectly (e.g. via decline in coral reef and habitats and increase in the incidence of ciguatera poisoning) (Brodie et al., 2020; World Health Organization, 2018). Higher temperatures will also increase the risk of heat waves, threatening food safety and security (World Health Organization, 2018). Higher ocean temperatures may affect the distribution of tuna as they might seek cooler waters at depth and become more difficult to catch, which

[1] From: https://ocean.si.edu/ocean-life/invertebrates/ocean-acidification

increases the vulnerability of the fishery (Williams et al., 2015). Simultaneous local impacts (e.g. pollution and overfishing) act together with climate change impacts, such as sea-level rise, ocean warming and acidification, leading to interactive, complex and amplified impacts for species and ecosystems (Valmonte-Santos et al., 2016), thus affecting catches and food production in the sea.

7.1.3 Agricultural context

Agriculture is predominantly focussed on subsistence production because poor soil fertility limits cash cropping to coconuts (World Health Organization, 2018). The main traditional foods consumed in the country are giant swamp taro, breadfruit, pandanus, native fig and coconut. The introduction of imported protein, carbohydrates (rice) and processed food has caused a decline in consumption of traditional foods, partially due to the convenient nature of imported foods. Traditional foods are now used only during shortages of food imports or in emergencies (World Health Organization, 2018). Only 60 species of plants are cultivated in Kiribati and their cultivation varies between the island groups according to soil and rainfall conditions. The Gilbert Islands receive high rainfall and can support a wide range of food crops, including water-sensitive species such as banana and edible aroids such as *Cyrtosperma, Alocasia*, *Xanthosoma*, and *Colocasia* as well as relatively water-insensitive crops such as breadfruit, cassava, and sweet potato. These plants are also cultivated in the Line Islands such as Tabuaeran and Teraina (World Health Organization, 2018). More recently, The SPC has initiated a program to increase diversity of food crops to reduce imported food dependency and insecurity. The study has found that sweet potato varieties from Papua New Guinea have the highest yield in outer islands, and cassava cultivars can grow well if adequate compost is available.

7.1.4 Fisheries context

The ocean is a major natural resource for Kiribati – the combined production value of coastal, offshore, and aquaculture fishing was AU$1.3 billion in 2014, with offshore foreign-based operations dominating the catch. The fishing contribution to Gross Domestic Product (GDP: A$31.2 million) is 16.2% of the A$192.9 million GDP of Kiribati in 2014 (Gillett, 2016a). Women often play a hidden but crucial role in the sourcing, marketing, and preparing of fish in island societies (Thomas et al., 2021).

Fish (mostly tuna species) is the main source of protein and income in Kiribati and the country has the highest rate of fish consumption in the world – 62 kg per person per year. (Gillett, 2016b). Fisheries access fees have an average annual value of US$128.3 million, contributing to 70.6% of government revenue. Bell et al. (2021) predict that under a business-as-usual global emissions scenario, total catches will decline by 8% and government revenue by 5.8%. Sea cucumbers (or bêche-de-mer) are also an important export commodity and seaweed farming is the nation’s largest and longest running aquaculture project (World Health Organization, 2018). Other important aquaculture products include milkfish, and giant clams for both food consumption and export to aquarium markets (Gillett, 2016b). The gross value of total aquaculture production in 2014 was estimated to be A$289,757 to fisher-farmers (Gillett, 2016a).

Fish resources are overall in good condition and are abundant especially in the outer islands, but localised over-exploitation exists around urban areas, especially in South Tarawa (Gillett, 2016b). Fishing pressure has been growing in proportion to the increase in the number of households owning fishing boats. A noticeable result is the decline in fisheries production in the Tarawa lagoon. Another important trend in Kiribati is the increase in commercialisation of coastal fisheries, which could have short-term positive impacts on livelihoods, but may jeopardise long-term natural resource access if not managed correctly (Gillett, 2016b). Provision of incomes from commercial coastal fisheries can lead to unhealthy food choices if parallel actions are not taken to change food environments. Under climate change it is projected that fish available to people will reduce from 50 to 42 kg per person per year, indicating a need to substitute this protein source with an alternative.

7.1.5 Socio-economic context

The population of Kiribati grew by 1.7% in 2020 and rates have been varying between 1.5% and 2.2% since 2000. About 57% of the population lives in urban centres, one of the highest levels of urbanisation in the Pacific. Urbanisation is strong, growing at 3.2% per year (United Nations, 2019). Population pressure has led to increased pollution of the limited freshwater resources, and marine ecosystems have been polluted by urban and agricultural runoff. These trends in population growth and urbanisation have led to the degradation of water quality affecting marine ecosystems, particularly fisheries, and human health (Brodie et al., 2020; Gillett, 2016b; Graves et al., *in press*). The population's gender balance in 2020 was 49% men and 51% women. The population is relatively young, with 41% less than18 years old, and only 14% of the population over 50 years old (Republic of Kiribati, 2016). About 71% of the population (over 3 years old) can read and write, with similar literacy rates among men and women.

Population is anticipated to continue to increase strongly, from 112,000 (2015) to 178,000 (2050) and 211,000 (2100). The urbanised population is also expected to continue to grow over the next 30 years at an average annual rate of between 2.8% (2020-2025) and 1.6% (2045-2050), which in absolute numbers represents almost a two-fold increase in the current population, from 68,000 people in 2020 to 126,000 in 2050 (United Nations, 2019). By 2050 about 70% of the population will live in urban centres, as opposed to 57% in 2020 (United Nations, 2019). This growing population, if it stays in Kiribati's sovereign territory, will need more space, food and freshwater to live.

Urbanization will require built infrastructure such as centralized water and sewerage facilities, and more permanent housing and roads. These changes are expected to cause substantial modifications in the shoreline (Bell et al., 2011) and the ocean as infrastructure adapts to sea level rise.

7.1.6 Hot Spot analysis

The climate and population variables for the island groups were collated for business-as-usual development (Table 1). A visualised summary of the Hot Spots for Kiribati is shown in Figure 6. The results suggest some marked differences between the three island groups: the Phoenix Islands will experience the most radical change, driven largely by climatic factors, such as the highest increase in sea temperature and annual rainfall, which in combination with the highest population growth will lead to more densely populated areas due the reduction in land area. The Gilbert Islands will experience medial changes largely because sea temperatures and population growth (and density) are expected to be slightly lower. Finally, the Line Islands are expected to experience the least changes because temperatures both on land and at sea, annual rainfall and population will change less compared to the Phoenix and Gilbert Islands. The primary stressors across the three island groups will be sea level rise and ocean acidification.

Table 1: Projected business-as-usual changes in population and climate drivers in Kiribati. Sources: Population (United Nations, 2018). Biophysical data projections are for a 'very high global emissions' scenario (BOM and CSIRO, 2014d).

Driver of change	2020	2030	2050
Population	122,000	142,000	178,000
Urban population	68,000 (56%)	88,000 (62%)	126,000 (71%)
Rural population	54,000 (44%)	54,000 (38%)	52,000 (29%)
Gilbert Group			
Surface air temperature / sea surface temperature (°C)	28	+0.9 (0.2–1.4)	+1.5 (1–2.2)
Total annual rainfall (mm) (% change) (South Tarawa)	2,000	+18 (2–43)	+30 (-2–70)
Mean sea level (cm)	0	+12 (7–17)	+24 (16–33)
Ocean acidification (Ωar)[2]	3.9	-0.3 (-0.6 – -0.1)	-0.6 (-0.9 – -0.4)
Cyclones (average number per decade)	Rare	Rare	Rare
Phoenix Group			
Surface air temperature / sea surface temperature (°C)	28	+0.9 (0.5–1.2)	+1.5 (0.9–2.2)
Total annual rainfall (mm) (%) (Canton)	500	+13 (1–34)	+23 (-1–60)
Mean sea level (cm)	0	+12 (7–17)	+24 (16–33)
Ocean acidification (Ωar)[2]	3.9	-0.3 (-0.6 – -0.1)	-0.6 (-0.9 – -0.4)
Cyclones (average per decade)	Rare	Rare	Rare
Line Group			
Surface air temperature / sea surface temperature (°C)	28	+0.8 (0.6–1.1)	+1.4 (1–2)
Total annual rainfall (mm) (%) (Christmas Island)	1,050	+5 (-1–11)	+9(-2–19)
Mean sea level (cm)	0	+12 (7–17)	+24 (16–33)
Ocean acidification (Ωar)[1]	3.9	-0.3 (-0.6 – -0.1)	-0.6 (-0.8 – -0.4)
Cyclones (average per decade)	Rare	Rare	Rare

[2] *Arangonite saturation state < 3, shell fish, corals become stressed, and < 1, they begin to dissolve.*

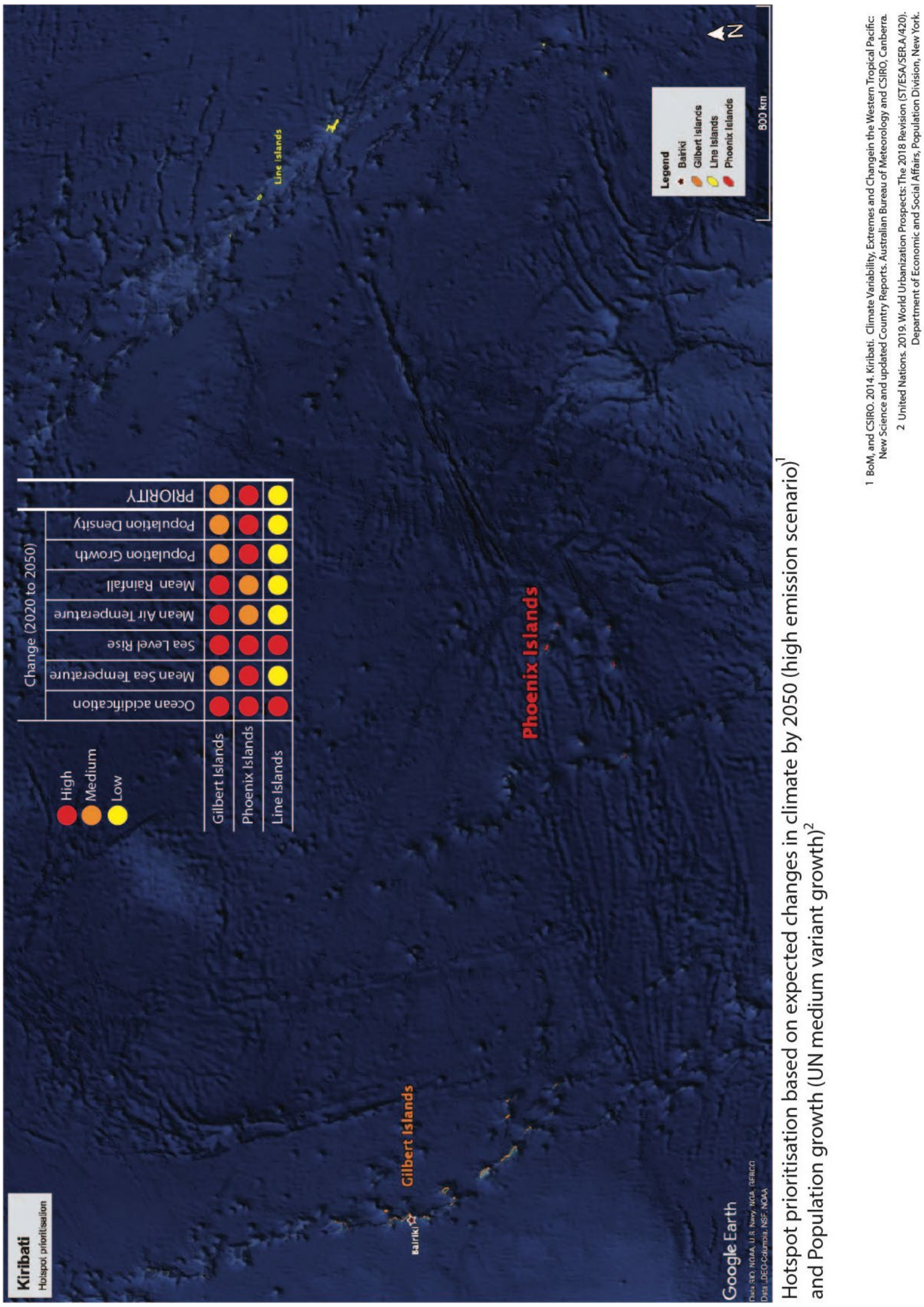


Figure 6: Hot Spots of projected changes across Kiribati in 2050, compared by island groups

7.1.7 A transformed food system in Kiribati

Figure 7 summarises the current drivers influencing the food system (outer circles) and the potential transformations that may take place in a future (2050) system. In blending existing data from published information on trends in the food system, and using narratives and futuring to identify stories of the future, we start to provide some insights about the uncertainties and assumptions that exist in planning for a transformed food system. In Figure 7, we identify possible major transformations by 2050 requiring possible new skills amongst individuals and institutions over the next decade. The transformed system may include characteristics such as:

- **Energy governance** for de-centralised hydrogen and/or solar technologies, including renewable energy-based boat transportation. The remoteness of islands and distribution of food between island groups will require novel energy sources to support food security. Abundant solar capacity may be harvested, requiring new technical and social skills to work in solar power technology.
- **Labour and skills** based on ocean management will be required in light of sea level rise and disappearing land. The ocean is the country's largest asset and core to its identity, offering opportunities to develop a skilled ocean-based labour force for the future.
- **'Acidification ready aquaculture'** is a potential reality given ocean acidification trends. With acidification impacting corals and reef fish habitats, ocean-based food production may have to focus on acid-tolerant species.
- **Remotely-governed ocean resources** after mass-emigration. Customary land ownership rights may remain with individuals and communities after complete inundation of their islands. Kiribati may even become the first mainly ocean state. This has implications for the diaspora population and how they will still govern their traditionally-owned resources.
- **Traditional knowledges and voices** will be important and elevated in the management of the food system, including the growing, distribution and consumption of food, as well as managing the ocean resource.

Figure 7: Current drivers and possible transformed future food system for Kiribati

The analysis above provides a potential future for Kiribati's food system extrapolated from the current trajectories of drivers of change. However, Box 1 goes further by providing a personalised narrative for 'Erena', a young woman living within the potential food system projected for 2050, when there will be a radically altered land and ocean, and a larger population that still has a sense of place and identity, and chooses to reside within the sovereign state boundaries of Kiribati.

Box 1. Future imaginary - living in a 2050 food system in Kiribati

Born in 2025, Erena starts preparing her boat outside her apartment on her 25th birthday ready for another day of work. She is looking forward to the evening – her family continues to celebrate important events through feasting and food sharing, following the traditions of their ancestors. Erena packs her bag and starts rowing her boat – she recently 3D-printed some new rudders and paddles, so it moves seamlessly through the water. She could have called one of the automated water taxis but she likes the physicality of rowing. She quickly looks at the sun rising above the short 4 bedroom town houses that have been built on the enormous nano-carbon platforms 10 km from the remaining atoll landmass that was her parents traditional home. Each platform holds small 'villages' of 3000 people and are connected by satellite communication and 'ocean highways' between the 60 villages that house the current 178,000 people of Kiribati.

As Erena rows 2 km to her main office, she passes the fenced-off area – the size of Sydney – that holds the solar panels that support Kiribati's energy and freshwater needs. The ocean is crystal clear, and she can see fish swimming peacefully near the 1 m wide cables that provide support for under-water desalination systems. Erena rows 2 km in 25 minutes – a standard time for the fit youth of Kiribati who have grown up rowing every day since the land all but disappeared. She recalls the photos of her great grandparents, overweight from an early age, and reflects on how society transformed from a sedentary to highly active rowing society.

In her job as a fishery manager, she is responsible for monitoring the strict fishing that takes place in Kiribati's EEZ. Despite years of political tensions with foreign agencies, Kiribati has been able to retain sovereign governance of the ocean as its largest asset. Through satellite technology and extended reality, Erena is able to observe health and safety practice on foreign fishing vessels, food safety standards in real time, and the total catch and processing of fish by international vessels.

Over her birthday dinner, her mother and father celebrate the fortunes of this young generation. The challenges of the generations of the 2020s were largely mitigated by innovative investments that sought to blend traditional oral histories and practices with adequate technologies focused on the trends affecting Kiribati. The climate shocks of the 2030s and 2040s, for example, required acceleration in infrastructure developments that helped develop materials tolerant to harsh saline environments, as well as fast-printing systems to build infrastructure above and below the waves. The decline in solar battery prices supported storage of the abundance of electro-voltaic energy produced in Kiribati. Youth at the time, deeply connected to place and culture, were trained in manual skills through the knowledge-based economy to support the needs of an ocean-based society.

They feast all evening with abundant local food. The integrated food systems enabled by five decades of research and development now support rich and diverse diets in the country. Livestock has been saved for special occasions, and protein continues to be sourced from the sea. Underwater marine hydroponics are supported by the underwater de-salination plant, and daily 'scuba-farmers' harvest the required food for each of Kiribati's 60 villages. Erena and her family celebrate, eat and drink, and prepare for another active day of rowing in the world's first Ocean Republic……….

7.2 Solomon Islands: Hot Spots and food system futures

The Solomon Islands is an archipelago of 997 islands spread across a total land area of 29,900 km^2 within 1.34 million km^2 of the Pacific ocean (FAO, 2019b). Its Main Group Archipelago stretches for approximately 1,700 km between Papua New Guinea and Vanuatu. The central archipelago is comprised of a double chain of six large islands (Guadalcanal, Choiseul, Santa Isabel, New Georgia, Malaita and Makira). The islands are geographically diverse, encompassing a mix of mountainous land and low-lying coral atolls (CIA, 2021; Dixon-Jain et al., 2014) located within the Pacific's Ring of Fire (an area prone to earthquakes) and within the cyclone belt (FAO, 2019b). This makes the Solomon Islands highly vulnerable and exposed to natural disasters.

The Solomon Islands have abundant natural resources. There are diverse ecosystems, native forests, freshwater ecosystems, and marine resources. Minerals are also present in some parts of the country. While there is resource abundance, it is not evenly distributed, with some remote islands (e.g. Ontong Java atoll in Malaita Province) being resource-limited. Such geographical diversity and isolation shapes the structure of food systems, and the associated livelihood and food security outcomes that they generate across the country.

7.2.1 Food and nutrition security context

Food consumption patterns have been constantly negotiated between cultures, geographies, and economics in the Solomon Islands. Indigenous traditional diets characterised by the consumption of fresh fish, meat, tubers, fruit and green leafy vegetables, legumes and meat are transitioning to westernised diets mostly based on fatty and processed food, oils and confectionary, as shown by increased dependency on imported rice and flour-based foods like noodles and biscuits (FAO, 2019b; Farmery et al., 2020). A recent study identified the different types of food environments in the Solomon Islands, and the associated diet quality of each. Out of six food environments (wild, cultivated, kin and community, informal retail, formal retail, and food aid), the cultivated food environment accounted for 60% of the quantity and 33% of the value of food acquired nationally. The authors also found that reliance on cultivated, wild, kin and community food environments are significantly positive predictors of fruit and vegetable acquisition (Bogard et al., 2021).

The prevalence of moderate or severe food insecurity in the Solomon Islands is one of the highest among PICs (16.5%), with over half of agricultural households reporting that they worry about their level of food insecurity (Solomon Islands National Statistics Office et al., 2017). National data also indicates that consumption of fruits and non-starchy vegetables is less than half of the WHO-recommended daily intake of 400g/day per person (FAO, 2021). However, this data is based on food expenditure data, which is a proxy of dietary intake. Low diet diversity has been reported among rural populations (Albert et al., 2020), with one study of four rural communities in Malaita and Western Provinces finding that diets generally consisted of fish, sweet potato (and/or rice) and slippery cabbage, usually boiled in coconut milk or baked.

Studies have tended to find higher diet diversity among rural populations compared to urban populations (Vogliano et al., 2021). Compared to urban populations in Honiara, rural populations in Rendova Island and Eastern Central Guadalcanal reported higher diet diversity, acquired more energy from wild and cultivated foods and were more likely to meet WHO recommendations of >400g of non-starchy fruits and vegetables daily (Vogliano et al., 2021). Urban populations were also less able to self-cultivate agri-food products or collect wild foods, which was reflected in their lower diet diversity and higher consumption of ultra-processed foods and takeout foods (Vogliano et al., 2021). A low consumption of a variety of nutritious foods and a high consumption of energy-dense processed foods was also reported among adult populations in Auki, with white rice being reported as the most commonly-purchased food item. A study of coastal and inland village communities found that diets consisted generally of carbohydrate-rich staples and a limited supply of animal-source foods (mostly fresh marine fish and canned tuna). Regular consumption of imported foods, in particular rice and noodles, was also evident among these communities. Participants reported that climate change influencing agricultural crop production, changing traditional family roles; and migration to urban areas were the main reasons for choosing imported foods over local foods. While the majority of participants perceived imported foods as “bad kaikai” (bad food), they were consumed almost daily and were mixed with everyday local ingredients (“good kaikai”).

The prevalence of undernourishment in Solomon Islands was steadily decreasing from 15% in 2001 to 10.6% in 2011. However, by 2017 the prevalence of undernourishment had risen to 12.3%. The percentage of children under 5 years old who are stunted had declined from 32.8% in 2007 to 31.6% in 2015, but wasting had increased during the same time period from 4.3% to 7.9%. while the obesity prevalence was lower than the Pacific regional average. Consequently, the Solomon Islands are currently not expected to meet obesity or non-communicable disease targets, with almost one-third (30.4%) of adult women and one-fifth (21%) of adult men being obese (Global Nutrition Report, 2021). The prevalence of overweight children under 5 years old is 4.5% (Global Nutrition Report, 2021). Diabetes is reported to affect 17.5% of adult women and 14.4% of adult men (Global Nutrition Report, 2021). Prevalence of anaemia is concerning, affecting over one-third (37.7%) of women of reproductive age (15 to 49 years) and more than one in three children under the age of 5 years (Global Nutrition Report, 2021).

7.2.2 Socio-economic context

The Solomon Islands are home to approximately 647,000 people, and are experiencing rapid population and urban growth trends similar to other Pacific countries (United Nations, 2019). The population is growing on average at 1.9% per year (2015-2020) and growth rates have been above 2% since 2000. About 20% of the population live in urban centres, mostly Honiara, Gizo and Auki. Urbanisation is strong, with urban population growing on average at 3.9% per year between 2015 and 2020 (United Nations, 2019). Such strong population and urbanisation growth have led to overfishing, declines in water quality and degradation of ecosystems with negative effects on food production and human health (FAO, 2019b; Gillett, 2016c; McEvoy et al., 2020; Wenger et al., 2020). While urbanization is growing, the majority of the population of the Solomon Islands lives in rural areas, and remains heavily dependent on subsistence agriculture and fishing for their food security and livelihoods. The country has a very young population, with 41% of people being under the age of 15 years old. The 2009 census projects that by the year 2050, the population will reach 1.3 million.

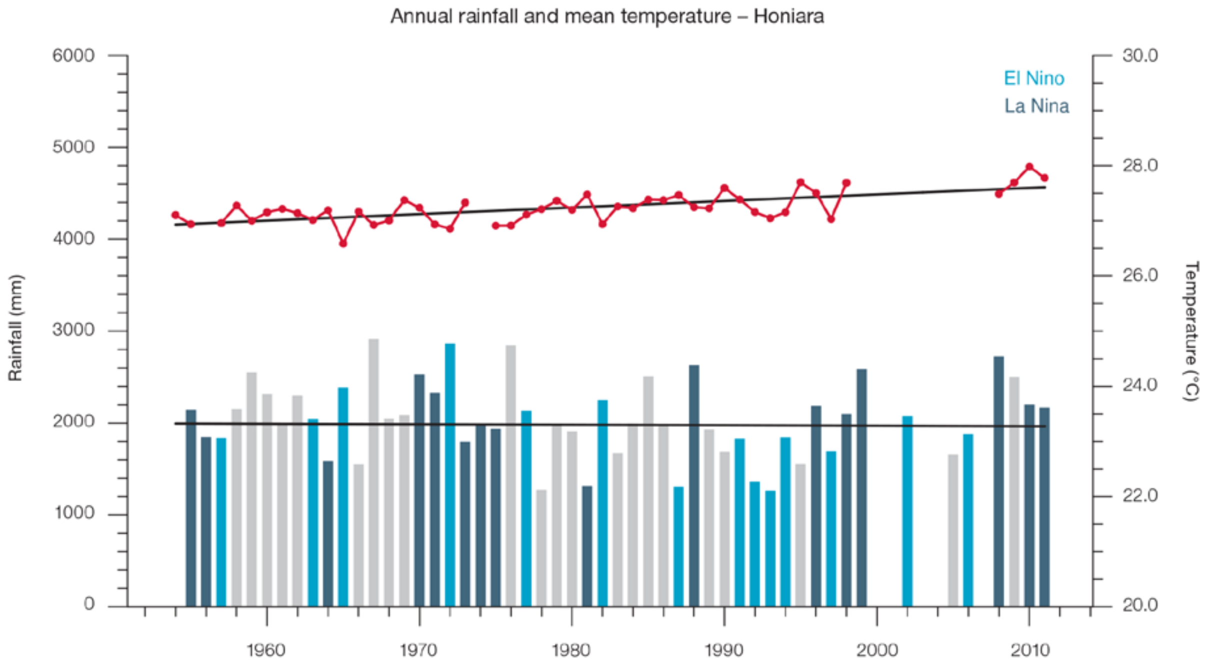
A mix of natural resource-based activities provide the backbone to formal national economic activity. Subsistence agriculture is considered below. The forestry sector is growing in the country – the last two decades have witnessed severe overharvesting of forest resources beyond sustainable yield limits. The Solomon Islands has over 25 threatened tree species, including ebony, rosewood, rattan and some palms. Plantation forests are also common. A combination of highly accessible forests, land tenure, governance challenges and a lack of monitoring have led to a challenging context for achieving sustainable forestry (Katovai et al., 2015). A similar trend is taking place in the minerals sector, with foreign mining companies developing rural customary lands for bauxite and gold. While these sectors contribute to national GDP, there have been mixed impacts on rural communities, and the wealth from minerals has not been equitably distributed.

Civil unrest and political tensions have been major drivers of development in the Solomon Islands. ‘The Tensions’ was a period in the late 1990s where escalating violence took place between different ethnic militant groups throughout the country, leading to complex governance and security problems. Substantial efforts by the national government and regional bilateral donors led to a long-term easing of tensions and improvements in national security. Parallel to domestic security challenges, the country (and broader Pacific region) has a long history of contestation over maritime and national security matters. Much research and scholarship in these domestic and regional geopolitics remains focused on economics and security studies, with minimal explorations of the implications for domestic food systems and food security.

7.2.3 Climate context

The Solomon Islands climate is tropical with two distinct seasons: a wet season (November to April), and a dry season (from May to October), with some regional differences. For example, there is a marked wet season in the west of the country, while in the east rainfall is constant year-round (FAO, 2019b). Year-to-year rainfall variability is strongly influenced by the El Niño Southern Oscillation (ENSO) which moves warm ocean waters from the west to the east of the Pacific Ocean. In the Solomon Islands, ENSO effects are stronger on the east of the country, bringing stronger rainfall during the wet season, while its influence weakens towards the west where annual and half-year rainfall trends for Honiara and Munda show little change (BoM and CSIRO, 2014b).

Average temperatures have been increasing significantly since the 1950s (Figure 8), with minimums increasing more than maximums, along with an increase in the frequency of warm nights, decreasing frequency of cool nights, and fewer cool days, which are consistent with global warming (BoM and CSIRO, 2014b). On average 29 cyclones develop within or cross the Solomon Islands EEZ per decade. They are more frequent and intense during ENSO years (BoM and CSIRO, 2014b).



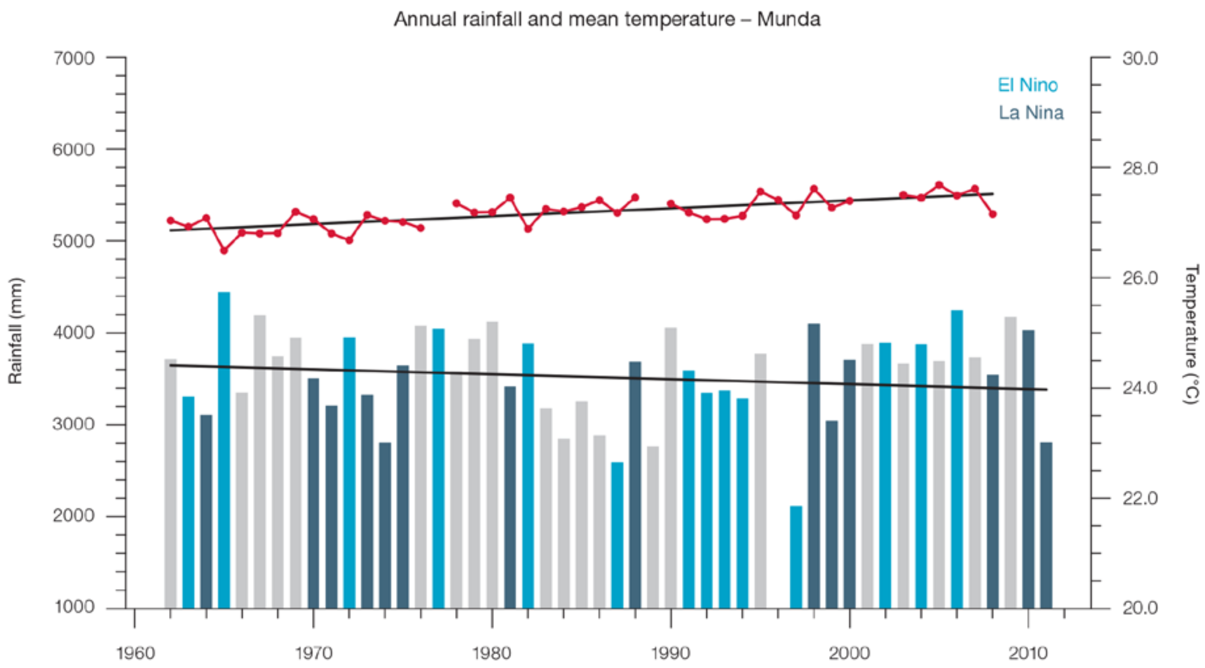


Figure 8: Observed time series for annual average values of air temperatures (red dots and line) and total rainfall (bars) for Honiara (top) and Munda (bottom). Light blue, dark blue and grey bars denote El Niño, La Niña and neutral years respectively. Solid black trend lines indicate a least-squares fit.

Climate change is already impacting food production systems in the Solomon Islands. Sea level rise, increases in seasonal and annual temperatures, and changes in rainfall patterns have already been observed (BoM and CSIRO, 2014b). As a result of climate change, coral reef habitats experienced major bleaching events driven by global sea surface temperature anomalies, but these were moderated at local scales by anthropogenic factors (e.g. fisheries extraction, land-use impacts, marine management) and environmental (e.g. hydrodynamics) conditions. This suggests that relatively healthy reefs persist at some locations despite climate change impacts, and are mainly associated with local stewardship practices at subregional scales (Denley et al., 2020). Climate change is also negatively impacting crops (Iese et al., 2017), where changes are noticeable in the prevalence of crop species (e.g. use of traditional root crops such as taro and pana shifting to sweet potato), yields, and reduction in fallow periods associated with both an increased demand for food and climate change (Iese et al., 2015), and coral reef fisheries (Bell et al., 2013).

7.2.4 Agriculture context

Most agriculture involves mixed garden production, but there is an increasing prevalence of cash crops such as oil palm, copra and cocoa. Forestry is also a major land use activity in the country. The productivity of agricultural systems is partially attributed to high biodiversity and the quality of volcanic soils (FAO, 2019b). Across all provinces, income from agricultural activities is the highest in Guadalcanal, contributing 51% of annual household income, or S$232.3 million per annum, followed by Malaita where it accounts for 15% of household annual income, or S$67 million per annum. The most common garden crops are sweet potato, cassava and banana, with root vegetables such as taro and yam and leafy greens also produced. Livestock is limited to pigs and poultry.

The country is home to over 4,500 different species of plants – 3,200 of which are indigenous and at least 120 are edible and nutrient-rich (Vogliano et al., 2021). Subsistence gardens are the most important source of staples and vegetables to the predominantly rural population, despite ongoing urbanisation and associated increases in the supply of imported foods (FAO, 2019b). Traditional agro-forests also provide subsistence food and livelihood needs to the rural population, buffering sediment runoff and its impacts on coastal ecosystems (Wenger et al., 2020). Many indigenous species have traditionally supplied carbohydrates, for example *Amorphophallus campanulatus*, *Tacca leontopetaloides*, sago (*Metroxylon sagum*, *M. bougainvillense* and *M. salomonense*), the Polynesian or Tahitian chestnut (*Inocarpus fagiferus*), *Haplolobus floribundus* and *Corynocarpus* spp. Some of these plants are still important food sources, but today their use is in decline as they generally only provide seasonal or occasional food (FAO, 2019b).

Three major commercial tree crops supplement local income: coconuts (which is an integral part of local diet and also produces export commodities) in the form of copra and coconut oil), cocoa and palm oil (which are exclusively export commodities; (FAO, 2019b). Coffee is also increasingly being grown as a cash crop

7.2.5 Fisheries context

Forming part of the eastern portion of the Coral Triangle, the Solomon Islands has rich marine biodiversity. It is estimated that 95% of Solomon Islanders are associated with the coastal environment, where 50-90% of the daily protein intake comes from coastal waters, especially coral reef, mangrove, and seagrass habitats (FAO, 2019b). On average, annual per capita consumption of fish is around 35kg (Bell et al., 2013). Subsistence catches represent around 59% of all catches and commercial catches 41%. Most of the commercial catch (77%) is consumed domestically, and 22% is exported, and a small proportion (0.5%) is for baitfish to support pole-and-line tuna fishing (Gillett, 2016c).

Coastal small-scale commercial fisheries are located mainly near the main urban area of Honiara and to a much lesser extent around the towns of Auki (Malaita Province) and Ghizo (Western Province). These fisheries are focused on providing finfish to wage-earning residents and non-perishable fishery products (predominantly beche-de-mer, trochus) to export markets (Gillett, 2016c). These export commodities have become important sources of household income, especially in isolated islands that once relied upon copra, which has seen increasingly limited market opportunities for Pacific countries. (Gillett, 2016c).

Despite being a large sector, limited statistical monitoring of the fisheries sector prevents the identification of national fishery trends (Gillett, 2016c). However, it appears that coastal fisheries are increasingly subject to overfishing close to urban centres (FAO, 2017). Population growth is fuelling domestic demand for fish, with perceived declines in the quantities landed, most notably in Western and Malaita Provinces, and an increase in Central Island (Gillett, 2016c). The high demand for beche-de-mer has led to overfishing and closure of the sea cucumber fishery in 2005, 2009 and 2012 (FAO, 2017; Gillett, 2016c; Pakoa et al., 2014). Other coastal resources that have been subjected to over-exploitation for both subsistence and commercial use include greensnails, blacklip and goldlip shells, coconut crabs and giant clams, while other species, such as trochus, lobsters and turtles are also threatened despite some level of protection (FAO, 2019b).

Tuna catches are inversely correlated with ENSO in the Solomon Islands, where catches decrease during ENSO years as purse seine catches characteristically move eastwards from Papua New Guinea and the Solomon Islands towards Kiribati, Tuvalu and Tokelau (FAO, 2017; Gillett, 2016c). Tuna species fished in Solomon Islands waters include albacore, bigeye, skipjack and yellowfin. Bigeye and albacore are currently overfished (FAO, 2017).

Aquaculture production includes seaweed and some culture of corals for the marine aquarium trade. Minor aquaculture activities (tilapia, milkfish, giant clams and freshwater prawns) represent about 1.5% of the total volume of fish harvested in 2014 (Gillett, 2016c). NZ Aid has been piloting in-land tilapia aquaculture through its *Strengthening Tilapia Farming in Solomon Islands* program, focussing on Malaita Province, and considering modifying this system to aquaponics.

In summary, food systems in the Solomon Islands are changing due to population growth, urbanisation and associated habitat modification and destruction, the introduction of invasive species, climate change, over-exploitation of natural resources (e.g. logging and overfishing), and loss of traditional knowledge (FAO, 2019b). These changes are clearly affecting food production and nutrition as the country has shown limited progress towards achieving diet-related non-communicable disease targets (e.g. obesity, diabetes, anaemia among women of reproductive age), despite improvements in statistics for maternal, infant and young child nutrition (Global Nutrition Report, 2020).

7.2.6 Hot Spot analysis

The Solomon Islands population is expected to continue to grow, from 587,000 in 2015 to 1.033 million in 2050. The proportion of the population that is urban is also expected to continue to grow over the next 30 years at an average annual rate between 2.4% (2045-2050) and 3.6% (2020-2025), which in absolute numbers represents an increase from 160,000 people in 2020 to 385,000 in 2050 (United Nations, 2019). By 2050 about 37% of the population will live in urban centres, as opposed to 25% in 2020 (United Nations, 2019). The growing population will need more space, food and water to live. Diets are expected to continue to change as a result of urbanisation, further increasing demand of marine resources and imported processed food (Farmery et al., 2020). Urbanization will also require more built infrastructure such as centralized water and sewerage facilities, more permanent housing and roads. These changes are expected to cause substantial modifications to the shoreline (Bell et al., 2011), causing adverse impacts on water quality and quantity, which will lead to negative impacts on ecosystems, habitats and farms, with flow on effects on food production (Morrison, 1999; Zann, 1994). The growing population means that even if coastal resources are well-managed, they will be unable to supply the current level of 35 kg of fish per capita per year due to the limited coral reef habitat (Bell et al., 2013).

Climate will continue to change, exacerbating the impacts of population growth (Table 2) and urbanisation on food systems. As carbon dioxide emissions rise, oceans will continue to warm, rise and acidify (BoM and CSIRO, 2014b). These changes will affect the health of marine ecosystems, and particulalry coral reefs that provide many ecosystem services, including food and coastal protection (BoM and CSIRO, 2014b). Simultaneous local pressures (e.g. pollution and overfishing) will act together with climate change pressures such as sea level rise, ocean warming and acidification, leading to interactive, complex and amplified impacts for species and ecosystems (Valmonte-Santos et al., 2016), thus affecting catches and food production in the sea. The synergistic effects of climate pressures will amplify local impacts on ecosystems such as coral reefs, affecting fish productivity (Dutra et al., 2021).These changes will contribute to increased malnutrition and dependency on food imports (McIver et al., 2016).

Recent projections suggest that seas are expected to rise by 1.35 m by 2100 (Grinsted and Christensen, 2021), an increase of 25 cm from previous projections (IPCC, 2019b). This is because the climate is changing quicker than initially predicted (Duffy et al., 2021). Higher seas will place further pressure on land, causing coastal erosion and flooding, and saltwater intrusion to low-lying areas, negatively affecting fresh groundwater, crops and reducing the amount of land available for housing and agriculture (Iese et al., 2015).

Table 2: Projected business as usual changes in population and climate drivers in the Solomon Islands. (Sources: population (United Nations, 2019); biophysical data (BoM and CSIRO, 2014b). Projections shown are for a 'very high emission' scenario. Surface air temperatures are closely related to sea-surface temperatures (BoM and CSIRO, 2014b). Biophysical data shown for 2030 and 2050 represent change from 2020.

Driver of change	2020	2030	2050
Population	647,000	773,000	1,032,000
Urban population	160,000 (25%)	225,000 (29%)	385,000 (37%)
Rural Population	488,000 (75%)	548,000 (71%)	647,000 (63%)
Surface air temperature / Sea surface temperature (°C)	29.5	0.7 (0.5–1.0)	1.3 (1.0–1.9)
Total Annual Rainfall (mm) (%) (Honiara)	2,250	3 (-1–7)	3 (-3–9)
Mean sea level (cm)	0	13 (8–18)	25 (16–35)
Aragonite saturation state (War)	3.9	-0.4 (-0.7 – -0.1)	-0.7 (-1.0 – -0.4)
Cyclones (average number per decade)	29	Decrease in frequency, increase in intensity	Decrease in frequency, increase in intensity

Year-to-year and decadal variability in temperature is expected to continue following ENSO cycles, although it is not known whether ENSO will change in intensity or frequency in the future (BoM and CSIRO, 2014b). Air and sea temperatures will continue to rise, increasing the incidence of extreme events, such as hot days (BoM and CSIRO, 2014b; World Health Organization, 2020), the intensity and frequency of category 4-5 cyclones, and annual rainfall. Oceans will continue to acidify, causing negative impacts on marine ecosystems and species. For example, more acidic waters will negatively affect calcification of reef-building corals and other species that secrete calcium carbonate shells, such as lobsters and other crustaceans, and these affects are already being documented (Agnalt et al., 2013; Bednaršek et al., 2020; Whiteley, 2011). These changes in environmental drivers will impact crops and fish, both directly and indirectly (World Health Organization, 2020). Higher ocean temperatures can also affect the distribution of tuna as they may swim deeper in search of cooler waters and therefore become more difficult to catch, threatening the viability of the fishery (Williams et al., 2015).

Changes in rainfall patterns and higher air and sea surface temperatures, along with more frequent extreme weather events, higher sea levels and socio-cultural changes will exacerbate malnutrition and diet-related non-communicable diseases. These affects will play out directly through local food production, and indirectly by exacerbating underlying risk factors such as water insecurity, dependency on imported foods, urbanisation and migration, and health service disruption (World Health Organization, 2020).

Notwithstanding the negative impacts of population growth, urbanization and climate change, there may be also opportunities to develop adaptive farming systems in the Solomon Islands to mitigate negative impacts (Iese et al., 2017). These were also explored in Malaita Province by a previous ACIAR SRA, WAC–2019-148 *Climate change and Pacific food systems: Decision-making for transformational change* (Butler et al., 2021).

Figure 9 shows the Hot Spots in the Solomon Islands, demarcated by province and forecasted to 2055. The results highlight the widespread diversity in potential future conditions within the country. Guadacanal will experience the most radical change, driven by the highest changes in air temperature and population growth. Choiseul is expected to experience the least changes, mostly because population and rainfall will alter little. Data for Temotu was limited, and therefore not included in the analyses. Population growth in Guadalcanal, including urbanisation, is likely to drive pressure on natural resources, which will potentially render livelihoods and ecosystems at greater exposure to climate change pressures. This will likely generate future demand for other provinces to supply food to Guadalcanal to meet growing food demand and food insecurity. All provinces will see large changes in ocean acidification and sea level rise – creating declines in coastal fisheries stocks and forcing relocation inland or emigration away from islands.

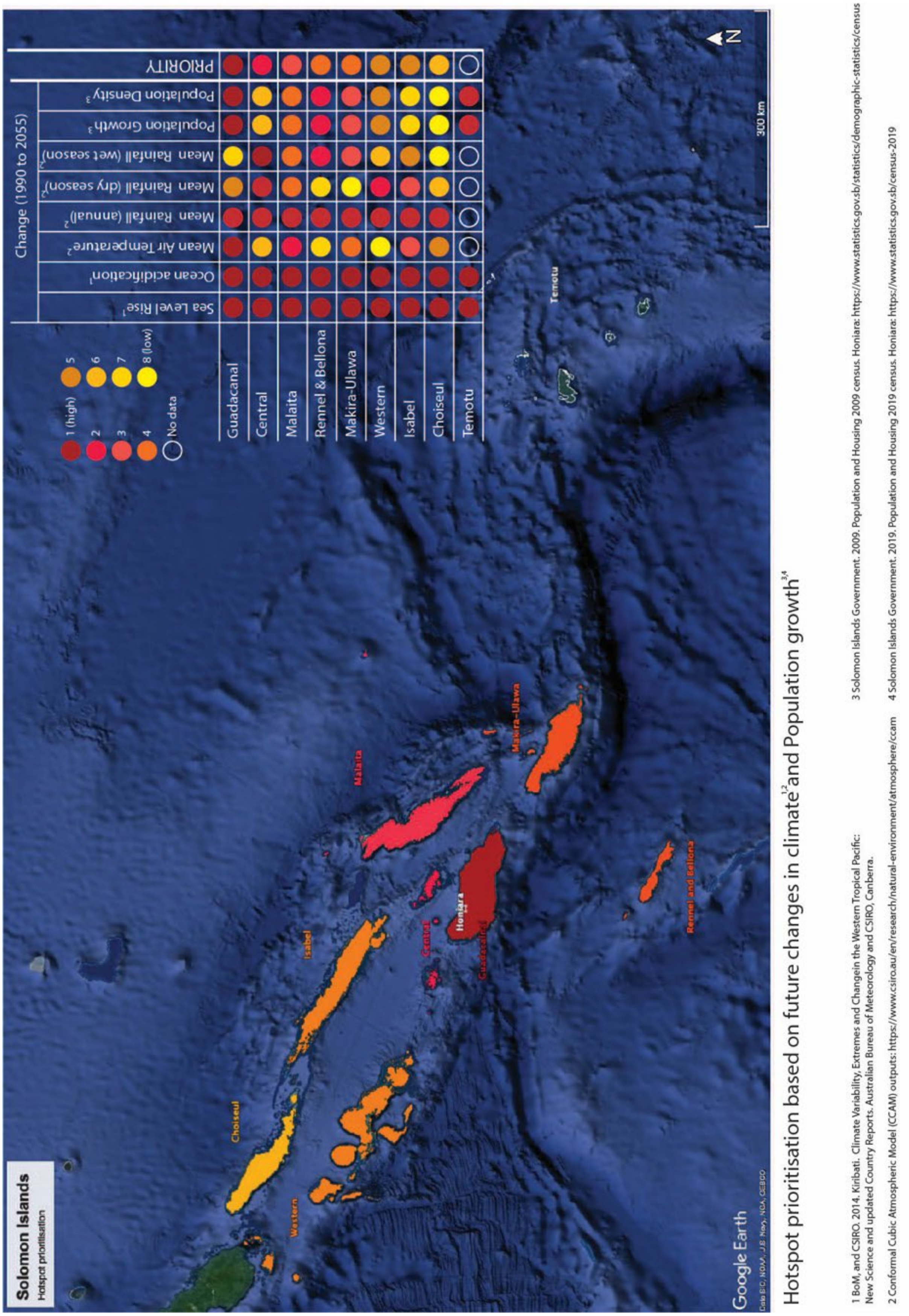


Figure 9: Hot Spots of projected changes across the Solomon Islands in 2055, compared by province

7.2.7 A transformed food system in the Solomon Islands

Figure 10 summarises the current drivers influencing the food system and the potential transformations that may take place in a future (2050) system. The major characteristics of a transformed future food system may include:

- A substantial **decline in forest cover** from unfettered and unmanaged legal and illegal logging;
- Gravitation in **labour and population** within the country towards Guadalcanal Province and urban centres due to emerging knowledge economy opportunities, creating civil tensions and localised pressure on food production;
- Diverse types of **land and ocean access and governance** to manage escalating competition between customary owners and international interests for abundant natural resources;
- Changes in **smallholder production** in urban and peri-urban areas, and in traditional home villages where population fluctuates due to emigration and immigration caused by civil conflict;
- Decline in **coastal fish stocks** caused by coral reef declines and ocean acidification.

Figure 10: Current drivers and possible transformed future food system for the Solomon Islands

The analysis above provides a potential future for the Solomon Islands' food system extrapolated from the current trajectories of drivers of change. However, Box 2 goes further by providing a personalised narrative for 'Moses', a young man living within the potential food system projected for 2050, when technology, natural resources and labour changes intersect to create different dynamics in the food system.

Box 2. Future imaginary - living in a 2050 food system in the Solomon Islands

Moses wakes up and starts packing his bags. He looks out of his window and can see far into the distance – there is no high forest canopy in sight. Decades of accelerated forestry brought substantial wealth to the state and the businesses managing the resources, with mixed results for traditional land holders throughout the province. His family was lucky – strong leadership from his village enabled them to retain forestry access fees which generated income for his family.

With less forest and habitat for biodiversity, Moses has noticed increased pest outbreaks in his home gardens. The hotter days, much hotter than what his mother experienced in the year 2030, continue to affect his fruit trees and vegetables. Moses values his home garden, unlike many others around him. The chore of maintaining a garden is seen as unnecessary, now that the middle class has spread throughout the provinces. Forestry and cash crop businesses have employed large numbers of people to support their production, distribution and marketing of export crops. With declining forest resources, the Solomon Islands has rapidly changed land use to produce export commodities.

There are now more supermarkets selling domestically produced fruit, fresh fish and vegetables. With more of the population working for international forestry and agriculture businesses, they have less time to prepare traditional foods. Western diets are normalised. This contrasts with the high-end tourist resorts which have proliferated in each provincial capital, where visitors and wealthy Solomon Islanders pay for celebrity chef-curated menus of traditional Melanesian cuisines.

Moses continues to pack his bag and gets ready for his 1-hour hyperloop commute from Ghizo to Honiara. The highly efficient transport system was developed to link the islands and enable resource exchange and trade in the 2030s. It now offers rapid public transport for the large population and the ever-increasing number of tourists. Moses jumps on the hyperloop train and looks as it zooms past the beautiful islands and coast lines. He remembers the fishing boats that used to be there before the people started working in buildings and the reefs died. There are now larger vessels with professional local divers who harvest the underwater saline-tolerant vegetables and acid-tolerant seaweed grown to meet the increasing demand in the country. Moses arrives in Honiara and gets ready for his workday at the 'Underwater Farmers' Association', where he oversees the procurement of materials……

7.3 Transformative capacity indicators

The first use of intentional transformative capacity was by business scholars Garud and Nayyar (1994), who defined it as an ability to continually redefine a portfolio of activities within emerging technological opportunities in a business. The concept was further defined by Weiss (1998) as the ability of a state to adapt to external shocks and pressures by generating ever-new means of governing the process of industrial change. This definition focused on how the nation state could manage the process of disruptive changes, such as industrialization and population growth. Building from the traditions of social-ecological systems and adaptive capacity noted earlier, Olsson et al. (2010) defined transformative capacity as the ability to move a system's intention towards ecosystem stewardship, focusing at the landscape scale. These definitions acknowledge the capacities required to be prepared for the fundamental shifts that may occur, yet are constrained to the nation state or natural resource management.

Acknowledging the fragmented nature of the transformative capacity concept, Wolfram (2016) developed a multi-indicator-based framework for analysing transformative capacities. The framework is retrospective in nature, and looks at historical and current capacities in a system rather the underlying socio-structural dynamics that influence long-term transformative change. Wolfram proposes 60 factors that cluster around 10 interdependent components. These 10 components are further clustered around three major domains: a) types of governance spaces, b) core transition processes and c) reflexivity and social learning.

Ziervogel et al. (2016) draw from urban case studies to define transformative capacity as the capacity of individuals and organisations to be able to both transform themselves and their society in a deliberate, conscious way. This definition includes notions of imagining alternative futures, setting normative directions, and cultivating social cohesion and emancipation. Ziervogel et al. identify three further aspects of transformative capacity: a) an awareness of and reconnection to visible systems that support wellbeing, b) a well-developed sense of agency, and c) strong social cohesion. While much transformational change is argued to require fundamental shifts in practices, governance, and paradigms, there is substantial potential for small and incremental transformations to build up to long-term change through small gains (Termeer et al., 2016). Capacity-building across the multiple domains conceptualised by Wolfram may offer avenues for supporting wins at different scales, building towards long-term transformations.

With such an opaque and diverse set of definitions, we integrated from these recent scholars to focus on intentional transformative capacities for food system sustainability, defining them as follows:

> *"Intentional transformative capacities are the capacities of individuals, institutions, and governance systems to iteratively transform each other in a deliberate, conscious way towards diverse potential future systems".*

Building transformative capacities intentionally thus required clarification of who builds that capacity, for who, and for what agreed future. This requires attention to two different types of capacities:

1. **Capacities for living in a transformed system.** These relate more closely with the established concepts of adaptive capacity and adaptation, and capacities to manage the impacts of more frequent cyclones or inundated caused by sea level rise. They have an element of certainty and draw on future projections and best estimates of what the future may look like. The Hot Spots presented above point towards the types of changes that will occur under current scenarios – and thus capacities that can be built to target that future system.

2. **Capacities for intentionally transforming and setting the direction of a future system,** given uncertain climate scenarios and socio-political conditions.

Applications of transformative capacities analysis or intentional planning in food systems is extremely limited, but scholars continue to test Wolfram's framework, for example Ziervogel et al. (2019) in urban systems in South Africa and Brodnik and Brown (2018) in the urban water sector in Melbourne, Australia.

How transformative capacities can be enabled and built through processes of co-production, transformative spaces and future planning have also been explored. These studies have pushed elements of transformative capacity to new areas of enquiry in the fields of futures thinking, sustainability science, and society and technology studies, however the intentional design of transformative capacity remains unexplored.

The lacuna of analysis of transformative capacity thus creates an important knowledge theoretical gap, especially as most of the transformative capacity scholarship has taken place in urban settings and with a macro-nation state scale of focus. This mirrors the abundant food system transformation scholarship, which while useful, remains largely global and theoretical in scale (Dornelles et al., 2022), without addressing the multi-scale and socio-political dimensions of change discussed in previous sections. An initial set of indicators for the measurement and monitoring of emerging transformative capacity in food systems is presented in Table 3. This will be tested and refined with partner and community input in the new ACIAR-funded project, CLIM/2020/178 *Transformation pathways for Pacific coastal food systems*.

Table 3: Draft indicators to measure the emergence of intentional transformative capacity in food systems, colour coded by food system component

Sub-indicators	Indicator	Food system component
• Participation and inclusiveness • Diverse governance modes and network forms • Sustained boundary agencies and shared vision-building	Inclusive and multi-form governance	Governance
• Multi-sectorial leadership • Translation of global issues to local arenas • Political leadership to champion systemic change	Transformative leadership	
• Social networks and communities of practice • Self-efficacy, agency, and emancipation of citizens	Empowered and autonomous communities of practice	
• Analysis of the diversity of hard and soft systems • Recognition of path dependencies	Systems awareness and memory	Transition processes enabled by visions and foresighting
• Transdisciplinary co-production of knowledge • Collective futuring of potential development pathways	Foresighting for sustainability	
• Experiments are placed-based and community-led • Experiments deal with disrupting hard (physical) and soft (social) technologies	Diverse community-based experimentation with disruptive solutions	
• Access to resources for capacity-building • Embedding transformative capacity into workplans and institutional management	Innovation embedded	
• Monitoring and reflection embedded in interventions • New knowledge about transformations documented and formalised for management	Reflexivity and social learning	Relational dimensions and social learning
• Agency enabled across individuals and institutions, and across sectors	Working across human agency	
• Cross-regional capacities built as required	Working across political-administrative levels	

7.4 Options for transformed food production

7.4.1 Categorising food production for two Pacific island types

Six overarching production categories were identified as being ubiquitous throughout the Pacific. These included fisheries, aquaculture, traditional cropping systems, agroforestry, household livestock and commercial farming. These were further classified into 26 food production systems typical to Pacific coral atolls (e.g. Kiribati) and Pacific volcanic islands (e.g. Solomon Islands; Table 4). There was a greater diversity of food production present on volcanic islands due to their broader range of terrestrial environments and soil conditions in comparison to the relatively nutrient-poor state of coral atoll soils. Non-existent or non-ubiquitous food production systems with high potential were also considered (e.g. open ocean aquaculture (OOA), integrated multi-trophic aquaculture (IMTA), aquaculture from ocean thermal energy conversion (OTEC) and backyard aquaponics).

Table 4: Food production typical to two Pacific Island types (coral atolls, volcanic islands). Ticks indicate presence of the food production system, asterisks indicate high potential for new food production systems. Acronyms are: open ocean aquaculture (OOA), integrated multi-trophic aquaculture (IMTA), aquaculture from ocean thermal energy conversion (OTEC)

Production categories	Food production systems	Coral atolls (e.g. Kiribati)	Volcanic islands (e.g. Solomon Islands)
Fisheries	Inland fisheries		✓
	Mangrove fisheries	✓	✓
	Offshore fishing (mostly tuna)	✓	✓
	Coastal fishing	✓	✓
	Shoreline fishing/reef gleaning	✓	✓
Aquaculture	Mariculture	✓	✓
	OOA	*	*
	Inland aquaculture		✓
	IMTA	*	*
	OTEC	*	*
	Backyard aquaponics	*	*
	Capture / culture wild species	✓	✓
Traditional cropping systems	Subsistence gardens	✓	✓
	Pit cultivation	✓	✓
	Pond field pit cultivation		✓
	Urban backyard gardens (e.g., 'supsup')		✓
	Seasonal production systems		✓
	Raised bed crops		✓
Agroforestry	Non-permanent agroforestry (extensive, low input)		✓
	Permanent agroforestry (intensive)		✓
	Traditional village agroforestry	✓	
	Commercial agroforestry		✓
Household livestock	Pig farming	✓	✓
	Chicken farming	✓	✓
Commercial farming	Cattle, sheep, goats		✓
	Insect farming	*	*

7.4.2 Exploring alternative production options – coral atolls

The integration potential of our proposed atoll food production systems is summarised in Table 5. The integration of offshore tuna waste as feed for certain types of aquaculture (mariculture and IMTA) were awarded the highest integration scores, as this process is already occurring in some coral island nations. Incorporating waste/scraps from offshore tuna and artisanal coastal fishing as feed for household livestock (i.e. pigs/chickens) were also awarded high integration scores due to the current subsistence nature of many Pacific communities' livelihoods residing on atolls, reliance on coastal fisheries for protein, and the ubiquity of household livestock. Manure from household livestock as a fertilising agent for subsistence gardens and village agroforestry was considered to have the highest integration potential. Lateral integration of aquaculture waste into other aquaculture systems scored reasonably highly, with the exception of OTEC. While waste from marine food production (i.e. fisheries, aquaculture) were considered to have some integration potential to terrestrial systems (typically as components for soil amelioration), the reverse (terrestrial to marine) scored poorly, with the exception of farmed insects as potential bait for fisheries, or as processed feed for aquaculture. The primary integrative opportunities are explored in more detail below:

Opportunity 1: Improved utilisation and integration of landed tuna waste

As one of the largest industries in the country, the tuna sector generates a large amount of waste from discarded bones and off-cuts that, if processed, could be used as a resources in other food production systems. The opportunity lies in using the processed waste resource for a) feed for lagoon-based IMTA production, b) feed for aquaculture, and c) as feed for household livestock. There is also an opportunity to then link these livestock systems with household biowaste used as liquid fertilizer for household crops.

Potential impact: There is potentially a large volume of fish waste from tuna processing (1 tonne of waste per 1 tonne of processing). Atolls also have very poor-quality soils with poor nitrogen, phosphorous and potassium (NPK) balances, and having waste-derived fertiliser could provide opportunities for growing food on limited land. and a high prevalence of small-scale plots and gardens that would benefit from fertilisation. The NPK content of fish waste could be very high. There is also potential to monetize the processed waste product through chemical processing. The ‘impact’ of processing tuna waste could vary – benefits could accrue to smallholders growing food on atolls, businesses developing the processing, or entrepreneurs linking farmers with the processed products.

Limitations: The concept of using fish wastes as a fertiliser has been explored previously within the Pacific context by the SPC (Sharp and Mariojoul, 2012), and also in Hawai’i (Dominy et al., 2010). A major limitation identified by both analyses was how to add value to the raw product due to infrastructural limitations, exacerbated by remoteness and distance to potential markets. Energy needs for processing are also currently insufficient, but could be met from solar power which is feasible in Kiribati. There would also need to be human skills and capacity to maintain the specialized equipment used to process the product.

Information needs: To link tuna waste and marine/terrestrial production systems, several information gaps need to be filled:

- Waste extraction and processing should be trialled as a proof of concept;
- Techniques to stabilise and preserve the waste are needed to avoid rapid decomposition;
- Driers must be developed to achieve this;
- The end user market must be clarified (i.e. gardens, livestock and/or aquaculture);
- Review what tuna cannery companies (e.g. Golden Oceans in Suva) are already practicing.

Table 5: Integration potential of food production systems on Pacific coral atolls. Numbers indicate the potential to use waste streams from food production systems (columns) as inputs for food production systems (rows). Key: 0 = not possible, 1 = possible but limited feasibility, 2 = average, needs lots of scoping, 3 = looks promising, 4 = excellent opportunity. Numbers also accompanied by explanatory text where appropriate.

		Production for these systems ↓ / Waste from these systems →	Fisheries			Aquaculture				Terrestrial					
			A Mangrove fisheries	**B** Offshore tuna	**C** Coastal fishing	**D** Mariculture	**E** OOA	**F** IMTA aquaculture	**G** OTEC	**H** Subsistence gardens	**I** Pit cultivation	**J** Village agroforestry	**K** Modern agroforestry	**L** Household livestock	**M** Insect farming
Fisheries	**A**	**Mangrove fisheries**	2 bait	2 bycatch bait	2 bait	1 limited bait production	1 limited bait production	2 Bait production. Nutrients and nursery for fisheries	1	1	1	1	1	1	2 bait
	B	**Offshore tuna**	2 bait	2 bycatch bait	2 bait	1 limited bait production	1 limited bait production	1 Limited bait production	1	1	1	1	1	1	2 bait
	C	**Coastal fishing**	2 bait	2 bycatch bait	2 bait	1 limited bait production	1 limited bait production	3 Bait production. Nutrients and nursery for fisheries	1	1	1	1	1	1	2 bait
Aquaculture	**D**	**Mariculture**	2 Feed (direct or processed), bycatch grow out	4 Processed tuna waste for aqua feed already occurring	2 Feed (direct or processed), bycatch grow out	3 Feed (direct or processed), lateral integration	3 Feed (direct or processed), lateral integration	3 Feed (direct or processed), lateral integration	2 OTEC technology provides nutrient rich water	1	1	1	1	1	2 Processed insect larvae as aquaculture feed
	E	**OOA**	2 Feed (direct or processed), bycatch grow out	3 Processed tuna waste for aqua feed - depends on target spp.	2 Feed (direct or processed), bycatch grow out	3 Feed (direct or processed), lateral integration	3 Feed (direct or processed), lateral integration	3 Feed (direct or processed), lateral integration	1	1	1	1	1	1	2 Processed insect larvae as aquaculture feed
	F	**IMTA**	2 Feed (direct or processed), bycatch grow out	4 Processed tuna waste for aqua feed	2 Feed (direct or processed), bycatch grow out	3 Feed (direct or processed), lateral integration	3 Feed (direct or processed), lateral integration	3 Feed (direct or processed), lateral integration	2 OTEC technology provides nutrient rich water	1	1	1	1	1	2 Processed insect larvae as aquaculture feed

	G	**OTEC**	1		1		1		1		1		1		2	OTEC technology provides nutrient rich water	1		1		1		1		1		2	Processed insect larvae as aquaculture feed
Terrestrial	H	**Subsistence gardens**	2	Soil amelioration	2	Processed tuna waste for soil amelioration	2	Soil amelioration	2	Soil amelioration	2	Soil amelioration	2	Soil amelioration	1	Soil amelioration	2	Leafy vegetation for nutrient rich compost	2	Leafy vegetation for nutrient rich compost	2	Leafy vegetation for nutrient rich compost	3	Coconut husks for soil amelioration	4	Manure for soil fertilisation - already occurring	1	
	I	**Pit cultivation**	2	Soil amelioration	2	Processed tuna waste for soil amelioration	2	Soil amelioration	2	Soil amelioration	2	Soil amelioration	2	Soil amelioration	1	Soil amelioration	2	Leafy vegetation for nutrient rich compost	2	Leafy vegetation for nutrient rich compost	2	Leafy vegetation for nutrient rich compost	2	soil amelioration	3	Manure for soil fertilisation - already occurring	1	
	J	**Village agroforestry**	2	Soil amelioration	3	Processed tuna waste for soil amelioration	2	Soil amelioration	2	Soil amelioration	2	Soil amelioration	2	Soil amelioration	1	Soil amelioration	2	Leafy vegetation for nutrient rich compost	2	Leafy vegetation for nutrient rich compost	2	Leafy vegetation for nutrient rich compost	2	soil amelioration	4	Manure for soil fertilisation - already occurring	1	
	K	**Modern agroforestry**	1	Agroforestry already well established	1	Agroforestry already well established	1	Agroforestry already well established	1	Agroforestry already well established	1	Agroforestry already well established	1	Agroforestry already well established	1	Agroforestry already well established	1	Agroforestry already well established	1	Agroforestry already well established	1	Agroforestry already well established	1	Agroforestry already well established	2	Agroforestry already well established	1	Agroforestry already well established
	L	**Household livestock**	3	Feed for pigs. Fish meal for chicken pellets	4	Tuna waste for livestock consumption	4	Fish waste for livestock consumption	2	Volume of waste is smaller than fisheries	2	Volume of waste is smaller than fisheries	2	Volume of waste is smaller than fisheries	1	Processed waste as insect feed	3	Edible vegetation, fruit for livestock feed	2	Edible vegetation, fruit for livestock feed	3	Edible vegetation, fruit for livestock feed	2	Coconut waste for livestock consumption	1		2	Insect as feed for livestock
	M	**Insect farming**	1	Processed fish waste as insect feed	1	Processed fish waste as insect feed	1	Processed fish waste as insect feed	1	Processed waste as insect feed	1	Processed waste as insect feed	1	Processed waste as insect feed	1	Processed waste as insect feed	2	Processed vegetation for certain insect feed	2	Processed vegetation for certain insect feed	2	Processed vegetation for certain insect feed	1		2	Processed manure for certain insect feed	1	

Opportunity 2: IMTA development

Integrated multi-trophic aquaculture (IMTA) offers opportunities for growing seafood efficiently, reducing its environmental footprint, and harnessing the abundant ocean resources that atoll countries own. These are flexible and adaptable farming systems that can accommodate and integrate different species with different levels of interdependency and connectivity, being farmed with different levels of technology and infrastructure both in land and ocean operations. Therefore, they can be adapted to a specific region's environmental, social and cultural priorities. Currently, seaweed and sea cucumbers have been the preferred target for integration into IMTA systems due to their ecological regulatory functions, nutritional and commercial value. However, there are opportunities to explore other species that could provide high nutrition and be integrated within IMTA.

Potential impact: There could be a high potential for economic impact and also for food security if the range of products derived from IMTA could be expanded. Kiribati already has experience in cultivating some marine based products (e.g. milkfish), and therefore there is an opportunity to build on this. There is also potential for IMTA to generate resilience to climate change pressures (e.g. ocean acidification) by selecting species that are less impacted and even favoured by future conditions.

Limitations: IMTA is largely limited by the fact that open-ocean production and infrastructure is hard to control, for example in terms of nutrient flows. Spacing and species coupling is important to ensure adequate growth, because being a complex interlinked food production system there are more risks (e.g. species interdependency, differential species climate change susceptibility). Inshore IMTA and aquaculture may be more exposed to ocean acidification, meaning that deeper water locations may be needed. This would be more costly.

Information needs: There is a need to understand what species are available and their compatibility in order to become candidates for IMTA, and species that could be grown under future environmental conditions. An economic feasibility assessment is also necessary for remote atoll contexts. In addition, an understanding of the political and economic appetite from different countries to attempt IMTA is required, plus regulatory limitations and the availability of space for production, and communities' interest and capacity.

Opportunity 3: Small-scale livestock farming

Opportunities: This links to the tuna waste opportunity mentioned above, but also to opportunities for protein diversification and energy production at the household level. Large livestock such as pigs are common in coral atolls such as Kiribati, and are an important household asset. The manure from these animals can be integrated in home gardening or any waste processing to produce biofertilizer, providing an opportunity for a circular linkage between marine and terrestrial production. Waste biogas (e.g. methane) can also be captured and used for household energy needs.

Potential impact: The main impact lies in the provision of renewable energy supplies for households, and the possibility of organic fertiliser production for home gardens. There could be business opportunities for the conversion of waste product fertiliser.

Limitations and information needs: The technique of separating biogas from liquids remains undetermined in an atoll context, and will require appropriate infrastructure. There is also a need to better understand the liquid fertilisation process, but technology transfer from southeast Asia is possible, where the approach is already practiced in smallholder agriculture.

Opportunity 4: Open ocean aquaculture

Opportunities: Open ocean aquaculture (OOA) is an emerging approach where farm sites are established some distance offshore. In coral atoll nations such as Kiribati there is a significant opportunity to explore OOA beyond the limited and contested lagoon and terrestrial areas. While offshore finfish aquaculture is being explored in New Zealand, technology is also in development for cost-effective, robust and simple structures suitable for seaweed and shellfish cultivation. With continued research it is hoped that these structures will be sufficiently adaptable to accommodate a variety of conditions and species, and for community-based ownership and management.

Potential impact: OOA may be more resilient to extreme weather events than inshore-based sites, and may serve as an additional avenue for food and livelihood security without the need to occupy valuable and contested inshore locations.

Limitations and information needs: OOA is still in its infancy. As such there are currently significant information gaps that would need to be addressed with regard to technology trials, appropriate species and their climate change tolerance, identifying suitable offshore sites, plus community and political support and economic feasibility.

Opportunity 5: Small indigenous species

Opportunities: Small indigenous fish species (SIS) are considered an easily digestible food item and a rich source of animal protein, vitamins and minerals essential for human bone, teeth, skin and eyes, and immuno-response (Thilsted et al. 1997). SIS are underutilised in most PICs, but there is potential for the harvesting and cultivation of a number of locally available, easily digestible and highly nutritious species (e.g. flying fish, sprats, fusiliers, sardinella, herrings, diamond-back squid). There are also potential avenues to improve the existing utilisation of SIS. Pacific SIS are usually highly perishable and consumed unprocessed, which if addressed could enhance their utility, for example through:

- Post-harvest stabilization (e.g. freezing, drying, salting, canning), capacity-building of fishers and technology transfer;
- Product development, such as ‘fish powder’ which has a shelf-life of weeks rather than days, and has a market in Asia as an ingredient for soups, stews and curries;
- Production of SIS through low-technology aquaculture, to supplement fishing for SIS.

Potential impact: The capture and cultivation of SIS is already being promoted as a potentially transformative option for South Asian artisanal fisheries and aquaculture, due to its potential to alleviate poverty and promote food security.

Limitations and information needs: There is a need to conduct an inventory of available and utilised SIS species within coral atoll nations, including Kiribati. Also it is necessary to assess their potential contribution to local food security (i.e. which species are locally preferred or valued?), suitability for low-tech aquaculture systems (i.e. which species are easily cultivated?), and for marketability (i.e. which species are suitable for trade or export?).

7.4.3 Exploring alternative production options – volcanic islands

Relative to coral atoll types, volcanic islands (e.g. many contexts in the Solomon Islands) have a greater diversity of production systems, and relatively more of these are based on terrestrial than fisheries systems (Table 4). The potential integration of waste from offshore tuna and coastal fisheries, plus coconut husks as fertiliser inputs and soil amelioration for terrestrial food production (e.g. gardens and raised bed crops) was considered to have high integration potential. Likewise, the incorporation of household and commercial livestock waste as fertiliser for terrestrial systems (e.g. gardens, watermelon production, raised crop beds, pond fields, permanent agroforestry) was scored highly due to the ubiquity of both livestock and terrestrial garden/agroforestry systems. Incorporation of vegetation waste from agroforestry systems for habitat creation and restoration of mangrove systems was scored highly, along with the integration of farmed insect waste as bait for inland fishing systems and feed for inland aquaculture systems. The primary opportunities which warrant further investigation are:

Opportunity 1: Tuna fisheries and coconut waste transfer

Coconut husks, after being left to partially decompose naturally, are grated and added to soil, enhancing its water retention properties. The husks are high in carbon, however, so nitrogen also needs to be added to prevent the husks from absorbing the available nitrogen from the soil. Processed fish waste (e.g. from tuna), and waste from central urban fish markets are a potential source of this additional nitrogen. Crushed shells from aquaculture operations or wild capture of crabs or shellfish could also be used for soils that would benefit from calcium inputs.

Potential impact: There is a large volume of fish waste potentially available from tuna processing, and small-scale gardens and urban backyards are ubiquitous, and likely to expand in urban and peri-urban areas. Also, fish markets in urban areas produce waste which is so far unutilised, either as left-over fish or offcuts/offal, and these markets are likely to grow with projected urbanisation. Growing population, particularly in the Solomon Islands, would benefit from more productive gardens and improved waste management in urban areas.

Limitations: As discussed for coral atoll islands, the concept of using fish wastes as a fertiliser has been considered within a Pacific context by SPC and others, and the range of technical and economic barriers would also apply to volcanic islands.

Information needs: There are three primary knowledge gaps which must be addressed. First, the yield benefits from fertilising soil with coconut husks and fish waste, and the crops or production systems which would benefit most must be determined. Second, as for coral atolls, the technical and economic feasibility of processing waste from tuna fisheries should be assessed. Finally, the practicality of transporting and distributing fish waste must be assessed in different contexts, for example by considering more remote regions versus urban or peri-urban areas nearer port and processing infrastructure.

Table 6: Integration potential of food production systems on Pacific volcanic islands. Numbers indicate the potential to use waste streams from food production systems (columns) as inputs for food production systems (rows). Key: 0 = not possible, 1 = possible but limited feasibility, 2 = average, needs lots of scoping, 3 = looks promising, 4 = excellent opportunity. Numbers also accompanied by explanatory text where appropriate.

		Waste from these systems →	Fisheries			Aquaculture		Terrestrial									
↓		**Production for these systems**	**A** Inland fisheries	**B** Mangrove fisheries	**C** Offshore tuna	**D** Coastal fisheries	**E** Mariculture	**F** Inland aquaculture	**G** Subsistence gardens	**H** Water melon production	**I** Seasonal production systems	**J** Raised bed crops	**K** Pond-field crops	**L** Non-permanent agroforestry	**M** Permanent agroforestry	**N** Household livestock	**O** Commercial livestock	**P** Insect farming
Fisheries	**A**	**Inland Fisheries**	2 bait	2 bait	2 bait	2 bait	1	1	2 Fishing equipment from unused material	1	2 Fishing equipment from unused material	1	1	2 Fishing equipment from unused material	2 Fishing equipment from unused material	1	1	3 bait
	B	**Mangrove fisheries**	2 bait	2 bait	2 bait	2 bait	1	1	2 Fishing equipment from unused material	1	2 Fishing equipment from unused material	1	1	3 Vegetation for mangrove restoration	3 Vegetation for mangrove restoration	1	1	2 bait
	C	**Offshore tuna**	2 bait	2 bait	2 bait	2 bait	1	1	1	1	2 Fishing equipment from unused material	1	1	2 Fishing equipment from unused material	2 Fishing equipment from unused material	1	1	1
	D	**Coastal fisheries**	2 bait	2 bait	2 bait	2 bait	1	1	2 Fishing equipment from unused material	1	2 Fishing equipment from unused material	1	1	2 Fishing equipment from unused material	2 Fishing equipment from unused material	1	1	2 bait
Aquaculture	**E**	**Mariculture**	2 Feed (direct or processed)	2 Feed (direct or processed)	2 Processed tuna waste for aquaculture feed	2 Feed (direct or processed), bycatch grow out	2 Feed (direct or processed), lateral integration	2 Feed (direct or processed), lateral integration	1	1	1	1	1	1	1	1	1	2 Augmented feed for certain species

	F	Inland Aquaculture	2	Feed (direct or processed), bycatch grow out	2	Feed (direct or processed), bycatch grow out	2	Processed tuna waste for aquaculture feed	2	Feed (direct or processed), bycatch grow out	2	Feed (direct or processed), lateral integration	2	Feed (direct or processed), lateral integration	1		1		1		1		1		1		1		1		1		3	Processed feed for aquaponics
Terrestrial	G	Subsistence gardens	2	Soil amelioration	2	Soil amelioration	4	Processed tuna waste for soil amelioration	3	Soil amelioration	2	Soil amelioration	2	Soil amelioration	2	Leafy vegetation for nutrient rich compost	1		2	Leafy vegetation for nutrient rich compost	2	Leafy vegetation for nutrient rich compost	1		1		2	Leafy vegetation for nutrient rich compost	3	Waste as fertiliser	3	Waste as fertiliser	1	
	H	Watermelon production	2	Soil amelioration	2	Soil amelioration	2	Processed tuna waste for soil amelioration	2	Soil amelioration	2	Soil amelioration	2	Soil amelioration	2	Leafy vegetation for nutrient rich compost	1		2	Leafy vegetation for nutrient rich compost	2	Leafy vegetation for nutrient rich compost	1		1		2	Leafy vegetation for nutrient rich compost	3	Waste as fertiliser	3	Waste as fertiliser	1	
	I	Seasonal production systems	2	Soil amelioration	2	Soil amelioration	3	Processed tuna waste for soil amelioration	2	Soil amelioration	2	Soil amelioration	2	Soil amelioration	2	Leafy vegetation for nutrient rich compost	1		2	Leafy vegetation for nutrient rich compost	2	Leafy vegetation for nutrient rich compost	1		1		2	Leafy vegetation for nutrient rich compost	3	Waste as fertiliser	3	Waste as fertiliser	1	
	J	Raised bed crops	2	Soil amelioration	2	Soil amelioration	4	Processed tuna waste for soil amelioration	3	Soil amelioration	2	Soil amelioration	2	Soil amelioration	2	Leafy vegetation for nutrient rich compost	1		2	Leafy vegetation for nutrient rich compost	2	Leafy vegetation for nutrient rich compost	1		1		2	Leafy vegetation for nutrient rich compost	3	Waste as fertiliser	3	Waste as fertiliser	1	
	K	Pond-field crops	2	Soil amelioration	2	Soil amelioration	2	Processed tuna waste for soil amelioration	2	Soil amelioration	2	Soil amelioration	2	Soil amelioration	2		1		1		1		1		1		1		3	Waste as fertiliser	3	Waste as fertiliser	1	
	L	Non-permanent agroforestry	1	low input system	1	low input system	1	low input system	1	low input system	1	low input system	1	low input system	2	Leafy vegetation for nutrient rich compost	1		2	Leafy vegetation for nutrient rich compost	2	Leafy vegetation for nutrient rich compost	1		1		1		2	Waste as fertiliser	2	Waste as fertiliser	1	
	M	Permanent agroforestry	2	Soil amelioration	2	Soil amelioration	2	Processed tuna waste for soil amelioration	2	Soil amelioration	2	Soil amelioration	2	Soil amelioration	2	Leafy vegetation for nutrient rich compost	1		2	Leafy vegetation for nutrient rich compost	2	Leafy vegetation for nutrient rich compost	1		1		1		3	Waste as fertiliser	3	Waste as fertiliser	1	

N	Household livestock	3	Feed for pigs. Fish meal for chicken pellets	2	Feed for pigs. Fish meal for chicken pellets	3	Tuna waste for livestock feed	2	Feed for pigs. Fish meal for chicken pellets	2	Volume of waste is smaller than fisheries	2	Volume of waste is smaller than fisheries	3	Edible vegetation, fruit for livestock feed	1	
O	Commercial livestock	1	Fertiliser for grass. Shellfish shells for cattle tracks.	1		2	Tuna waste for commercial livestock feed	2	Processed waste as feed for livestock	1	Volume of waste is smaller than fisheries	2	Volume of waste is smaller than fisheries	2	Edible vegetation, fruit for livestock feed	1	
P	Insect farming	1		1		1		1		1		1		2	Vegetation for insect feed	2	Vegetation for insect feed

N	Household livestock	2	Edible vegetation for livestock feed	2	Edible vegetation, fruit for livestock feed	2	Edible vegetation, fruit for livestock feed	2	Edible vegetation, fruit for livestock feed	2	Edible vegetation, fruit for livestock feed	1		1		2	Augmented feed for livestock
O	Commercial livestock	2	Edible vegetation, fruit for livestock feed	2	Edible vegetation, fruit for livestock feed	2	Edible vegetation, fruit for livestock feed	2	Edible vegetation, fruit for livestock feed	2	Edible vegetation, fruit for livestock feed	1		1		2	Augmented feed for livestock
P	Insect farming	2	Vegetation for insect feed	2	Vegetation for insect feed	2	Vegetation for insect feed	2	Vegetation for insect feed	2	Vegetation for insect feed	2	Processed waste for certain insect feed	2	Processed waste for certain insect feed	2	Feed (direct or processed), lateral integration

Opportunity 2: Urban backyard food production

Currently urban backyard gardens are increasingly important for food security, particularly during crises such as the COVID-19 pandemic. Government and NGOs are promoting the growing of food by urban households to promote self-sufficiency, improved nutrition and resilience. In addition, aquaponics (i.e. combining tilapia and vegetable production in small tanks linked by circulated water) is being trialled in the Solomon Islands and is suitable for small scale backyard operations.

There are several options to enhance food production in backyard gardens:

- Use biosolids from municipal waste streams as a feed source for insects, which can be grown and fed to fish in aquaponic systems;
- Use waste vegetable matter from garden produce to augment fish feed, and use waste water from tanks to fertilise gardens;
- Use biosolids from human waste directly as a fertiliser for food crops;
- Integrate fish waste from Opportunity 1 into backyard food production.

Potential impact: The enhancement and diversification of backyard gardens will have a potentially significant impact on nutrition and food security, especially in urban areas which are likely to expand, and where diets are becoming increasingly import-dependent. In addition, the techniques would be easily scalable across urban settlement areas.

Limitations: Soil must often be bought by urban households for their gardens, but once established its fertility could be maintained using the suggested approaches. Capital costs and skills to install aquaponic tanks and infrastructure may be a limitation, as will the redirection of municipal wastewater and the establishment of insect processing units. Cultural resistance to using human waste is also a barrier.

Information needs: The feasibility of using municipal wastewater and developing insect processing is unknown, and requires further study in the relevant urban contexts. Although aquaponics is already being trialled in the Solomon Islands, the relative cost-benefit ratios of integrating waste streams (i.e. insect and vegetable fish food, waste tank water) have to be assessed. The use of human waste is also a sensitive issue, although several projects have begun to assess and trial approaches that would overcome cultural and social barriers in the Pacific. These challenges and attitudes are also likely to be context-specific, requiring detailed local assessments.

Opportunity 3: Agroforestry waste for marine habitat creation

Coastal mangroves provide important ecosystem services, including carbon sequestration (‘Blue Carbon’), coastal protection from storm surges and seal level rise, nursery habitat for many fishery species, and resources for gleaning, especially by women (e.g. mud crabs, molluscs). Mangrove areas are under pressure from harvesting for fuel and building wood, and clearance for coastal development. Waste from coastal agroforestry systems (e.g. coconut timber and fronds) could be utilised to restore mangrove areas, trapping sediment and creating habitat for harvested species. This source of material could be integrated with mud crab and sea cucumber ranching initiatives. Offshore, coconut tree waste (e.g. wood and fronds) have long been used as temporary Fish Aggregating Devices (FADs).

Potential impact: The quantity of agroforestry waste material and the ability to move it into areas requiring enhancement are likely to limit the scale of benefit. However, most coastal strips are dominated by coconut plantations and other tree crops, and are therefore adjacent to mangrove and estuarine areas, making transport and integration relatively simple.

Limitations: Any habitat enhancement will require ongoing management and maintenance. FADs created from biodegradable waste will only be temporary, but may be more cost-effective than commercially-produced FAD infrastructure (e.g. buoys, moorings). Labour, tools and machinery sufficient to transport and install waste material must be available, but could be seasonally limited due to other demands and livelihood activities.

Information needs: The skills and techniques of using waste material for habitat enhancement may already be established in traditional knowledge and practice, but the extent of these practices, and the feasibility of restoring them, should be assessed. Methods of integrating waste placement with mangrove restoration and planting techniques should also be assessed.

7.4.4 Bio-circular modelling: integration flow diagrams

The team also trialled the use of modelling diagrams to illustrate the details of material flows for the integration opportunities. Figure 11 demonstrates this for the tuna/livestock waste opportunity identified for volcanic islands, based on flow diagrams developed by Mazzetto et al. (2023). Different wastes or co-products from one sector could be used as an input for the other sector. For example, bones and off-cuts (usually waste) could be processed and transformed to feed to the pork sector, while the wastewater from tuna processing could be treated and used as potable water for the pork sector. At the same time, the co-products from the pork processing (e.g. offal, bones, blood) could be composted and transformed in fertiliser for household crops that are producing feed for pigs. The manure of the pigs could be collected in a biodigester to generate biogas and energy for the household, or for the tuna processing plant.

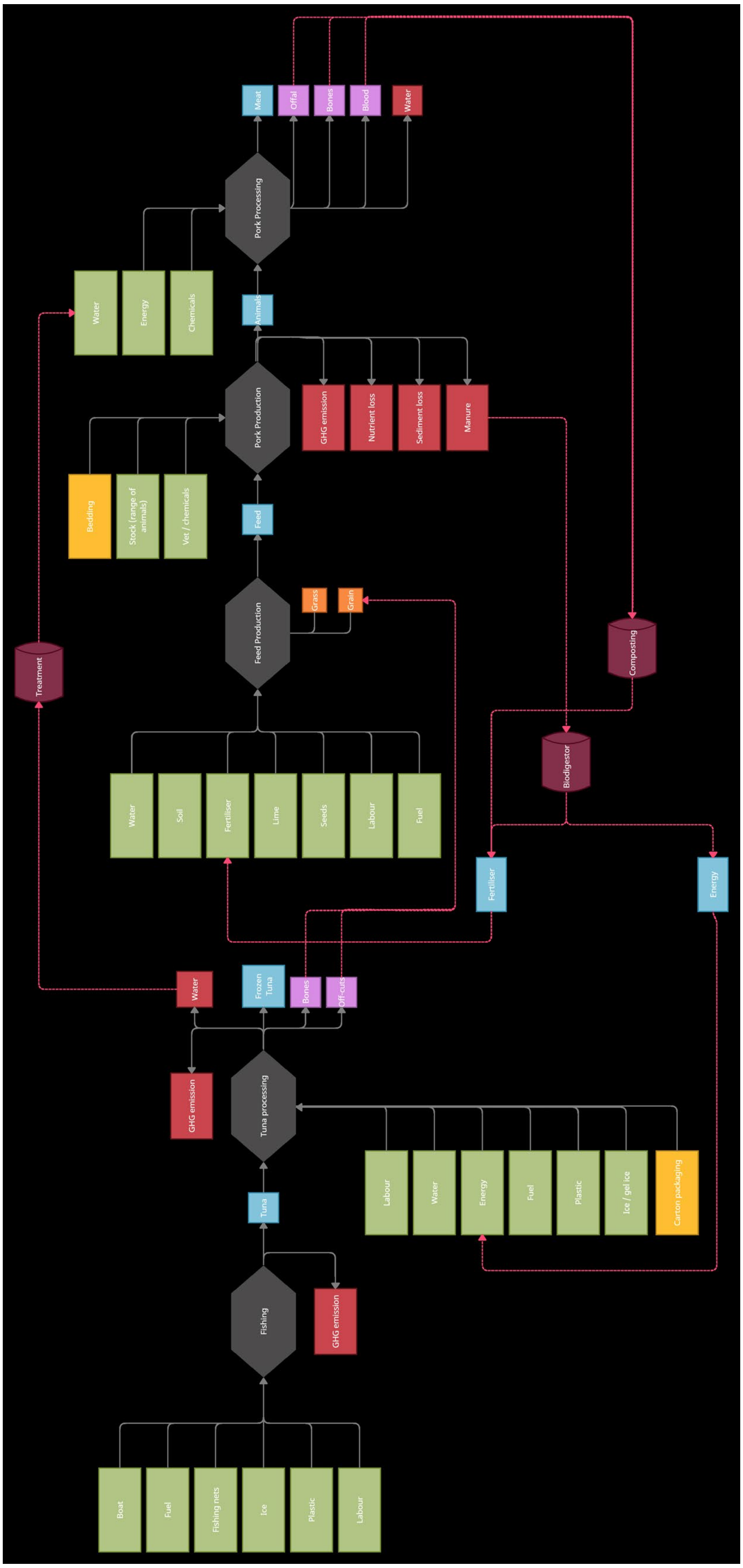


Figure 11: Flow model diagram of alternative food production system components, using the opportunity involving tuna and livestock waste for fertiliser and energy production. Grey boxes represent the main processes in both systems, green boxes represent inputs, blue boxes represent the main product; pink boxes represent the co-products, red boxes represent the 'waste' that can potentially be used by another system, and purple boxes represent the actions necessary to implement the use of the waste.

7.5 Assessing future climate compatibility of alternative food production options

7.5.1 Makin Island, Kiribati

Makin Island in Kiribati is a low-lying coral atoll. The analysis of potential future climate impacts on key food products (see Appendix 3 for details) suggests that land-based production is highly vulnerable to the impacts of inundation due to sea level rise (Figure 12). For marine species, sea level rise may bring some positive impacts because it will increase the extent of habitats (e.g. for sea cucumbers). In the near future (i.e. a 2030 scenario), small increases in temperature may encourage primary growth rates, benefiting both terrestrial production (Naresh Kumar and Aggarwal, 2013), and aquatic production (e.g. invertebrates such as sea cucumbers and clams). Ocean acidification is expected to affect organisms with calcareous skeletal structures (e.g. sea cucumbers, fish, clams; (Dupont et al., 2010; Yuan et al., 2015) via reproduction and growth, and also indirectly via food web effects (Dueri et al., 2013). Although a mix of positive and negative effects are expected with climate change, net effects for marine invertebrates are expected to be slightly more negative for most species (Plaganyi et al., 2013).

However, Figure 12 shows that land-use changes and resource utilization due to increases in human population are as, or more important drivers than climate change for some marine species. Tilapia is a temperature-resistant species that has the potential to both provide food and income to coastal communities, and could mitigate fishing pressure by substituting for marine species.

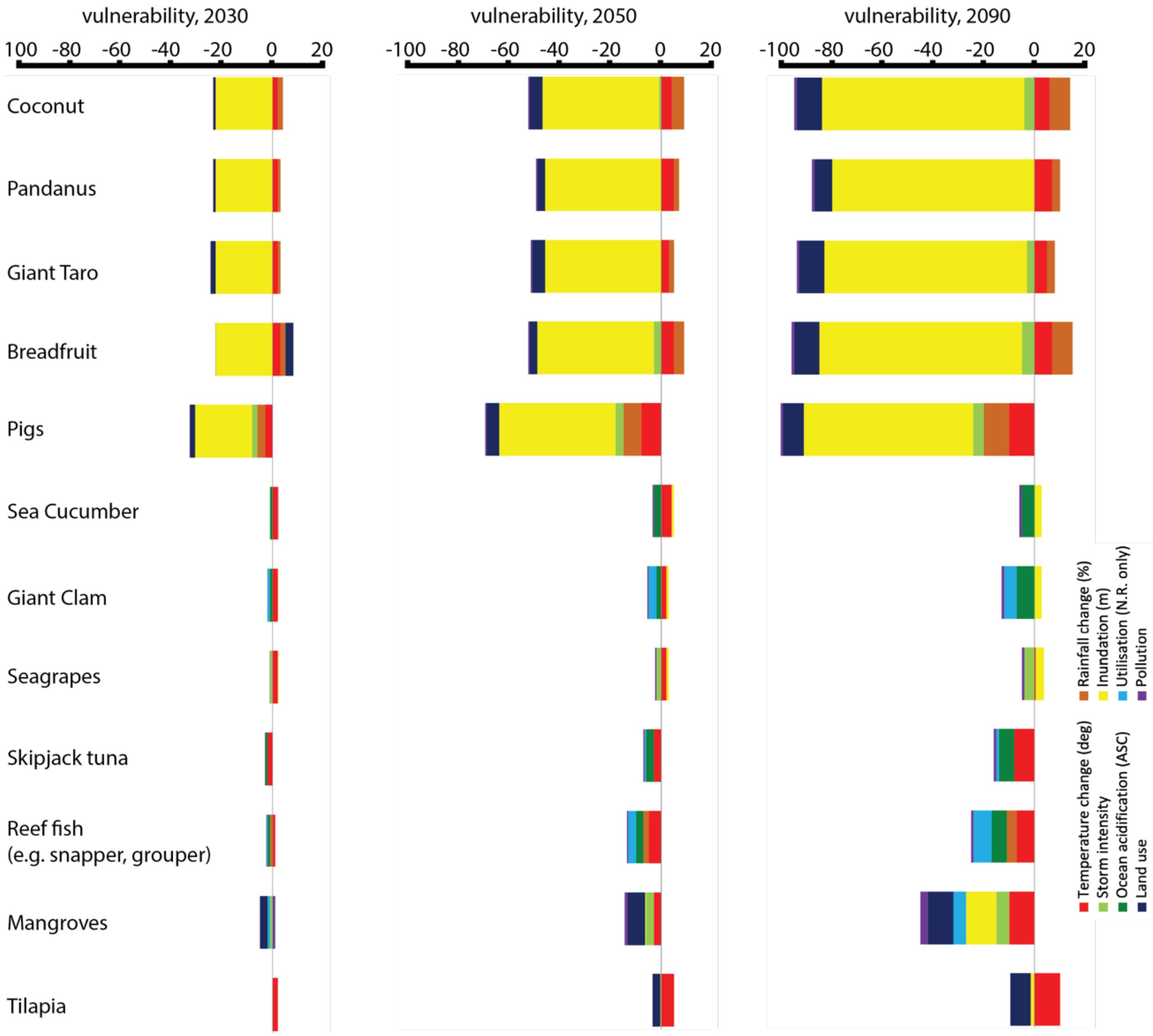


Figure 12: Vulnerability assessment for primary food products for Makin Island, Kiribati for 2030, 2050 and 2090 scenarios under business as usual climate change and population growth projections

An on-line workshop held amongst the team then considered the ramifications of these potential impacts for the alternative food production options identified for a coral atoll type (see section 7.4.2). The participants were presented with the analysis in Figure 12 and reminded about the opportunities prioritised in section 7.4.2. They were then asked to assess the alternatives' ecological and physical viability, considering that many of the current food products would be components of the integrated options.

The workshop suggested that three purely marine-based food production options were still viable if some mitigation measures were taken, along with land-based aquaponics systems (Table 7). Two food production options with significant terrestrial components (i.e. fish waste as fertiliser, livestock waste for fertiliser and energy) scored lower due to the vulnerability of low-lying land to inundation, where gardens and production sites would be located. The results of this analysis and refinements to the potential production options were collated into an infographic for typical coral atoll islands, which also highlighted potential co-benefits for other ecosystem services (Figure 13).

Table 7: Future climate compatibility assessment of six alternative food production options for Makin Island, Kiribati. For the overall assessment column, colour denotes climate viability: green = highly viable, yellow = viable with some mitigation, amber = somewhat viable with much mitigation, red = not viable.

Alternative food production system	Main crops / animals / fisheries	Waste streams for integration	Ecological viability: climate impact on production species	Physical viability: impact of extremes (spikes) on production and infrastructure	Overall assessment
Tuna waste → garden fertiliser	*Tuna, reef fish, garden crops*	*Fish waste*	Small climate impacts on tuna and reef fish; gardens impacted mostly by inundation. Garden crops remain ecologically feasible - temperature rise may be positive	Flooding of gardens, storm surges. Salinization of ground water. Could be mitigated by raising land level and infrastructure.	Donation species unaffected, but viability of gardens may be risky due to inundation. This assessment does not consider infrastructural viability
Integrated multi-trophic aquaculture development	*Seaweed, sea cucumbers, milkfish, shellfish*	*Fish waste, shells*	Potential climate impacts on seaweed - including *Kappaphycus*. Little data on sea grape vulnerability. Sea cucumbers may be resilient, depending on species. Clams may be affected by acidification.	Open coastal systems less impacted by temperature - lagoons more protected than open sea.	Coastal, open areas less affected by climatic factors than closed ponds. Strain selection for temperature resilience could be possible. Potential hatchery production of sea cucumbers
Open ocean aquaculture	*Shellfish, seaweed*	*Shells, inedible parts of harvested seaweed*	Small climate impacts on tuna and reef fish; gardens impacted mostly by inundation. Garden crops remain ecologically feasible - temperature rise may be positive	Technical constraints and exposure to extremes can/will be overcome	Land-based infrastructure will be necessary.
Small scale livestock farming → garden fertiliser → biofertilizer production (energy)	*Reef fish / tuna, pigs, household crops*	*Fish waste, pig waste*	Pigs sensitive to heat. Reef slightly more vulnerable to climate change than off-shore fish, depending on coral reef health, but both quite resilient. Composting might cause more soil acidification.	Pigs sensitive to heat waves. Inundation a general risk - could be mitigated by raising land level	Could introduce new heat-tolerant breeds of pigs, or selectively breed for pigs to cope with the 1-2^{0}C increase in air temperature. Targeted composting might be necessary.
Underutilised small indigenous species	*Marine species: flying fish, sprats, fusiliers, sardinella, herrings, diamond back squid*	*Fish waste*	Mixed effects - most small pelagic species will be resilient. Those reliant on reef shelter will depend on reef health. Decreased diversity of species also a risk, and reduced growth/size	Coral bleaching impacts on reef-based species. Small pelagic species less vulnerable	These species are underutilised with much potential. Novel/improved fishing methods may be needed e.g. pumping at night with a light for small pelagic's scads? Fry transfer into inland flood pools for milk fish (as traditional in Nauru)?
Aquaponics	*Tilapia (land-based), vegetables (e.g. food cubes, aquacubes) - plus bio-manuring*	*Seaweed or crop waste*	Could introduce diversity of crops into aquaponics (e.g. bananas). Tilapia very resilient - can also be manure-producers rather than only a food source	Inundation a general risk - could be mitigated by raising land level. Risk of predation by land crabs	Could introduce diversity of crops into aquaponics (e.g. bananas). Aquaponics can be designed to be inundation-resilient - more so than other land-based options. But system might be fragile to technological failure

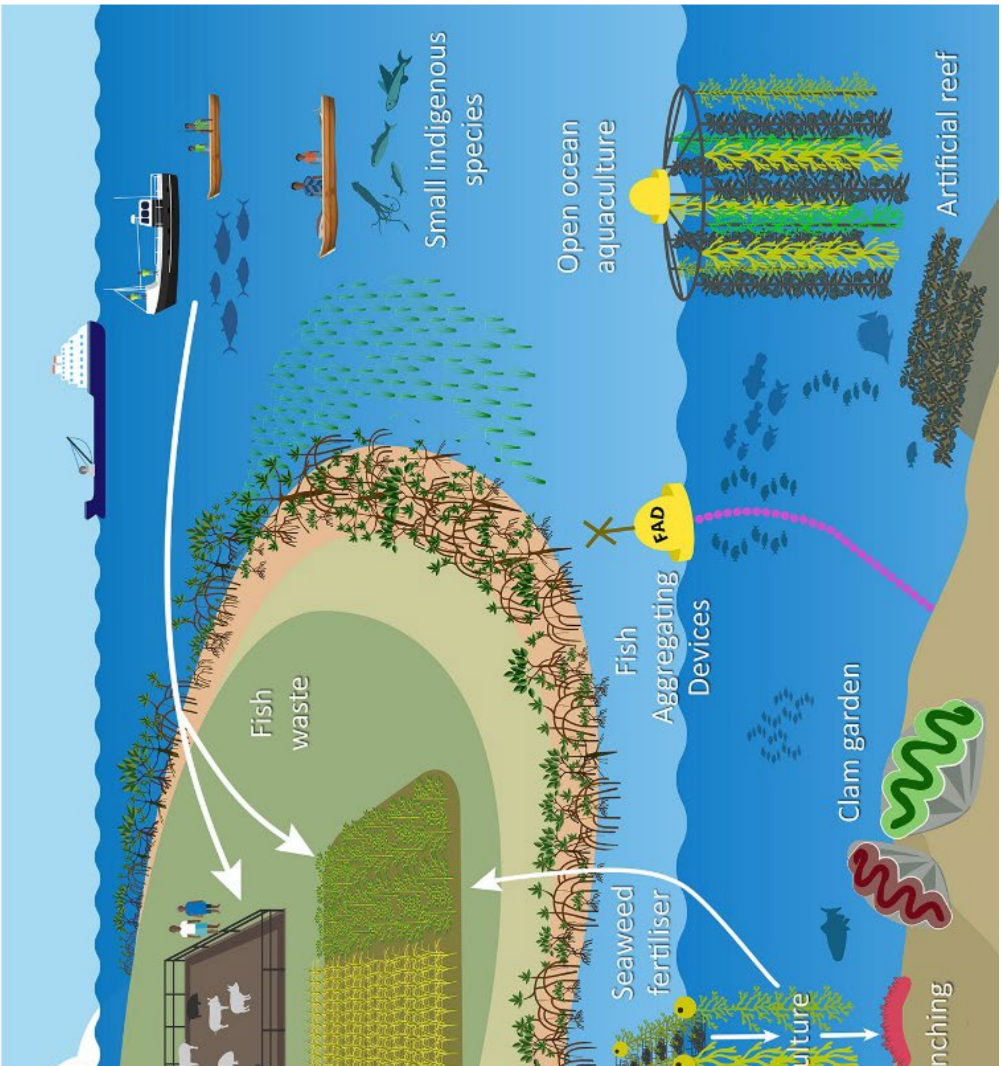


Figure 13: Infographic of alternative food production options for a coral atoll island, such as Makin Island in Kiribati. Arrows indicate flows of waste materials as inputs to another production system. Italics highlight the other ecosystem service co-benefits provided by the integrated production

7.5.2 Ghizo Island, Solomon Islands

Ghizo is a high volcanic island and therefore expected to be much less impacted by future sea level rise, compared to Makin Island (see Figures 12 and 14). As a result, land-based food products are relatively less impacted, as there is space inland to continue agricultural production (see Appendix 3 for details). Combined with a wider range of food products, this makes Ghizo's current food production system less exposed to future change. Similarly to Makin, small increases in temperature are expected to be marginally beneficial for both terrestrial and aquatic food production until about 2050 (Figure 14), while ocean acidification is expected to negatively affect marine species. Land-use changes and increased resource exploitation due to growing population pressure are key factors that will negatively impact food production both in the short- and long-term. As for Kiribati, temperature-resistant species such as tilapia have the potential to positively contribute to coastal food production because they can provide food and income, and divert fishing pressure from over-fished marine species.

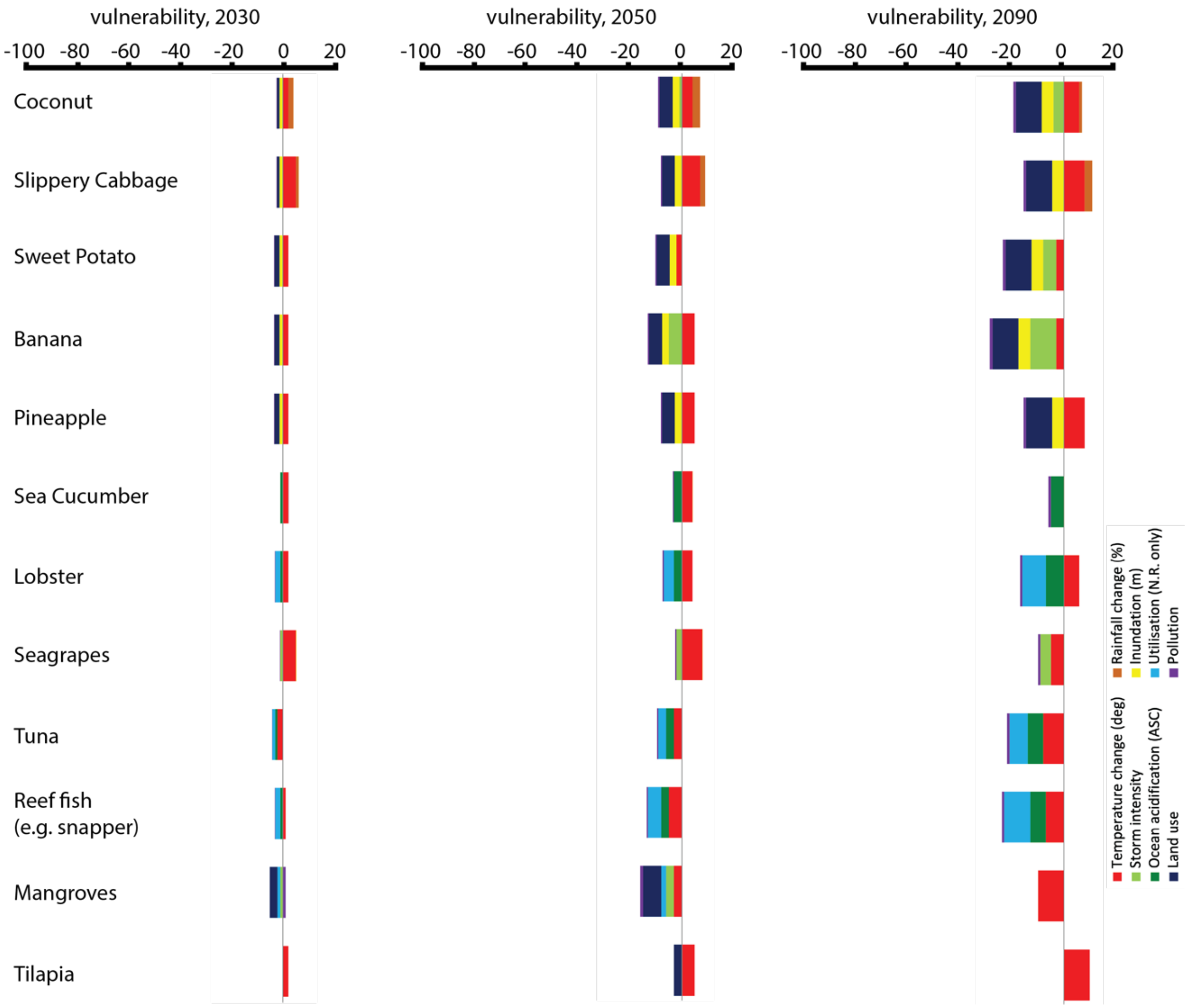


Figure 14: Vulnerability assessment for primary food products for Ghizo Island, the Solomon Islands, for 2030, 2050 and 2090 scenarios under business as usual climate change and population growth projections.

The workshop suggested that the two alternative food production systems with garden components scored highly due to their relative immunity to storms and sea level rise, and better soil conditions relative to Makin Island. Intertidal ponds scored lowest due to coastal vulnerability to storms and inundation. The results of this analysis and refinements to the potential production options were collated into an infographic for typical volcanic islands, which also highlighted potential co-benefits for other ecosystem services (Figure 15).

Table 8: Climate compatibility assessment of four alternative food production options for Ghizo Island, Solomon Islands. For the overall assessment column, colour denotes climate viability: green = highly viable, yellow = viable with some mitigation, amber = somewhat viable with much mitigation, red = not viable

Alternative production system	Main crops / animals / fisheries	Waste streams for integration	Ecological viability: climate impact on production species	Physical viability: impact of extremes on production and infrastructure	Overall assessment
Tuna waste + coconut waste + shells → garden fertilisers	*Artisanal tuna/reef fish, coconut, bivalve and crab shells*	*Coconut husks (C - but elevate soil salinity through sodium), fish waste (N), mollusc shells (Ca)*	Minimal impacts on tuna, reef fish and coconuts; uncertain about crabs and bivalves. Gardens (e.g. slippery cabbage) may benefit from rising temperatures	Some gardens (e.g. bananas) may be impacted by severe storms	Most species involved will remain viable. Managing coconut sodium is possible
Urban gardens: Biosolids from municipal waste + crop waste → food for insects farms → food for aquaponics → garden production	*Insects, aquaponics tilapia, urban garden crops*	*Municipal waste, garden vegetable waste, fish waste, aquaponics waste*	Garden crops benefit from temperature increases. Could include diversity of crops into aquaponics (e.g. bananas). Tilapia very resilient - can be manure-producers rather than food source only	Storm impacts on infrastructure	Could introduce diversity of crops into aquaponics (e.g. bananas). Greater flexibility than in Makin with adding/adapting integration components of system. System might be fragile to technological failure
Agroforestry for marine habitat creation	*Mangrove ecosystems, coconut, mud crabs, plus oysters to create habitat*	*Coconut timber and fronds*	Coconuts not impacted by climate change - may benefit; mangroves impacted by land use change but can retreat if space allowed. Calcifying organisms such as mud crabs and oysters may have growth rates affected by acidification	Storm impacts on coconuts and mangroves	Mangroves need to be protected
Inter-tidal / coastal fishponds	*Black tiger prawns, milkfish, sea cucumbers, oysters*	*Prawns are by-catch from milk fish fisheries*	Acidification will impact shellfish. Impacts on oysters can be managed by moving them offshore to cooler water	Inundation and storm surge exposure - but oysters resilient	Risks associated with pond farming generally are quite high - especially storm surges

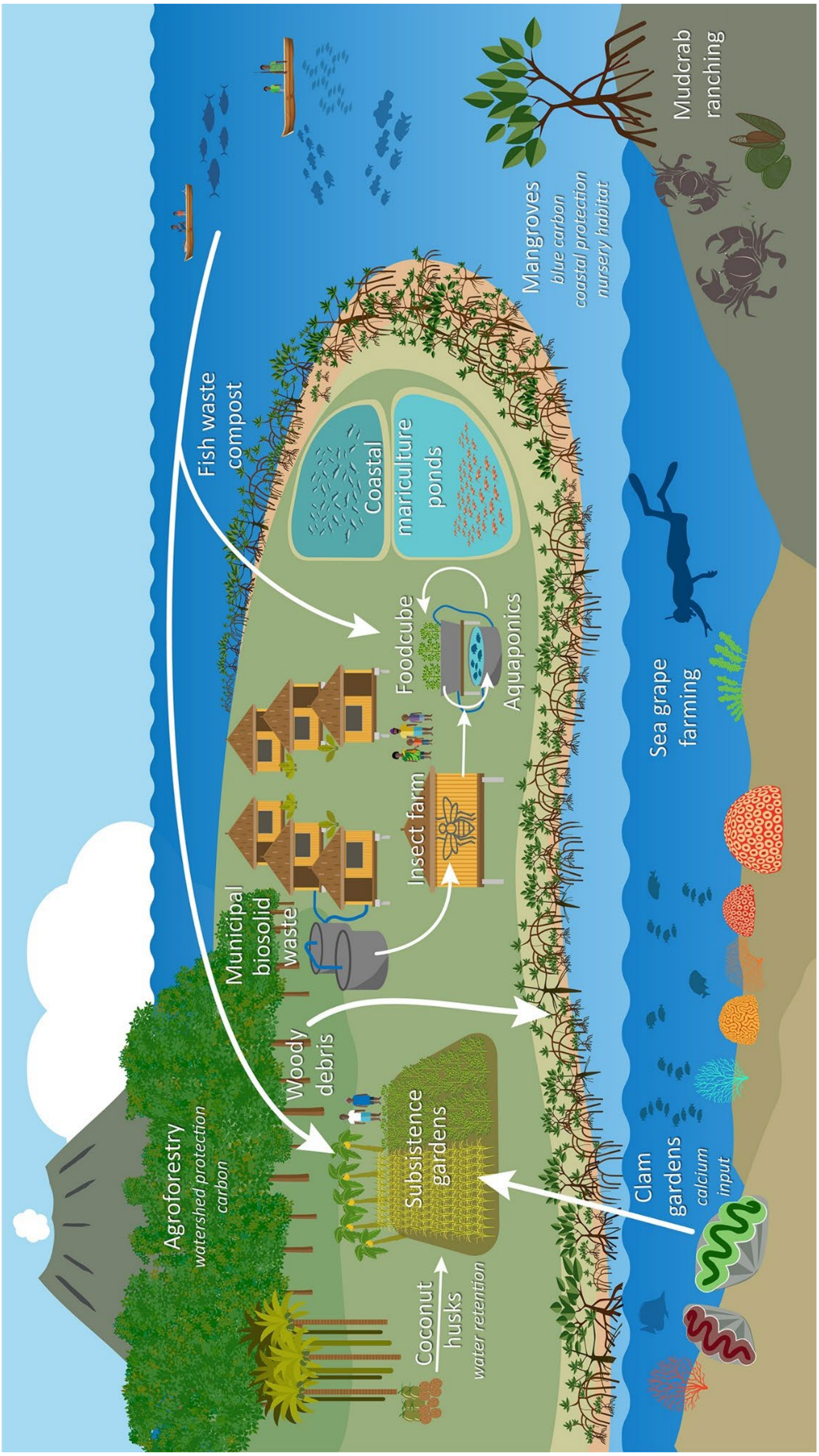


Figure 15: Infographic of alternative food production options for a volcanic island, such as Ghizo Island in the Solomon Islands. Arrows indicate flows of waste materials as inputs to another production system. Italics highlight the other ecosystem service co-benefits provided by the integrated production

7.6 Preliminary assessment framework

The research team developed eight broad indicator groups to assess potential benefits and costs of any alternative production system. Within these groups, 33 indicators were suggested and tested against the criteria using the example of tuna waste:

- Production (9 indicators)
- Circular bio-economy principles (one indicator)
- Environmental sustainability (6 indicators)
- Livelihoods (one indicator)
- Nutrition (four indicators)
- Resilience to shocks (6 indicators)
- Social equity (3 indicators)
- Culture (3 indicators)

Table 9 provides a description of each indicator and its performance against criteria (e.g. how explainable it would be to local stakeholders, possible scoring mechanisms, data needs to measure and report it). The exercise showed that not all indicators will be relevant for every production system or location. For the tuna waste example, labour use (production), land area used (environmental sustainability) and resilience to market changes (resilience to shocks) are only somewhat relevant due to its processing-orientated characteristics, but the remaining 30 were all easily applicable.

The exercise demonstrated an initial inventory of indicators that can be weighted, modified or culled to suit the context of any alternative food production system that is being proposed. However, this initial draft list of indicators would have to be tested and refined in a participatory setting with local stakeholders. While many of the technical indicators (e.g. nutrition) are robust and well-founded in scientific literature, the social and cultural indicators will need ground-truthing and adaptation to local community needs and cultural contexts. Thus, weighting of particular indicators will probably change amongst different communities.

Table 9: Draft assessment indicators for alternative food production systems (FPS). Table includes broad indicator groups (different colours in the first column illustrate different indicator groups), name and brief explanations of each indicator, explainability (ease of translating indicator to local stakeholders), possible scores and criteria, data needs and weighting of indicators by relevance to the tuna waste example (blue column).

Indicator group	Indicator	Indicator explanation	**Explainability** **High**: easy to translate to communities **Somewhat**: somewhat translatable **Low**: hard to translate to communities	Possible scores and criteria	**What are the data needs?** what data do we need for us to be able to use this indicator?	**Existing data sources** What data currently exists to help us use this indicator?	**Use of processed tuna waste to feed household livestock --> manure for fertiliser and biogas** Highly relevant Somewhat relevant Not relevant
Production	Space used for production	How much space is needed, and how much food can be produced in that space.	High	Targeting more efficient production systems. Food production systems could be ranked based on actual or expected yields. **Good** = Production per unit of space increases. **Bad** = Production per unit of space decreases. **NC** = no change in production	Space needed to produce food and whether there will be any changes by integrating multiple food production units that could make the system more efficient (i.e., producing more food in the same space). End users knowledge	Depending on whether the food productions units already exist or they are novel to the setting being considered. Reference values could be obtained from experiences elsewhere. Potential changes due to integration could be estimated	Highly relevant. Good indicator if can assess how much this would improve livestock weights and garden yields
Production	Labour effort	How much work required per day during the production cycle of the targeted food.	High	Targeting more efficient production systems. Food production systems could be ranked based on actual or expected effort. **Good** =less time needed to produce the same or more amount of food. **Bad** = more time needed to produce the same or less amount of food. **NC** = no change in time and amount of food produced	How long it takes to produce the food and how much effort (time) goes into it. If the times can be changed (i.e., reduced) by integrating multiple food production units or more food could be produced with the same effort due to the integration. End users knowledge	Production cycles and effort required for existing crops and food sources. Potential changes due to integration could be estimated	Somewhat relevant. Probably less relevant for this issue unless it adds a lot of labour requirements, and this is not available (but note opportunity for employment at processing factory). Relevant if suggested integration makes a big difference in terms of potential time invested and amount and quality of food produced (faster growth rates, with higher nutrition)
Production	Production costs	How much is spent within a production a cycle	High	**Good** = More affordable. **Bad** = Less affordable. **NC** = no change in affordability	Level of investment needed and running costs for the production cycle of each food and whether this will change due to the integration of other food production units. End users knowledge	Costs associated for the production of existing food products. Potential changes due to integration could be estimated	Highly relevant: Relevant if costs associated with acquiring, processing and transporting tuna waste

Production	Production returns	Is there scope to make an economic gain after satisfying basic needs (perhaps more relevant than from a business point of view)	High	Related to cost indicator (keep separate because high cost can indicate risk and investment need). **Good** = A significant increase in earnings. **NC** = no change in earnings (not sure if this is a bad thing? Depends on the context)	Value of goods produced and whether there will be a change in earning due to integration of different food production units. End users knowledge	Value of good produced	Relevant if there is a surplus in production that can be traded
Production	Self-sufficiency (food security)	How much food is produced locally and is it enough to provide for the community or do you have to get food from other places?	High	Two elements. 1) how reliant is the new system on external inputs? 2) how does this change reliance of the community on external food? This can be measured by some sort of index based on reliance on external food, or an actual diet survey which will identify how much of the food consumed is produced locally vs externally. The index can be calculated as a ratio between food consumed that is locally vs externally produced.	Quantity of food consumed per household that is produced locally or/and food consumed that comes from outside. Another measure could be a survey in the local market to collect data about food produced locally vs externally sold in the market.	Food imported to the country. Likely difficult to have readily available data at local scales.	High relevance for this system. Related to Resilience indicator (e.g what happens if tuna stock collapses or factory ceases production?)
Production	Production waste in the supply chain	How much unused waste if produced at the end of a food production cycle	High	Favouring food production systems with minimal, actual or expected, waste production. **Good** = lower waste production. **Bad** = higher waste production. **NC** = no change in waste production	How much waste is produced for within each production cycle and whether this is reduced or not due to the integration of different food production units. End users knowledge	Indication of waste produced? Changes due to integration could be estimated	Highly relevant as there is a direct reutilization of waste from one production unit into another
Production	System simplicity (vs complexity)	Simpler systems are likely to be more resilient. More complicated food systems that rely on import or export markets have more things that can go wrong	High - though might conflict with desire for export earnings	**Good** = simple enough for local self-sufficiency **Medium** = Complex but multiple options for imports and exports; **Bad** = complex, reliance on limited number of importers or exporters; lots of things to go wrong, or requires considerable outside intervention	Can be assessed intuitively. More nuanced assessment would involve Number of different inputs required; Number of import and export options; Reliance on foreign vs domestic inputs and sales.		
Production	System resilience to disease	Associated with biological risk of the food production system being considered. Disease/pathogen transmision from one production unit to another - negative interactions or interations that result in an improvement	Probably Low	Favouring integration of food production units with a lower associated potential biological risk. **Good** = There is an improvement in health due to the integration (e.g., biocontrol, biorremediation services provided by one of the food production units). **Bad** = There is a known or expected biological risks asociated with the food production system. **NC** = No known or expected detrimental effects asociated to the food production system.	Known and expected pathogens and their vectors associated with the production of each food production unit to build a biological risk matrix when considering their integration. End users knowledge		Highly relevant, effects of tuna waste on the other selected food production units?

Production	Economic scalability	We want food systems that will work in different settings or that can be scaled up to large businesses that provide many people with food and employment.	High	**Good** = system applicable in many contexts or for large number of people **Medium** = scalable to large enterprise in limited number of contexts. **Bad** = system suited to limited number of situations and little scope for scaling to large enterprise	Environmental, social and economic conditions required for the food system; whether the system is amenable to large enterprises (ie has economies of scale)		
Circular bio - economy principles	Material Circularity Indicator (MCI)	How circular is the final product/system, based on the feedstock and the final destination of the product(s)	Somewhat – describe in terms of re-using waste	MCI ranges from 0 (linear) to 1 (fully circular). Good - > 0.5 Bad - <0.5	Bill of materials for the production systems and assessment whether the feedstock is from recycled/reused sources and if the final product can be recycled/reused		Highly relevant
Environmental sustainability	Water footprint (L of water)	The amount of fresh water needed to grow food.	High	**Poor** (water requirements exceeding natural rain/table water supply) **Even** (water requirements matching natural rain/table water supply) **Good** (water requirements below natural supply)	1. Amount and availability of locally-sourced freshwater for FPS. 2. Prediction/modelling of how much fresh water is required for the FPS.	Online rainfall data, water table lens data/reports. Freshwater input data from other FPS.	Highly relevant
Environmental sustainability	Carbon footprint (kg of CO2e)	How much fossil fuel is used to produce a product	Somewhat	**Poor** (GHGE exceeding X) **Good** (GHGE below X)			Highly relevant
Environmental sustainability	Land use area (ha)	How much land is necessary to produce a product	Somewhat - depending on indirect land use (e.g. imported goods) is also considered in the calculation	Needs to be compared against another (e.g. not circular) system	Total area of the system and list of all brought-in inputs (in-country and offshore), plus their origin	Databases or papers/reports can be used for calculating the indirect land use. For the direct land use needs primary data	Somewhat relevant
Environmental sustainability	Abiotic Resource Depletion - Fossil fuel (MJ)	How much fossil fuel is used to produce a product	Somewhat- depending on indirect fossil fuel (international transport) is also considered in the calculation	Needs to be compared against another (e.g. not circular) system	Total amount of fossil fuel (in L or $ values) and list of all brought-in inputs, plus their origin	Databases or papers/reports can be used for calculating the indirect land use. For the direct land use needs primary data	Highly relevant
Environmental sustainability	Eutrophication (freshwater, marine)	How much nitrogen and phosphorus from the land-based production are discharged in fresh/marine water	High	Needs to be compared against another (e.g. not circular) system	All sources of nitrogen and phosphorus applied to the land (e.g. fertiliser, manure, ec)	emissions can be calculated using standard factors but needs primary data	Highly relevant
Environmental sustainability	Waste generation	We want to limit the generation of waste that is not useable for other purposes.	High	**Good** = most or all waste from the FPS can be used in another FPS or for other local purpose **Medium** = considerable amount of waste not useable elsewhere, but most of it is organic and will decompose. **Bad** = large amount of inorganic waste not useable for other purposes	Knowledge of waste streams (organic and inorganic) and other potential uses		

Livelihoods	Business & income opportunity	Opportunity to generate household cash income from this FPS	High	**Good** = the FPS provides to generate surplus for cash sale, to set up small business, or gain local employment, as well as food for the household. **Poor** = the FPS provides food but no opportunity for economic gain or trade.	Knowledge of what scale of system is most viable, whether start-up requirements suit small business or large enterprise, how much labour such enterprises would employ.		Highly relevant
Nutrition	Food group diversity	Diversity of food groups produced	High	Integer score from 0-10. **Good** = 5 or more food groups **Moderate** = 3-4 food groups **Poor** = 2 or less food groups	1. List of foods produced in the proposed system	1. Background information on the proposed production system	Highly relevant
Nutrition	Nutritional gap	Ability to address gaps in local diets (e.g. low fruit consumption)	High	**Good** = targets 2 or more foods/food groups that are limiting in current diets **Poor** = does not target foods/food groups that are limiting in current diets	1. List of foods produced in the proposed system. 2. Data on current dietary patterns in the community	1. Background information on the proposed production system 2. Scientific literature (surveys of food consumption) or grey literature reports on household surveys such as household income/expenditure surveys (HIES) housed by SPC or other nutrition surveys such as Demographic and Health Surveys (ministries of health) or WHO Steps Surveys (WHO). For Kiribati and Solomons examples, best source is new FAO/SPC reports on food consumption.	Highly relevant
Nutrition	Nutritional yield	Ability to improve consumption of specific nutrients in the community (like vitamin A or iron)	Low	No specific threshold, good and poor will be relative to the systems being compared	1. Annual yield (kg or tonnes/hectare or other area unit) of each individual food from the proposed system. 2. Recommended nutrient intakes for adults (selected nutrients). 3. Nutrient composition of foods being produced by proposed system.	1. Background information on proposed production system. 2. Country specific requirements not available for Pacific region so use WHO global recommendations (e.g. see http://apps.who.int/iris/bitstream/handle/10665/42716/9241546123.pdf?sequence=1). 3. Pacific Nutrient Database https://www.spc.int/DigitalLibrary/SDD/Events/Food%20Composition%20Tables%20for%20Pacific%20Island%20HIES	Highly relevant
Nutrition	Rao's quadratic entropy	Ability to improve overall nutrition in the community	Somewhat	No specific threshold, good and poor will be relative to the systems being compared	1. Annual yield (kg or tonnes/hectare or other area unit) of each individual food from the proposed system. 2. Area devoted to new production system (and each individual food) 3. Recommended nutrient intakes for adults (selected nutrients). 4. Nutrient composition of foods being produced by proposed system.	1. Background information on proposed production system. 2. Country specific requirements not available for Pacific region so use WHO global recommendations	Highly relevant

Resilience to shocks	Resilience to storm damage and increased extreme weather events	How well is food production protected from storms?	High	**Bad** = FPS is located in hurricane prone zone. Has high exposure to the elements and no infrastructural protection. **Good** = FPS is located in 'calm' zone (e.g., equator), and is sheltered due to positioning or infrastructural protection.	Forecast reports of the effects of climate change on Kiribati / Solomon coastal environments		Highly relevant
Resilience to shocks	Carrying capacity	More people in the villages will need more food to provide for them. The fishing grounds and land for agriculture are limited and may not be able to provide for large population.	High	**Good** = available habitat space and innovation of FPS will provide to the local population in the mid-term future **Bad** = population has/will exceed carrying capacity within the mid-term future	Population, land area available for agriculture, agriculture productivity, fishing areas, size of fish stocks, catch, maximum sustainable yields, availability of freshwater for consumption and agriculture	Population, agricultural land area, CIA World factbook provides some data for agricultural products: https://www.cia.gov/the-world-factbook/ water security data can be obtained on covid19 water security index: http://www.watercentre.org/covid-19-water-security-risk-index/ Also see Gillet 2016 (fisheries data)	Highly relevant - particularly relevant to Kiribati atolls due to poor soils / water security issues
Resilience to shocks	Resilience to market changes	Is food produced for local people (consumption/local trade) or for export?	High	**Good** = FPS resilient against changes in external markets **Bad** = FPS susceptible to changes in external markets			Somewhat relevant - depends on local or international market focus
Resilience to shocks	Resilience to seal level rise	How well is food production protected from coastal erosion?	High	**Good** = FPS is protected from SLR induced damage. **Bad** = FPS is vulnerable to SLR induced damage (eg., located in vulnerable coastal zone, no infrastructural protection etc).	Forecast reports of the effects of climate change on Kiribati / Solomon coastal environments		Highly relevant
Resilience to shocks	Resilience to Temperature Change (air & sea)	Slightly higher temperatures of the water and air can make fish and plants grow a bit faster, but if it becomes too hot they may die or move away. For Ocean Acidification: Climate change will change ocean characeristics. THis can make corals and shells from shelfish weaker or make them grow slower.	High	**Poor** = Likely to fail at higher sea or air temp. **Good** = Able to do well with increasing sea or air temp	Sea surface temperature, air temperature	Several data sources exist: https://niwa.co.nz/climate/island-climate-update http://www.bom.gov.au/climate/pccsp/ https://climatedataguide.ucar.edu/climate-data/sst-data-hadisst-v11 http://oceanportal.spc.int/portal/ocean.html	Highly relevant
Resilience to shocks	Resilience to Drought/Flood/ ENSO cycles (Climate variability)	Natural periods of droughts and floods and even cyclones can become more frequent or intense in the future due to climate climate change.	Somewhat	**Good** = FPS is 'hardy'. Can withstand climate variability **Bad** = FPS is sensitive to climate variability	Sea surface temperature, Southern Oscillation Index, sea level anomalies. Lots of data needed and still not able to predict ENSO for more than a few months in advance.	https://www.ncdc.noaa.gov/teleconnections/enso/ http://www.bom.gov.au/climate/enso/	Highly relevant
Social equity	Gender equity	Are women included in the decision making, production, capture or processing of food?	High	**Good** = women are included in FPS operations and outputs / women are empowered. **Bad** = operation and outputs of FPS only benefit one gender.	Feedback, interviews, data from affected communities and implementers.		Highly relevant

Social equity	Social justice – inclusion / empowerment of all relevant social groups	Is decision making and benefits shared among the community?	High	**Good** = high level of inclusion and shared benefits from FPS for all groups within a community. **Bad** = low level of inclusion. Benefits of FPS for only select community groups.	Feedback, interviews, data from affected communities and implementers.	Some papers outline a process of Pacific community feedback to elicit social equity factors (e.g. Piggott-McKellar et al., 2020)	Highly relevant
Social equity	Extent of child labour	Are children forced to work against their will?	High	Threshold – no forced child labour	Feedback, interviews, data from affected communities and implementers.		Highly relevant - separate choice from forced labour
Culture	Cultural compatibility	How are crops/species rated in importance by the community?	High	**Good** = high local/cultural compatibility **Bad** = low local/cultural compatibility	Feedback, interviews, data from affected communities and implementers.		Highly relevant
Culture	Enabling local medicines/ traditions		High	**Good** = FPS enables local traditions and festivities **Bad** = FPS does not enable local traditions and festivities	Feedback, interviews, data from affected communities and implementers.		Highly relevant
Culture	Enable traditional bartering		high	**Good** = FPS lends itself to traditional bartering systems **Bad** = FPS does not lend itself to traditional bartering systems	Feedback, interviews, data from affected communities and implementers.		Highly relevant

7.7 SRA contribution to project design

The SRA's outputs have informed the design of the larger follow-on project, CLIM/2020/178 *Transformation pathways for Pacific coastal food systems*, and will also be key elements of the project's participatory-based activities:

- **Hot Spots analysis**: The identification of Hot Spot provinces (Solomon Islands) and island groups (Kiribati) have been incorporated into the Theory of Change for the larger project. Although the selected pilot sites for the project are located in areas of medium priority (Western Province for the Solomons, Gilbert Islands for Kiribati), the Theory of Change assumes that in-country partners will scale-out the approach to the high priority Hot Spots – Guadalcanal, Central and Malaita Provinces in the Solomons, and the Phoenix Islands in Kiribati.
- **Transformational capacity indicators**: The draft indicators developed by this SRA will form a starting point for discussions with the pilot sites' Advisory Committees. In Activity 1 Community and Stakeholder Engagement, the Advisory Committees, which will be comprised of local community leaders, will reflect on their interpretation of 'transformation', and build on these indicators to establish a set of measures that can be evaluated through the project.
- **Integrated or CBE food production options**: The list of potential alternative food production options will be presented in Activity 5 Transformation Pathways Planning to generate discussion about potential transformative strategies. The generic graphics produced for volcanic islands and coral atoll islands will be used as communication tools in the Activity 5 workshops.
- **Feasibility of alternative food production options**: The application of the ADWIM tool to assess the feasibility of the generic production options under business-as-usual climate and population growth projections has provided an initial assessment of the feasibility of these options for the pilot sites. These results will also be presented in the Activity 5 workshops to initiate discussions about those production options which are climate resilient.
- **Assessment framework for potential benefits and costs of alternative production options**: The draft indicator groups for assessing the feasibility and sustainability outcomes from production options and other strategies will be tested and refined during the Activity 5 workshops. The indicators currently form a foundation for further discussions and input from workshop participants.

8 Impacts

8.1 Scientific impacts – now and in 5 years

The concept of transformation is a highly topical issue during current global debates regarding climate change and society's response. With regards to food systems, the application of transformation is novel and relatively unexplored, particularly in the Pacific region. Hence the short-term scientific impacts of this SRA are potentially significant, and will become more so as the impetus for transformation grows in the next few years.

Specifically, the team sees current and growing scientific relevance of the SRA's outputs in the following areas:

- **Hot Spots analysis**: the methodology employed to forecast those regions likely to experience the greatest change in climate and population drivers is unique, since it combines these forces of change, whereas forecasting is usually only conducted for climate change parameters alone. The specific results for the Solomon Islands and Kiribati have important local ramifications for policy, and will guide the scaling out of the social planning process to be developed in CLIM/2020/178 *Transformation pathways for Pacific costal food systems*.

- **Transformational capacity indicators**: The initial draft set of indicators are novel, and unique in that they potentially measure intentional transformative capacity, rather than reactive capacity. Although based on previous attempts to define transformative capacity, our indicators are tailored to food systems, and will be applied and refined in a community setting through CLIM/2020/178. The international scientific originality of this conceptual approach will be tested through the publication of our results in an international scientific journal (see Section 10.2).

- **Integrated or CBE food production options**: The identification of alternative, integrated food production options across agriculture, fisheries and aquaculture is also novel, particularly using our distillation into coral atoll and volcanic island types. The refinement of these options for our CLIM/2020/178 pilot sites using ADWIM is also novel, and will guide local engagement when discussing climate impacts and their feasibility. The international scientific significance of these options, and opportunities for CBEs will also be established through the publication of a journal paper (see Section 10.2).

8.2 Capacity impacts – now and in 5 years

Since the SRA has been largely a desk-based exercise, stakeholder capacity-building was not a primary objective. However, the SRA did aim to build the relationships between the partner organisations, and to establish a platform for the forthcoming CLIM/2020/178. The concept of food systems and transformation explicitly require multi-disciplinary skills and integrated science, and the SRA's activities achieved this by bringing together expert opinion to develop transformative capacity indicators, integrated production opportunities, and the draft assessment framework for the production options, which considered social, economic, nutritional and other aspects of food systems. The capacity built will be fostered further through CLIM/2020/178.

8.3 Community impacts – now and in 5 years

None of the SRA's activities directly involved communities. However, CLIM/2020/178 will apply many of the outputs in community-driven planning processes and testing of alternative production strategies within the Solomon Island and Kiribati pilot sites, and hence will ultimately have community impacts. Once scaled out during and after CLIM/2020/178, these impacts will be expanded across the two countries, and in the broader Pacific region.

8.3.1 Economic impacts

As discussed above, the direct economic impacts of this SRA will only be evident during and after the roll-out of CLIM/2020/178.

8.3.2 Social impacts

As discussed above, the direct social impacts of this SRA will only be evident during and after the roll-out of CLIM/2020/178.

8.3.3 Environmental impacts

As discussed above, the direct environmental impacts of this SRA will only be evident during and after the roll-out of CLIM/2020/178.

8.4 Communication and dissemination activities

Two scientific papers are in draft (see Section 10.2), and will provide the primary scientific communication from the SRA. Two posters have also been produced illustrating alternative integrated production opportunities for coral atolls and volcanic islands (see Figures 13 and 15), and these will be used during Activity 5 of CLIM/2020/178 and for other communication opportunities by the partners. The more detailed outputs (e.g. transformational capacity indicators, assessment framework for production strategies) will also be disseminated and tested during CLIM/2020/178's activities. The Hot Spot maps have already been socialised amongst the project partners, and will guide future project prioritisation by of CLIM/2020/178's in-country partners, WWF-Pacific and Live and Learn.

9 Conclusions and recommendations

Although much of this SRA has been intended to develop tools, collate background information and to establish partnerships to be applied in the forthcoming CLIM/2020/178 *Transformation pathways for Pacific costal food systems*, some of the results have further-reaching consequences.

9.1 Conclusions

Through the Hot Spots analysis, it appears that within the Solomon Islands and Kiribati there are regional variations in the magnitude of change projected under business-as-usual climate change and population growth trajectories. In the Solomon Islands, Guadalcanal Province is likely to experience the greatest changes, partly due to intrinsic population growth, exacerbated by possible in-migration and urbanisation from other regions. Central Province and Malaita Provinces may experience less extreme change. Similarly, in Kiribati the Phoenix Islands group are most at risk due to a combination of sea level rise and population growth, followed by the Gilbert Islands. These results provide important information with which to guide ongoing government, donor and aid responses, and have informed the scaling-out strategy for the CLIM/2020/178 project. They also highlight the role of population growth as a ‘multiplier effect’ when combined with climate change, and as the detailed ADWIM analysis of impacts for the pilot sites shows, population impacts in more volcanic island settings may be greater than climate impacts over the next decades.

The differences both within and between these nations highlights the necessity of a sub-national analysis. Indeed, it may be useful to conduct a similar exercise at the sub-provincial level, although greater resources would be needed, and data resolution may be insufficient. Nonetheless, the method is simple and could be applied to all PICs, as was originally intended by this SRA.

The Hot Spots analysis method could not include projections of food and nutrition security, however, although this has been highlighted as a necessity by other research. Consequently, only trends in recent decades were available, and current status. If food and nutrition security could be projected it may be possible to provide a third variable with which to examine future Hot Spots. However, it may be that unlike climate and population, nutrition and food security are to some extent dependent variables, driven partly by environmental impacts on food systems, and therefore cannot be ‘predicted’ in the same way.

The alternative production options, and the assessment of their climate compatibility in two pilot locations in the Solomon Islands (volcanic) and Kiribati (coral atoll) for CLIM/2020/178, was an additional set of data which could be extrapolated to other locations in the Pacific. The suite of CBE ideas and opportunities bring together a range of knowledge held by SPC and produced by other research (including ACIAR) to create a picture of potential linkages in integrated food production systems. Interestingly, most of the material flows involved marine-terrestrial exchange, rather than vice versa, and due to sea level rise risks on coastal land provide the most climate-resilient options, particularly in Kiribati. While this might have been expected for coral atoll contexts, where land-based agricultural production is relatively limited, it was a surprise for volcanic islands. In both cases, the use of marine fish waste as an input to agriculture was one of the highest-ranked options. An additional emphasis for volcanic islands such as the Solomon Islands was the opportunity to enhance backyard food production in urban areas, which are likely to grow due to urbanisation and immigration.

Hence, when combined with other novel forms of production (e.g. IMTA, OOA, SIS), CBE opportunities could provide transformative pathways for coastal food systems. However, the prioritisation of these options, and their assessment using the draft indicator framework developed by this SRA, must be left to the participatory multi-stakeholder planning processes proposed in CLIM/2020/178. Furthermore, the technical feasibility of these options must be assessed *in situ* and/or in simulated agro-ecological conditions, particularly those that are more likely to be climate change-compatible (i.e. tuna waste and urban gardens in the Solomon Islands, and tuna waste and small scale livestock farming in Kiribati). Likewise, the indicators of intentional transformative capacity must also be tested and refined in CLIM/2020/178. One area still to be considered is how to build and measure capacity related to the identification and implementation of CBE and other integrated production systems.

9.2 Recommendations

Recommendation 1: Within the Solomon Islands and Kiribati, food system transformational efforts need to be targeted at the Hot Spots of Guadalcanal Province and the Phoenix Islands, followed by Central and Malaita Provinces and the Gilbert Islands.

Recommendation 2: The Hot Spots method should be applied to other PICs, and could be applied at a sub-province level if data resolution and resources allow.

Recommendation 3: Refine and test the transformative capacity and alternative production opportunities with PICs stakeholders, using the two indicator frameworks as an initial starting point.

Recommendation 4: Ground test the biophysical feasibility and potential of the alternative production options, particularly those involving CBE principles. A priority should be those options for the Solomon Islands and Kiribati pilot sites which are likely to be most climate change-compatible.

10 References

10.1 References cited in report

Albert, J., Bogard, J., Siota, F., McCarter, J., Diatalau, S., Maelaua, J., Brewer, T., Andrew, N. (2020) Malnutrition in the Solomon Islands: An analysis of the problem and its drivers. Maternal and Child Nutrition 2020;16:e12921. https://doi.org/10.1111/mcn.12921

Agnalt, A.-L., Grefsrud, E.S., Farestveit, E., Larsen, M., Keulder, F. (2013) Deformities in larvae and juvenile European lobster (Homarus gammarus) exposed to lower pH at two different temperatures. Biogeosciences 10, 7883-7895.

Agroforestry CMI, (2022) Agroforestry in the Climate of the Marshall islands - Longterm recommendations. University of Hawaii, Hawaii.

Bednaršek, N., Feely, R.A., Beck, M.W., Alin, S.R., Siedlecki, S.A., Calosi, P., Norton, E.L., Saenger, C., Štrus, J., Greeley, D., Nezlin, N.P., Roethler, M., Spicer, J.I. (2020) Exoskeleton dissolution with mechanoreceptor damage in larval Dungeness crab related to severity of present-day ocean acidification vertical gradients. Science of The Total Environment, 136610.

Beetham, E., Kench, P.S., Popinet, S. (2017) Future Reef Growth Can Mitigate Physical Impacts of Sea-Level Rise on Atoll Islands. Earths Future 5, 1002-1014.

Bell, J., Taylor, M., Amos, M., Andrew, N., (2016) Climate change and Pacific Island food systems the future of food, farming and fishing in the Pacific Islands under a changing climate, Wollongong, p. 39.

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

Bell, J.D., Johnson, J.E., A.S., G., P., G., Hobday, A.J., Hoegh-Guldberg, O., Le Borgne, R., Lehodey, P., Lough, J.M., Pickering, T.D., Pratchett, M.S., Waycott, M. (2011) Vulnerability of Tropical Pacific Fisheries and Aquaculture to Climate Change: Summary for Pacific Island Countries and Territories. Secretariat of the Pacific Community, Noumea, New Caledonia.

Bell, J.D., Senina, I., Adams, T., Aumont, O., Calmettes, B., Clark, S., Dessert, M., Gehlen, M., Gorgues, T., Hampton, J., Hanich, Q., Harden-Davies, H., Hare, S.R., Holmes, G., Lehodey, P., Lengaigne, M., Mansfield, W., Menkes, C., Nicol, S., Ota, Y., Pasisi, C., Pilling, G., Reid, C., Ronneberg, E., Gupta, A.S., Seto, K.L., Smith, N., Taei, S., Tsamenyi, M., Williams, P. (2021) Pathways to sustaining tuna-dependent Pacific Island economies during climate change. Nature Sustainability.

Bogard, J.R., Andrew, N.L., Farrell, P., Herrero, M., Sharp, M.K., Tutuo, J. (2021) A Typology of Food Environments in the Pacific Region and Their Relationship to Diet Quality in Solomon Islands. Foods 10, 2592.

BoM, CSIRO, (2014a) Kiribati, Climate Variability, Extremes and Change in the Western Tropical Pacific: New Science and updated Country Reports. Australian Bureau of Meteorology and CSIRO, Canberra, pp. 113-125.

BoM, CSIRO, (2014b) Solomon Islands, Climate Variability, Extremes and Change in the Western Tropical Pacific: New Science and updated Country Reports. Australian Bureau of Meteorology and CSIRO, Canberra, pp. 259-279.

BoM, CSIRO, (2014c) Tonga, Climate Variability, Extremes and Change in the Western Tropical Pacific: New Science and updated Country Reports. Australian Bureau of Meteorology and CSIRO, Canberra, pp. 281-300.

BOM and CSIRO, (2014d) Kiribati, in Climate Variability, Extremes and Change in the Western Tropical Pacific: New Science and updated Country Reports. . Australian Bureau of Meteorology and CSIRO, Canberra, pp. 113-125.

Bourke, R.M., McGregor, A., Allen, M.G., Evans, B.R., Mullen, B.F., Pollard, A.A., Wairiu, M., Zotalis, S., (2006) Solomon Islands Agriculture Study: Volume 1. AusAID, Canberra, Australia.

Breadfruit Institute, (2019) Horticulture. National Tropical Botanical Garden.

Brodie, G., Brodie, J., Maata, M., Peter, M., Otiawa, T., Devlin, M.J. (2020) Seagrass habitat in Tarawa Lagoon, Kiribati: Service benefits and links to national priority issues. Marine Pollution Bulletin 155.

Brodnik, C., Brown, R.R. (2018) Strategies for developing transformative capacity in urban water management sectors: The case of Melbourne, Australia. Technological Forecasting and Social Change 137, Issue C, 147-159.

Brown, C.J., Fulton, E.A., Hobday, A.J., Matear, R.J., Possingham, H.P., Bulman, C., Christensen, V., FORREST, R.E., Geherke, P.C., Gribble, N.A., Griffiths, S.P., Lozano-Montes, H., Martin, J.M., Metcalf, S., Okey, T.A., Watson, R., Richardson, A.J. (2010) Effects of climate-driven primary production change on marine food webs: implications for fisheries and conservation. Global Change Biology 16, 1194-1212.

Butler, J.R.A., Tikai, P., Fasi, J., Tutua, S., Nadelko, A., Webb, M., Macdonald, B., van Wensveen, M., Clothier, B., Yi, D., Newman, S., Dutra, L., Hayes, D., Kenny, G., Wilson, T., Tait, A., Crimp, S., Skewes, T.D. (2021). Climate change and Pacific food systems: Decision-making for transformational change. ACIAR Final Report SRA WAC–2019-148. ACIAR, Canberra.

CABI, (2022) Pandanus tectorius (screw pine), Invasive Species Compendium. CAB International, Wallingford, UK.

Carilli, J., Donner, S.D., Hartmann, A.C. (2012) Historical Temperature Variability Affects Coral Response to Heat Stress. PLoS ONE 7.

Carter, R., Ferdinand, T., Chan, C. (2018) Transforming Agriculture for Climate Resilience: A Framework for Systemic Change. World Resources Institute Working Paper. World Resources Institute, Washington DC. Transforming Agriculture for Climate Resilience: A Framework for Systemic Change | World Resources Institute (wri.org)

CIA, (2021) The World Factbook. Central Intelligence Agency, Washington DC.

Climate Central, (2021) Coastal risk screening tool: Land projected to be below annual flood level, Princeton.

Cochrane, K., Rakotondrazafy, H., Aswani, S., Chaigneau, T., Downey-Breedt, N., Lemahieu, A., Paytan, A., Pecl, G., Plagányi, E., Popova, E. (2019) Tools to enrich vulnerability assessment and adaptation planning for coastal communities in data-poor regions: application to a case study in Madagascar. Frontiers in Marine Science 5, 1-22.

CSIRO, SPREP, (2021) 'NextGen' Projections for the Western Tropical Pacific: Current and Future Climate for Kiribati. Final report to the Australia-Pacific Climate Partnership for the Next Generation Climate Projections for the Western Tropical Pacific project. CSIRO Technical Report, Melbourne.

Davis, B., Lipper, L., Winters, P. (2022) Do not transform food systems on the back of the rural poor. Food Security 14(3), 729-740. doi: 10.1007/s12571-021-01214-3

Denley, D., Metaxas, A., Scheibling, R. (2020) Subregional variation in cover and diversity of hard coral (Scleractinia) in the Western Province, Solomon Islands following an unprecedented global bleaching event. PLOS ONE 15.

Dennis, D.M., Skewes, T.D., Pitcher, C.R. (1997) Habitat use and growth of juvenile ornate rock lobsters, Panulirus ornatus (Fabricus, 1798), in Torres Strait, Australia. Marine and Freshwater Research 48, 663-670.

Dixon-Jain, P., Norman, R., Stewart, G., Fontaine, K., Walker, K., Sundaram, B., Flannery, E., Riddel, A., Wallace, L., (2014) Pacific Island Groundwater and Future Climates: First-pass regional vulnerability assessment. Geoscience Australia.

Dominy, W., Sato, V., Yong Ju, Z., Mitsuyasu, M. (2010). Fish Processing Waste: A Valuable Co-Product of the Fishing Industry. Western Pacific Regional Fishery Management Council, Honolulu.

Dornelles, Z.A., Boonstra, W.J., Delabre, I., Denney, J.M., Nunes, R.J., Jentsch, A., Nicholas, K.A., Schröter, M., Seppelt, R., Settele, J., Shackelford, N., Standish, R.J., Oliver, T.H. (2022) Transformation archetypes in global food systems. Sustainability Science. 17(5), 1-14 DOI:10.1007/s11625-022-01102-5

Dueri, S., Bopp, L., Maury, O. (2013) Projecting the impacts of climate change on skipjack tuna abundance and spatial distribution. Global Change Biology 20.

Duffy, K.A., Schwalm, C.R., Arcus, V.L., Koch, G.W., Liang, L.L., Schipper, L.A. (2021) How close are we to the temperature tipping point of the terrestrial biosphere? Science Advances 7, eaay1052.

Duke, N.C., Burrows, D., Mackenzie, J.R., (2015) Mangrove and Freshwater Wetland Habitat Status of the Torres Strait Islands - Biodiversity, Biomass and Changing Condition of Wetlands, a report to the National Environmental Research Program, Cairns, p. 117.

Dupont, S., Ortega-Martinez, O., Thorndyke, M. (2010) Impact of near-future ocean acidification on echinoderms. Ecotoxicology 19, 449-462.

Dutra, L.X.C., Haywood, M.D.E., Singh, S., Ferreira, M., Johnson, J.E., Veitayaki, J., Kininmonth, S., Morris, C.W., Piovano, S. (2021) Synergies between local and climate-driven impacts on coral reefs in the Tropical Pacific: A review of issues and adaptation opportunities. Marine Pollution Bulletin 164.

Eme, P.E., Burlingame, B., Douwes, J., Kim, N., Foliaki, S. (2019) Quantitative estimates of dietary intake in households of South Tarawa, Kiribati. Asia Pacific Journal of Clinical Nutrition 28, 131-138.

EMF (2015). Circularity Indicators: An Approach to Measuring Circularity: Methodology. Growth Within: A Circular Economy Vision for A Competitive Europe. https://circular-impacts.eu/library/1294#:~:text=The%20Circularity%20Indicators%20Project%20aims,journey%20from%20linear%20to%20circular.

FAO, (2017) Fishery and Aquaculture Country Profiles: Solomon Islands - Updated 5 June 2018, Country Profile Fact Sheets. FAO Fisheries Division [online], Rome.

FAO, (2019a) The state of Kiribati's biodiversity for food and agriculture, in: Bélanger, J., Pilling, D. (Eds.), The State of the World's Biodiversity for Food and Agriculture. FAO Commission on Genetic Resources for Food and Agriculture Assessments, Rome.

FAO, (2019b) The state of the Solomon Islands biodiversity for food and agriculture, in: Bélanger, J., Pilling, D. (Eds.), The State of the World's Biodiversity for Food and Agriculture. FAO Commission on Genetic Resources for Food and Agriculture Assessments, Rome.

Farmery, A.K., Scott, J.M., Brewer, T.D., Eriksson, H., Steenbergen, D.J., Albert, J., Raubani, J., Tutuo, J., Sharp, M.K., Andrew, N.L. (2020) Aquatic Foods and Nutrition in the Pacific. Nutrients 12.

Feola, G. (2015) Societal transformation in response to global environmental change: A review of emerging concepts. Ambio 44(5), 376-390.

Fulton, E.A., Hobday, A.J., Pethybridge, H., Blanchard, J., Bulman, C., Butler, I., Cheung, W., Dutra, L.X.C., Gorton, R., Hutton, T., Lozano-Montes, H., Matear, R., Pecl, G., Plagányi, E.E., Villanueva, C., Zhang, X., (2018) Decadal scale projection of changes in Australian fisheries stocks under climate change, Canberra.

Garud, R., Nayyar, P.R. (1994) Transformative capacity: Continual structuring by intertemporal technology transfer. Strategic Management Journal. 15, 365-385.

Gillett, R. (2016a) Fisheries in the Economies of Pacific Island Countries and Territories. SPC, Noumea.

Gillett, R. (2016b) Kiribati, Fisheries in the Economies of Pacific Island Countries and Territories. Pacific Community, Noumea, pp. 92-114.

Gillett, R. (2016c) Solomon Islands, Fisheries in the Economies of Pacific Island Countries and Territories. Pacific Community, Noumea, pp. 234-257.

Glatz, P.C. (2012) Sustainable small-scale poultry production: are local feeds a viable option for the Pacific region? http://knowledge.cta.int/en/Dossiers/Commodities/Livestock/Enhancing-competitiveness-in-the-ACP-poultry-value-chain/Feature-articles/Sustainable-Small-Scale-Poultry-Production-Are-Local-Feeds-a-Viable-Option-for-the-Pacific-Region

Global Nutrition Report (2021) Country Nutrition Profiles. Development Initatives, Bristol, UK.

Graves, C., Powell, A., Stone, M., Redfern, F., Biko, T., Devlin, M.J. (*in press*) Marine water quality of a densely populated pacific atoll (Tarawa, Kiribati): Cumulative pressures and resulting impacts on ecosystem and human health. Marine Pollution Bulletin.

Grinsted, A., Christensen, J.H. (2021) The transient sensitivity of sea level rise. Ocean Sci. 17, 181-186.

Guo, H., Yao, J.T., Sun, Z.M., Duan, D.L. (2015) Effect of temperature, irradiance on the growth of the green alga Caulerpa lentillifera (Bryopsidophyceae, Chlorophyta). Journal of Applied Phycology 27, 879-885.

Hebbar, K.B., Abhin, P.S., Jose, V.S., Neethu, P., Santhosh, A., Shil, S., Prasad, P.V.V. (2022) Predicting the Potential Suitable Climate for Coconut (Cocos nucifera L.) Cultivation in India under Climate Change Scenarios Using the MaxEnt Model. Plants-Basel 11.

Heider, B., Struelens, Q., Faye, É., Flores, C., Palacios, J.E., Eyzaguirre, R., de Haan, S., Dangles, O. (2021) Intraspecific diversity as a reservoir for heat-stress tolerance in sweet potato. Nature Climate Change 11, 64-69.

Howden, S.M., Crimp, S., Nelson, R. (2010) Australian agriculture in a climate of change. *Managing climate change: papers from the Greenhouse 2009 conference*. Commonwealth Scientific and Industrial Research Organization (CSIRO) Publishing, Collingwood, Australia, 2010.

HLPE 2020. Food Security and Nutrition: Building a Global Narrative towards 2030. A report by the High-Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome.

Iese, V., Maeke, J., Holland, E., Wairiu, M., Naidu, S. (2015) Farming Adaptations to the Impacts of Climate Change and Extreme Events in Pacific Island Countries: Case Study of Bellona Atoll, Solomon Islands. Impacts of Climate Change on Food Security in Small Island Developing States, 166-194.

Iese, V., Maeke, J., Holland, E., Wairiu, M., Naidu, S. (2017) Farming Adaptations to the Impacts of Climate Change and Extreme Events in Pacific Island Countries: Case Study of Bellona Atoll, Solomon Islands. Natural Resources Management: Concepts, Methodologies, Tools, and Applications, 852-875.

IPCC, (2019a) Chapter 4: Sea Level Rise and Implications for Low Lying Islands, Coasts and Communities, in: H.-O. Pörtner, D.C.R., V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama, N. Weyer (Ed.), IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

IPCC, (2019b) Summary for Policymakers, in: H.-O. Pörtner, D.C.R., V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, M. Nicolai, A. Okem, J. Petzold, B. Rama, N. Weyer (Ed.), IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

iplantz, (2022) Useful plants for warm climates - Abelmoschus manihot. Iplantz.

Johnson, J., Bell, J., Gupta, A.S., (2015) Pacific Islands Ocean Acidification Vulnerability Assessment, in: SPREP (Ed.). SPREP, Apia, Samoa.

Johnson, J.E., Welch, D.J. (2016) Climate change implications for Torres Strait fisheries: assessing vulnerability to inform adaptation. Climatic Change 135, 611-624.

Kates, R.W., Travis, W.R. Wilbanks, T.J. (2012) Transformational adaptation when incremental adaptations to climate change are insufficient. Proceedings of the National Academy of Science USA. 109, 7156-7161.

Katovai, E., Edwards, W., Laurance, W.F. (2015) Dynamics of Logging in Solomon Islands: The Need for Restoration and Conservation Alternatives. Tropical Conservation Science 8, 718-731.

Kiareti, A., Beiateuea, T., Liu, R., Teema, T., Moore, B., (2015) Monitoring the Vulnerability and Adaptation of Coastal Fisheries to Climate Change: Abemama Atoll Kiribati - Assessment Report No. 2, Tarawa.

Kile, N. (2000) Solomon Islands marine resources overview. Pacific Economic Bulletin 15, 143-147.

Lammers, P.J., Stender, D.R., Honeyman, M.S. (2007) Environmental Needs of the Pig. Niche Pork Production 210, 1-6.

Laurie, R.N., Laurie, S.M., Du Plooy, C.P., Finnie, J.F., Van Staden, J. (2015) Yield of drought-stressed sweet potato in relation to canopy cover, stem length and stomatal conductance. Journal of Agricultural Sciences 7, 201-214.

Lee, E.J., Kim, M., Kim, K.H. (2018) Connecting ENSO-related climatic variations with a long-term crop supply data to enhance agro-meteorological capability of Tongan stakeholders. International Journal of Climatology 38, E18-E27.

Lovelock, C.E., Reef, R. (2020) Variable Impacts of Climate Change on Blue Carbon. One Earth 3, 195-211.

Magel, J.M.T., Dimoff, S.A., Baum, J.K. (2020) Direct and indirect effects of climate change-amplified pulse heat stress events on coral reef fish communities. Ecological Applications 30.

Mangubhai, S., Strauch, A.M., Obura, D.O., Stone, G., Rotjan, R.D. (2014) Short-term changes of fish assemblages observed in the near-pristine reefs of the Phoenix Islands. Reviews in Fish Biology and Fisheries 24, 505-518.

Mausio, K., Miura, T., Lincoln, N.K. (2020) Cultivation potential projections of breadfruit (Artocarpus altilis) under climate change scenarios using an empirically validated suitability model calibrated in Hawai'i. PLoS ONE 15.

Mazzetto, A.M., Falconer, S., Ledgard, S. (2023) Carbon footprint of New Zealand beef and sheep meat exported to different markets. Environmental Impact Assessment Review. 98 (2023) 106946. https://doi.org/10.1016/j.eiar.2022.106946

McEvoy, D., Mitchell, D., Trundle, A. (2020) Land tenure and urban climate resilience in the South Pacific. Climate and Development 12, 1-11.

McIver, L., Kim, R., Woodward, A., Hales, S., Spickett, J., Katscherian, D., Hashizume, M., Honda, Y., Kim, H., Iddings, S., Naicker, J., Bambrick, H., McMichael, A.J., Ebi, K.L. (2016) Health Impacts of Climate Change in Pacific Island Countries: A Regional Assessment of Vulnerabilities and Adaptation Priorities. Environmental Health Perspectives 124, 1707-1714.

Morrison, R.J. (1999) The regional approach to management of marine pollution in the South Pacific. Ocean & Coastal Management 42, 503-521.

Munday, P.J., Jones, G.P., Sheaves, M., Williams, A.J., Goby, G., (2007) Chapter 12: Vulnerability of fishes of the Great Barrier Reef to climate change, Part II: Species and species groups. Great Barrier Reef Marine Park Authority, Townsville, pp. 357-392.

Munday, P.L., Jones, G.P., Pratchett, M.S., Williams, A.J. (2008) Climate change and the future for coral reef fishes. Fish and Fisheries 9, 261-285.

Naresh Kumar, S., Aggarwal, P.K. (2013) Climate change and coconut plantations in India: Impacts and potential adaptation gains. Agricultural Systems 117, 45-54.

Nataniel, A., Pennino, M.G., Lopez, J., Soto, M. (2022) Modelling the impacts of climate change on skipjack tuna (*Katsuwonus pelamis*) in the Mozambique Channel. Fisheries Oceanography 31, 149-163.

Norman-Lopez, A., Plaganyi, E., Skewes, T., Poloczanska, E., Dennis, D., Gibbs, M., Bayliss, P. (2013) Linking physiological, population and socio-economic assessments of climate-change impacts on fisheries. Fisheries Research 148, 18-26.

Nunn, P.D., Kumar, L., Eliot, I. *et al.* (2016). Classifying Pacific islands. Geoscience Letters 3, 7. https://doi.org/10.1186/s40562-016-0041-8

Obura, D., Mangubhai, S. (2011) Coral mortality associated with thermal fluctuations in the Phoenix Islands, 2002-2005. Coral Reefs 30, 607-619.

Olsson, P., Galaz, V., Boonstra, W.J. (2010) Sustainability transformations: a resilience perspective. Ecology and Society*,* 19.

Pacific Community (2020) Atoll Water Inventory: A climatic, socio-economic, and investment suitability overview of water security in Pacific islands. Pacific Community, Noumea.

Pakoa, K., Masu, R., Teri, J., Leqata, J., Tua, P., Fisk, D., Bertram, I., (2014) Solomon Islands sea cucumber resource status and recommendations for management, Noumea.

Paliwal, A., (2018) A Warming Climate Could Make Pigs Produce Less Meat: Farm animals raised in hotter conditions do not generate as much protein, which could make pork more expensive, Scientific American.

Park, S.E., Marshall, N.A., Jakku, E., Dowd, A.M., Howden, S.M., Mendham, E., Fleming, A. (2012) Informing adaptation responses to climate change through theories of transformation. Global Environmental Change*.* 22, 115-126.

Patterson, J., Schulz, K., Verwoort, J., van der Hel, S., Widerberg, O., Adler, C., Hurlbert, M., Anderton, K., Sethi, M., Barau, A. (2017) Exploring the governance and politics of transformations towards sustainability. Environmental Innovation and Societal Transitions*,* 24.

Plagányi, E., Haywood, M., Gorton, B., Condie, S., (2018) Environmental drivers of variability and climate projections for Torres Strait tropical lobster *Panulirus ornatus*. , CSIRO/AFMA Technical Report, March 2018. 156 pp.

Plaganyi, E.E., McGarvey, R., Gardner, C., Caputi, N., Dennis, D., de Lestang, S., Hartmann, K., Liggins, G., Linnane, A., Ingrid, E., Arlidge, B., Green, B., Villanueva, C. (2018) Overview, opportunities and outlook for Australian spiny lobster fisheries. Reviews in Fish Biology and Fisheries 28, 57-87.

Plaganyi, E.E., Skewes, T.D., Dowling, N.A., Haddon, M. (2013) Risk management tools for sustainable fisheries management under changing climate: a sea cucumber example. Climatic Change 119, 181-197.

Pouru-Mikkola, L., Wilenius, M. (2021) Building individual futures capacity through transformative futures learning. Futures 132, 102804.

Purcell, S.W., Mercier, A., Conand, C., Hamel, J.F., Toral-Granda, M.V., Lovatelli, A., Uthicke, S. (2013) Sea cucumber fisheries: global analysis of stocks, management measures and drivers of overfishing. Fish and Fisheries 14, 34-59.

Rahman, M.L., Shahjahan, M., Ahmed, N. (2021) Tilapia Farming in Bangladesh: Adaptation to Climate Change. Sustainability 13, 7657.

Rao, S., Taylor, M., Jokhan, A. (2013) A Rapid Screening Methodology for Salt Tolerance in Giant Swamp Taro (Cyrtosperma merkusii) and Its Diversity. Ii International Symposium on Underutilized Plant Species: Crops for the Future - Beyond Food Security 979, 319-325.

Rauw, W.M., de Mercado de la Peña, E., Gomez-Raya, L., García Cortés, L.A., Ciruelos, J.J., Gómez Izquierdo, E. (2020) Impact of environmental temperature on production traits in pigs. Scientific Reports 10, 2106.

Republic of Kiribati, (2016) 2015 Population and Housing Census - Volume 1: Management report and basic tables, Bairiki,Tarawa.

Rickards, L. Howden, S.M. (2012) Transformational adaptation: agriculture and climate change. Crop Pasture Science 63:240-250.

Robins, L., Crimp, S., van Wensveen, M., Bourke, R.N., Butler, J., Cosijn, M., Davila, F., Lal, A., McCarthy, J.F., McWilliam, A., Palo, A.S., Tomsom, N., Warr, P. and Webb, M. (2020) COVID-19 and food systems in the Indo-Pacific: An assessment of vulnerabilities, impacts and opportunities for action. ACIAR Technical Report Series, 96, 258 p.

Rojas-Sandoval, J., Acevedo-Rodríguez, P. (2013) Alocasia macrorrhizos (giant taro). CABI - Invasive species compendium.

Scoones, I., Stirling, A., Abrol, D., Atela, J., Charl-Joseph, L., Eakin, H., Ely, A., Olsson, P., Pereira, L., Priya, R., van Zwanenberg, P., Yang, L. (2020) Transformations to sustainability: combining structural, systemic and enabling approaches. Current Opinion in Environmental Sustainability 65-75, 42.

Sepri, Hartoko, A., Suradi, W.S., Ghofar, A. (2021) Impact of climate variability on skipjack tuna (Katsuwonus pelamis) catches in the Indonesian Fisheries Management Area (FMA) 715. IOP Conference Series: Earth and Environmental Science 800, 012003.

Sievert, K., Lawrence, M., Naika, A., Baker, P. (2019) Processed Foods and Nutrition Transition in the Pacific: Regional Trends, Patterns and Food System Drivers. Nutrients 11, 1328.

Sharp, M., Mariojouls, C. (2012) Waste Not, Want Not: Better Utilisation of Fish Waste in the Pacific. Secretariat of the Pacific Community, Noumea, New Caledonia.

Skewes, T.D., Hunter, C.M., Butler, J.R.A., Lyne, V.D., Suadnya, W., Wise, R.M. (2016) The Asset Drivers, Well-being Interaction Matrix (ADWIM): A participatory tool for estimating future impacts on ecosystem services and livelihoods. Climate Risk Management 12, 69-82.

Skewes, T.D., Pitcher, C.R., Dennis, D.M. (1997) Growth of ornate rock lobsters, *Panulirus ornatus*, in Torres Strait, Australia. Marine and Freshwater Research 48, 497-501.

Slater, S., Baker, P., Lawrence, M. (2022) An analysis of the transformative potential of major food system report recommendations. Global Food Security 32(1), 100610

DOI:10.1016/j.gfs.2022.100610

Solomon Islands Government, (2009) Population and Housing 2009 census, Honiara.

Solomon Islands Government, (2019) Population and Housing 2019 census. Solomon Islands National Statistical Office, Honiara.

SOPAC, (2007) National Integrated Water Resource Management Diagnostic Report - Kiribati, Noumea.

Secretariat of the Pacific Community (SPC) 2015. A New Song for Coastal Fisheries – Pathways to Change: The Noumea Strategy. Compiled by the Secretariat of the Pacific Community. SPC, Noumea, New Caledonia.

Spijkers, J., Merrie, A., Wabnitz, C.C.C., Osborne, M., Mobjörk, M., Bodin, Ö., Selig, E.R., Le Billon, P., Hendrix, C.S., Singh, G.G., Keys, P.W., Morrison, T.H. (2021) Exploring the future of fishery conflict through narrative scenarios. One Earth 4, 386-396.

Taylor, M., McGregor, A. Dawson, B. (Eds) (2016) Vulnerability of Pacific Island agriculture and forestry to climate change. The Pacific Community, Noumea Cedex, New Caledonia.

Termeer, C.J.A.M., Dewulf, A., Biesbroek, G.R. (2016) Transformational change: Governance interventions for climate change adaptation from a continuous change perspective. Journal of Environmental Planning and Management 60(4), 558-576.

The State of Queensland, (2022) Land requirements for growing pineapple. Departmenr of Agriculture and Fisheries, Brisbane.

Thilsted, S.H., Roos, N., Hassan, N. (1997) The role of small indigenous fish species in food and nutrition security in Bangladesh. NAGA 20 (3/4), 82-84.

Thomas, A., Mangubhai, S., Fox, M., Meo, S., Miller, K., Naisilisili, W., Veitayaki, J., Waqairatu, S. (2021) Why they must be counted: Significant contributions of Fijian women fishers to food security and livelihoods. Ocean & Coastal Management 205, 105571.

Tuia, V.S., Kambuou, R., Paofa, J., Malapa, R., Robert, N., Hadosaia, C., Navukiboro, C., Fink, A., Waqainabete, L.M., Sukal, A. and Shandil, A.S. (2015). Acta Hortic. 1102, 61-66 (2015) Sustainable conservation and utilisation of bele (Abelmoschus manihot), a Pacific indigenous vegetable. Acta Horticulturae 1102, 61-66.

United Nations, (2018) World Urbanization Prospects: The 2018 Revision United Nations, New York.

United Nations, (2019) World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420). Department of Economic and Social Affairs, Population Division, New York.

Valmonte-Santos, R., Rosegrant, M.W., Dey, M.M. (2016) Fisheries sector under climate change in the coral triangle countries of Pacific Islands: Current status and policy issues. Marine Policy 67, 148-155.

Van den Bergh, I., Ramirez, J., Staver, C., Turner, D.W., Jarvis, A. and Brown, D. (2012). Climate change in the subtropics: the impacts of projected averages and variability on banana production. Acta Hortic. 928, 89-99.

Varma, V., Bebber, D.P. (2019) Climate change impacts on banana yields around the world. Nature Climate Change 9, 752.

Vermeulen, S.J., Dinesh, D., Howden, S.M., Cramer, L. and Thornton, P.K. 2018. Transformation in practice: A review of empirical cases of transformational adaptation in agriculture under climate change. Frontiers in Sustainable Food Systems. 2, 65. https://doi.org/10.3389/fsufs.2018.00065

Vogel, C., O'Brien, K. (2021) Getting to the heart of transformation. Sustainability Science https://doi.org/10.1007/s11625-021-01016-8

Vogliano, C., Raneri, J.E., Coad, J., Tutua, S., Wham, C., Lachat, C., Burlingame, B. (2021) Dietary agrobiodiversity for improved nutrition and health outcomes within a transitioning indigenous Solomon Island food system. Food Security.

Walker, B., Sayer, J., Andrew, N.L., Campbell, B.M. (2010) Should enhanced resilience be an objective of natural resource management research for developing countries? Crop Science 50:S-10–S-19.

Watson, S.A., Neo, M.L. (2021) Conserving threatened species during rapid environmental change: using biological responses to inform management strategies of giant clams. Conservation Physiology 9.

Wenger, A.S., Harris, D., Weber, S., Vaghi, F., Nand, Y., Naisilisili, W., Hughes, A., Delevaux, J., Klein, C.J., Watson, J., Mumby, P.J., Jupiter, S.D. (2020) Best-practice forestry management delivers diminishing returns for coral reefs with increased land-clearing. Journal of Applied Ecology 57, 2381-2392.

Weiss, L. (1998) The Myth of the Powerless State. Cornell Studies in Political Economy. Ithaca, NY: Cornell University Press.

Whiteley, N. (2011) Physiological and ecological responses of crustaceans to ocean acidification. Marine Ecology Progress Series 430, 257-271.

Williams, A.J., Allain, V., Nicol, S.J., Evans, K.J., Hoyle, S.D., Dupoux, C., Vourey, E., Dubosc, J. (2015) Vertical behavior and diet of albacore tuna (Thunnus alalunga) vary with latitude in the South Pacific Ocean. Deep-Sea Research Part Ii-Topical Studies in Oceanography 113, 154-169.

Williams, P.A., Crespo, O., Atkinson, C.J., Essegbey, G.O. (2017) Impact of climate variability on pineapple production in Ghana. Agriculture & Food Security 6, 26.

Wolfram, M. (2015) Conceptualizing urban transformative capacity: A framework for research and policy. Cities http://dx.doi.org/10.1016/j.cities.2015.11.011

World Health Organisation, (2021) The Global Health Observatory. World Health Organisation, Geneve.

World Health Organization, (2018) Kiribati: Climate and health country profile - 2017, Geneva.

World Health Organization, (2020) Solomon Islands: Health & climate change country profile 2020, Geneva.

Yang, Z.M., Zhu, P.P., Kang, H., Liu, L., Cao, Q.H., Sun, J., Dong, T.T., Zhu, M.K., Li, Z.Y., Xu, T. (2020) High-throughput deep sequencing reveals the important role that microRNAs play in the salt response in sweet potato (Ipomoea batatas L.). Bmc Genomics 21.

Yuan, X., Shao, S., Dupont, S., Meng, L., Liu, Y., Wang, L. (2015) Impact of CO2-driven acidification on the development of the sea cucumber Apostichopus japonicus (Selenka)(Echinodermata: Holothuroidea). Marine pollution bulletin 95, 195-199.

Zann, L.P. (1994) The status of coral reefs in South Western Pacific Islands. Marine Pollution Bulletin 29, 52-61.

Ziervogel, G., Cowen, A., Ziniades, J. (2016) Moving from adaptive to transformative capacity: Building foundations for inclusive, thriving and regenerative urban settlements. Sustainability 8(9), 955; https://doi.org/10.3390/su8090955

10.2 List of publications produced by project

McCarthy, A., Mazzetto, A., Laurenson, S., Zamora, L., Heasman, K., Pickering, T., Iramu, E., Jimmy, R., Susumu, G., Whitford, J., Dutra, L., Revill, A., Davila, F. and Butler, J.R.A. in prep. How applicable are circular bio-economy principles to Pacific food production? To be submitted to *Agriculture, Ecosystems and Environment*.

Davila, F., Butler, J.R.A., Jacobs, B., Dutra, L., McCarthy, A. and Sinner, J. in prep. Conceptualising intentional transformative capacity for food systems. To be submitted to *Environmental Innovation and Societal Transitions*.

11 Appendixes

11.1 Appendix 1: Hot Spots data used to calculate the priority ranking for Kiribati and the Solomon Islands

We used current data (2020) and projections for the following variables:

- Air and sea surface temperature
- Yearly rainfall
- Aragonite saturation state (Ωar)
- Mean sea level rise (cm)
- Population

Data sources and analyses are as described below.

11.1.1 Kiribati

Phoenix Island Group

Present rainfall and air temperature from: http://world-heritage-datasheets.unep-wcmc.org/datasheet/output/site/phoenix-islands-protected-area/

Future rainfall and air temperature projections: (BoM and CSIRO, 2014a)

Present and future projections aragonite saturation: (BoM and CSIRO, 2014a)

Population: 2020 and 2050 population for each Island group was estimated based on 2015 census (Republic of Kiribati, 2016) using logistic growth from (United Nations, 2019).

Sea level rise: (BoM and CSIRO, 2014a)

Line Island Group

Present rainfall and air temperature from: https://www.climatestotravel.com/climate/kiribati (data for Christmas / Kiritimati Island)

Present and future aragonite saturation: (BoM and CSIRO, 2014a)

Population: 2020 and 2050 population for each Island group was estimated based on 2015 census (Republic of Kiribati, 2016) using logistic growth from (United Nations, 2019).

Sea level rise: (BoM and CSIRO, 2014a)

Gilbert Island

Present rainfall and air temperature from: https://www.climatestotravel.com/climate/kiribati (data for South Tarawa)

Present and projected (2050) aragonite saturation: (BoM and CSIRO, 2014a)

Population: 2020 and 2030 population for each Island group was estimated based on 2015 census (Republic of Kiribati, 2016) using logistic growth from (United Nations, 2019).

Sea level rise: (BoM and CSIRO, 2014a)

11.1.2 Solomon Islands

Outputs from the Conformal Cubic Atmospheric Model (CCAM) were available as an average value per province for air temperature and rainfall. CCAM outputs were not available for Temotu Province. The data was extracted for 2055 as follows:

Table columns:

province Province name

model GCM providing input data for CCAM

var_code Variable name

seas_code Season

nom_year Nominal year (middle of period for 20-year averages)

var_val Average value for province

var_change Average change for province

Models:

echam5

gfdlcm21

ukhadcm3

all Average of the three models

Variables:

tmaxscr Maximum screen temperature (deg. C)

tminscr Minimum screen temperature (deg. C)

rnd24 Rainfall (mm/day)

Seasons:

all Whole year

wet November-April

dry May-October

Nominal years:

1990, 2055, 2090

Aragonite saturation and sea level projections were obtained from BoM and CSIRO (2014a).

Population: Data for present day is from 2009 census (Solomon Islands Government, 2009). Population growth rates for each province was calculated based on growth from 2009 and 2019 using census data (Solomon Islands Government, 2019) and growth rates were used to calculate 2055 population for each province.

Sea level rise: BoM and CSIRO (2014a)

11.2 Appendix 2: Data and data sources used in ADWIM

11.2.1 Makin Island, Kiribati

Datasets for present and future scenarios (2030, 2050, 2070 and 2090) for climate and population for Makin or the Gilbert Island groups were sourced, depending on their availability at the appropriate scale. This was informed by data sourced for the earlier Hot Spots analysis (see Appendix 1).

Datasets for the following drivers of change were sourced from the literature:

- Air and sea surface temperatures
- Yearly Rainfall
- Aragonite saturation state (Ωar) (measures ocean acidification)
- Mean sea level rise (cm)
- Area of land inundation
- Population

Temperature

In the absence of available air temperature data for Makin Island, present day annual average air and sea surface temperatures were sourced for South Tarawa (as a proxy the Gilbert Island Group) from: https://www.climatestotravel.com/climate/kiribati

Current sea surface temperatures were found for Makin Island covering the period between November 2011 and April 2012, where temperatures recorded at 9 m deep varied between 26.1°C and 29.4°C in the lagoon and 26.3°C and 28.9°C in the outer reefs (Kiareti et al., 2015).

Future projections for the Gilbert Island Group published by BoM and CSIRO (2014a) and recently updated by CSIRO and SPREP (2021) were used to calculate future temperature – compared to a 1986-2005 baseline – for Makin Island.

Rainfall

In the absence of available data for Makin, present day (1986-2005) annual rainfall were sourced for South Tarawa as a proxy the Gilbert Island Group from: https://www.climatestotravel.com/climate/kiribati

Future projections for the Gilbert Island Group published by BoM and CSIRO (2014a) and recently updated by CSIRO and SPREP (2021) were used to calculate future rainfall – compared to a 1986-2005 baseline – for Makin Island.

Aragonite saturation

Present day and future projections of aragonite saturation were sourced from BoM and CSIRO (2014a).

Sea level

Changes in sea level relative to a 1986-2005 baseline were sourced from CSIRO and SPREP (2021).

Area of land inundation

GIS layers were sourced from Climate Central Website (Climate Central, 2021) using high emission scenarios for 2030, 2050, 2070 and 2090. Total area of inundation was used to calculate percentage of land inundated for each time period.

The Climate Central website uses a digital elevation model (DEM) based on the global Shuttle Radar Topography Mission (SRTM), which is known to be affected by trees and buildings. The processing applied to the data attempts to reduce that bias in coastal areas below 20 m elevation and applies corrections which depend on remotely-sensed vegetation cover among other factors. Overall the tool provides reasonable outputs. However, preliminary analyses of inundation outputs for some locations in Australia have shown that the algorithm tends to reduce heights even when there is no vegetation, so bare sand dunes for example will have their heights adjusted downwards resulting in over-estimation of inundation. In order to minimise this over-estimation, we applied a linear model based on sea level rise and area of inundation (assuming sea level rise to be linear over time):

$$Area\ Inundated_{year} = \frac{Area\ Inundated_{2070}}{Total\ Land\ Area} \times \frac{SLR_{year}}{SLR_{2070}}$$

Population

Data for 2015 population for Makin Island was sourced from the Kiribati census (Republic of Kiribati, 2016). Future population estimates were calculated using published yearly growth projections for Kiribati up to 2100 (United Nations, 2019).

Table 10: Drivers data for present (1990) and future (2050) scenarios derived from the literature for Makin Island, Kiribati.

Drivers	**1990**	**2050**
Temperature air (^{0}C)	28.0	29.5
Sea surface temperature (^{0}C)	28.9	29.6
Rainfall (mm/yr)	1940.0	2522.0
Storm intensity (% increase)	0.0	6.5
SLR (m)	0.00	0.27
Study area (ha)	789.00	789.00
Sea level rise inundation (ha)	0.00	427.7
Ocean acidification (ASC)	3.90	3.30
Population (inhabitants)	1800	2910
Population density (per km^2)	2.28	6.81
Change	**1990**	**2050**
Temperature air (^{0}C)	0.0	1.5
Sea surface temperature (^{0}C)	0.0	0.7
Rainfall (%)	0.0	30.0
Storm intensity (%)	0.0	6.5
Ocean acidification (ASC)	0.00	-0.60
Population density (%)	0.0	198.7

11.2.2 Sagheraghi, Ghizo Island, Solomon Islands

Temperature

Present day annual average air temperatures for Ghizo were calculated based on monthly averages between 2012 and 2022 sourced from: https://windy.app/forecast2/spot/407577/Gizo/statistics

The annual average for Ghizo (26.8°C) was similar to the CMIP6 yearly average (1996-2005) for the Solomon Islands (26.2°C) (https://climateknowledgeportal.worldbank.org/country/solomon-islands/climate-data-projections-expert). Both were relatively lower than previously published CCAM outputs (29.2°C for present day). For this reason we decided to update present and future air temperature scenarios whereby local data for Ghizo was used for present and CMIP6 outputs were used for future air temperature scenarios.

Present day annual average sea surface temperatures were sourced from: https://www.seatemperature.org/australia-pacific/solomon-islands/gizo-january.htm

Future projections for Solomon Islands published by BoM and CSIRO (2014a) and recently updated by CSIRO and SPREP (2021) were used to calculate future temperature – compared to a 1986-2005 baseline – for Sagheraghi.

Rainfall

Present day monthly rainfall averages published for Ghizo were sourced from: https://www.weather2visit.com/australia-pacific/solomon-islands/gizo-january.htm and used to calculate present day average annual rainfall.

Future projections for the Solomon Islands published by BoM and CSIRO (2014a) and recently updated by CSIRO and SPREP (2021) were used to calculate future rainfall – compared to a 1986-2005 baseline – for Sagheraghi.

Aragonite saturation

Present day and future projections of aragonite saturation were sourced from BoM and CSIRO (2014a)

Sea level

Changes in sea level relative to a 1986-2005 baseline were sourced from CSIRO and SPREP (2021) which incorporates an upward revision in projections from 54 cm to 100 cm by 2090 for high emission scenarios as a result of better understanding about Antarctic ice melting and its impacts on global sea level rise (IPCC, 2019a).

Area of land inundation

GIS layers were sourced from Climate Central Website (Climate Central, 2021) using high emission scenarios for 2030, 2050, 2070 and 2090. Total area of inundation was used to calculate percentage of land inundated under each time period.

As for Makin Island, potential overestimations of inundation was corrected using a linear model:

$$Area\ Inundated_{year} = \frac{Area\ Inundated_{2070}}{Total\ Land\ Area} \times \frac{SLR_{year}}{SLR_{2070}}$$

Population

Data for the present day was taken from the 2009 census (Solomon Islands Government, 2009). Population growth rates for each province was calculated based on growth from 2009 and 2019 using census data (Solomon Islands Government, 2019). Future population estimates for were calculated using yearly growth projections for the Solomon Islands up to 2100 (United Nations, 2019).

Table 11: Drivers data for present (1990) and future (2050) scenarios derived from the literature for Sagheraghi, Ghizo Island, Solomon Islands

Drivers	1990	2050
Temperature air (^{0}C)	26.2	27.5
Sea surface temperature (^{0}C)	29.4	30.7
Rainfall (mm/yr)	3,643	3,748.5
Storm intensity (% increase)	0.0	6.2
SLR (m)	0.00	0.27
Study area (ha)	12,862	12,862
Sea level rise inundation (ha)	0.00	337.04
Ocean acidification (ASC)	3.90	3.20
Population (inhabitants)	3,547	8,134
Population density (per km^2)	27	65
Change	**1990**	**2050**
Temperature air (^{0}C)	0.0	1.3
Sea surface temperature (^{0}C)	0.0	1.3
Rainfall (%)	0.0	2.9
Storm intensity (%)	0.0	6.2
Ocean acidification (ASC)	0.0	2.62
Population density (%)	0.0	5.24
Temperature air (^{0}C)	0.00	-0.70
Sea surface temperature (^{0}C)	0.0	135.5

11.3 Appendix 3. Literature review of impacts of climate change on each core food component

11.3.1 Makin Island, Kiribati

Core food components for Makin

No.	Habitat	Food component
1	Land/agriculture	coconut
2	Land/agriculture	pandanus
3	Land/agriculture	giant taro
4	Land/agriculture	breadfruit
5	Land/agriculture	pigs
6	Coastal/reef	sea cucumber
7	Coastal/reef	giant clam (*Tridacna* genus)
8	Coastal/reef	sea grapes
9	Offshore	skipjack tuna
10	Coastal/reef	reef fish (e.g. mullet)
11	Mangrove	mangroves
12	Freshwater	tilapia

Coconut

Coconut palm (*Cocos nucifera* L.) is mainly a crop of humid tropics and is distributed between 23° north and 23° south of the equator and up to altitudes of about 600 m. Climate variables such as temperature, precipitation, and salinity have enormous impacts on the growth and development of coconut as in other species (Hebbar et al., 2022). Optimal conditions for nut production requires well-distributed rainfall (1300–2300 mm/year), annual mean temperature of 27–29 °C (with diurnal variation of 5–7 °C) and about 2000 h of sunshine in a year with at least 120 h per month. Temperatures >40 °C decrease functional leaf area index, dry matter production and nut yield (Hebbar et al., 2022; Naresh Kumar and Aggarwal, 2013). In India, climate change is projected to increase coconut productivity by 4.3% in emissions scenario A1B 2030, 1.9% in A1B 2080, 6.8% in A2 2080 and 5.7% in B2 2080 of PRECIS over mean productivity of 2000–2005 period (Naresh Kumar and Aggarwal, 2013).

*Pandanus (***Pandanus tectorius***)*

According to CABI (2022)and references therein), Pandanus occurs naturally in tropical and subtropical coastal areas, especially on sandy and rocky beaches, raised coral terraces and recent lava flows, but including brackish areas on saline soils, coral atoll sands and peaty swamps. They grow in warm to hot temperatures throughout the year with little seasonal or diurnal variation in areas receiving 1500-4000 mm per year. Pandanus is known to tolerate longer drought periods with continuous but reduced fruiting, and it is considered more drought tolerant than coconut in atoll environments. The plant is adapted to an extraordinarily wide range of coastal soils, light to heavy, saline, infertile, acid or alkaline (pH 6-10), sodic, thin, infertile, basaltic, limestone, peaty and swampy sands, loams, clays and all combinations, free, impeded or seasonally waterlogged, being found on the margins of saltwater mangroves, and known to tolerate periodic saltwater inundation during high tides and storm surges. Pandanus is very tolerant of strong, salt winds and withstands moderate to severe tropical cyclones over much of its range. Pandanus is likely to be the most salt and drought tolerant food in the Pacific and expected to benefit from future climate change.

*Giant taro (***Alocasia macrorrhizos***)*

Giant taro occurs in tropical and subtropical regions in North, Central and South America, the West Indies, tropical Africa and the Indo-Pacific Islands. Optimal temperatures range from 25°C to 35°C, requiring more than 1700 mm of rainfall at elevations from sea level to 600–800 m (Rojas-Sandoval and Acevedo-Rodríguez, 2013). Giant land taro is easier to grow and can tolerate drought and salinity better than true taro and giant swamp taro (Agroforestry CMI, 2022).

Breadfruit (Artocarpus altilis)

Breadfruit grows best in equatorial lowlands below 600-650 m but is found at elevations up to 1550 m. It flourishes at 21-32° C and does not yield well where the temperature exceeds 40° or drops to 5° C. The latitudinal limits are approximately 17° N and S; maritime climates extend that range to the Tropics of Cancer and Capricorn. Optimum annual rainfall is 1500-3000 mm, but trees can yield regularly on Pacific atolls that receive 1000 mm. Deep, fertile, well-drained soils are preferred although some varieties are adapted to the shallow sandy soils of coral atolls (Breadfruit Institute, 2019). It is a long-lived tree crop that is a nutritious, carbohydrate-rich staple, which is currently neglected and underutilized, but which may play a role in mitigating and addressing challenges to agriculture and human nutrition as climate changes (Mausio et al., 2020). Studies looking into future climate change projections have suggested that breadfruit suitability increases in area and in quality, with larger increases occurring in the RCP 8.5 projection.

Pigs

Pigs are sensitive to temperature as they are unable to regulate their body temperature. As a result, heat stress results in slower growth rates, inconsistent market weights, altered carcass traits, infertility, increased health care costs and mortality (Rauw et al., 2020). Above 25°C pigs begin to store less protein where farmers have long observed that hot weather makes their hogs lethargic and thin (Paliwal, 2018). A recent study has shown that higher temperatures associated with climate change are expected to positively affect feed efficiency and growth rates, however, possible negative implications for animal health and welfare should be considered (Rauw et al., 2020). Increase in rainfall and associated humidity can increase the incidence of diseases (Lammers et al., 2007).

Sea cucumbers

Sea cucumbers are considered to have high vulnerability to climate change (Cochrane et al., 2019; Johnson and Welch, 2016) because much of their fishing occurs on tropical coral reefs, which are particular sensitive to higher temperatures and ocean acidification (Purcell et al., 2013). They also have calcareous skeletal structures, which are directly affected by ocean acidification (Dupont et al., 2010; Yuan et al., 2015). Recent studies have shown that climate change will have a mix of positive and negative responses on sea cucumbers depending on life history and physical and biological variables, with a net effect slightly more negative for most species (Plaganyi et al., 2013). Negative effects include increased larval and juvenile mortality due to higher sea surface temperatures and detrimental effects on juvenile seagrass habitats. Sea level rise is expected to cause mostly positive impacts due to increase in habitat area for shallow water species. Climate change is expected to affect distribution and phenology (likely changes in timing of spawning), and to a lesser extent the abundance of sea cucumbers (Fulton et al., 2018).

*Giant clams (*Tridachna *spp.)*

Climate change will have overall negative effects on molluscs both directly and indirectly. Direct impacts are related to increase in sea surface temperature, heat waves and ocean acidification and resulting impacts on growth and mortality rates. Indirect impacts are associated with declines of coral reefs due to coral bleaching and mortality. Again some small increases in temperture may have positive effects on growth rates. Giant clams are also sought after for their flesh and shells with nine species included in the Red List of Threatened species (Watson and Neo, 2021).

Seagrapes

Not much information about climate change impacts on seagrapes is available in the literature. The genus *Caulerpa* is known to grow on temperatures ranging from 15-39^{o}C, where under laboratory conditions, warm temperatures (25–30°C) induced the formation of branches in the seagrape species *C. lentillifera* (Guo et al., 2015). This study suggests that at least small amounts of temperature increase may have positive impacts on seagrapes.

*Skipjack tuna (*Katsuwonus pelamis*)*

Skipjack tuna play a significant role in global marine fisheries and stocks are expected to change with predicted increases in water temperature, decreasing pH and oxygen (Nataniel et al., 2022). Skipjack tuna stocks are expected to move eastwards by 2100 with decrease in biomass expected for Kiribati (Bell et al., 2016). Higher water temperatures are expected to change phenology, abundance and distribution of skipjack tuna where cooler waters are more conducive of higher catches, while lower catches are correlated with warmer waters (Sepri et al., 2021). Ocean acidification is expected to affect reproduction and growth of skipjack tuna both directly and indirectly via food web (plankton) effects (Dueri et al., 2013).

Reef fish (e.g. mullet)

Higher sea surface temperatures can negatively affect reproduction and behaviour and potentially increase growth rates and shorten incubation time of reef fishes (Munday et al., 2008). Field studies have shown that total reef fish biomass and abundance declined by >50% during heat stress, likely as a result of vertical migration of fish to cooler waters. One year after the cessation of heat stress, however, total biomass, abundance, and species richness had recovered to, or even exceeded, pre-heat stress levels. However, the biomass of corallivores declined by over 70% following severe coral loss, and reefs exposed to higher levels of local human disturbance showed impaired recovery following the heat stress (Magel et al., 2020). Increase in rainfall can negatively affect access to estuaries due to increase freshwater flow and sea level rise can have a positive impact on habitats for reef fish (Munday et al., 2007).

Mangroves

Mangroves are influenced by wind, waves and tidal currents, type and size of sediments, nutrients, sedimentation, and chemical pollution. They are threatened by direct human impacts including pollution (e.g. nutrients from sewage treatment plants and septic tanks and chemical leachate from poorly located refuse sites), urban development (land clearing to accommodate air strips and roads), mangrove cutting (for firewood, building material and traditional carving) and alteration of coastal zone hydrology. Other factors influencing mangroves include feral animal, root burial, fire, vehicle damage, and sea level rise (Duke et al., 2015; Lovelock and Reef, 2020). Mangroves are also linked with culture and are a strong component of the Islanders identity. Mangroves are sensitive to variation in precipitation and associated changes in sediment salinity (Lovelock and Reef, 2020). They are expected to decline due to submergence as a result of sea level rise but also to migrate landwards as more suitable habitat becomes available. Overall, the impacts from sea level rise are assumed to be neutral in the earlier climate change scenarios due to the combined positive and negative effects on mangroves, tending to more negative effects on sand bars and island stability due to changing oceanographic conditions (e.g. stronger waves, currents) (Lovelock and Reef, 2020). Rising sea levels may increase mangrove vulnerability to strong winds through toppling (Duke et al., 2015). Excess nutrients from untreated sewage may cause a positive impact on mangroves (Duke et al., 2015). The expected increase in the incidence of heat waves is also expected to cause negative impacts on mangroves.

Tilapia

Tilapia has the potential to become an alternative for changing climate conditions because of its high tolerance to changes in water quality (Rahman et al., 2021). For example, Tilapia usually has lower oxygen requirements than other fish, such as carp. In turbid water, tilapia can easily survive up to 200 mg/L levels of turbidity with no significant effects on specific growth rate and feed conversion ratio. Tilapia can survive under dissolved oxygen conditions as low as below 2.3 mg/L if other factors such as temperature and pH remain favourable. In the extreme rainy conditions or during the rainy season, dissolved oxygen levels may reduce due to the increase in turbidity, dropping oxygen levels. Seasonal and meteorological drought conditions may result in inadequate access to water on fish farms. Severe droughts often cause short culture periods for fish. Surprisingly, tilapia can easily survive in water depths as shallow as 50 cm, though suitable growth was recorded at around 100 cm water depth. This shows that tilapia can adapt to lower water volumes than other species due to drought condition and rainfall variation. Growth performance of tilapia significantly decrease after at 34^0C, although this showed a decreasing tendency towards high temperature changes. Higher temperatures often result in higher proportion of males in temperatures between 28-32^0C. The ultimate upper lethal temperature for *T. mossambica* lies at 38^0C, where tilapia can tolerate temperatures of up to 34^0C without any significant effect on their growth rate. The effects of temperatures $<21^0$C seem more apparent than with higher temperature. Tilapia is considered as euryhaline fish which can grow comfortably both in freshwater and brackish water (up to 7 NTU) higher salinity (>8 NTU) significantly decreases average weight gain.

11.3.2 Sagheraghi, Ghizo Island, Solomon Islands

Core food components for Sagheraghi

No.	Habitat	Food component
1	Land/agriculture	coconut
2	Land/agriculture	slippery cabbage
3	Land/agriculture	Sweet potato
4	Land/agriculture	banana
5	Land/agriculture	pineapple
6	Coastal/reef	sea cucumber
7	Coastal/reef	lobster
8	Coastal/reef	sea grapes
9	Offshore	tuna
10	Coastal/reef	reef fish
11	Mangrove	mangroves
12	Freshwater	tilapia

Coconut

See above for Makin Island.

Slippery cabbage (Abelmoschus manihot)

Slippery cabbage is one of the PICs' most nutritious indigenous vegetables, yet it is often neglected, unexplored and unexploited (Tuia, 2015). It grows in humid tropical climates – and as an annual crop in cool climates –across areas with annual lows of 12 to 25°C, annual highs of 22 to 35°C, annual rainfall of 1200 to 5000 mm and a dry season of 4 months or less. In warm areas with evenly distributed rainfall, it grows fast and produces lush, green leaves. In arid areas or in the dry season, the leaves quickly become leathery and fibrous (iplantz, 2022). Given its growth characteristics, Slippery cabbage has been identified as an important crop to support climate change resilience and nutrition in the Pacific (Tuia, 2015).

Sweet potato (Ipomoea batatas L.)

Sweet potato is a robust crop that grows at optimum temperatures varying between 24-30°C (Heider et al., 2021). It can withstand climate shocks and stresses relatively well because it is resistant to droughts and salt, is easy to propagate, has a short vegetative period and is capable of early bulking (Laurie et al., 2015; Yang et al., 2020). Future temperature scenarios suggest that temperatures between 1 and 6 °C warmer are expected to negatively impact most genotypes of sweet potatoes (Heider et al., 2021).

Bananas

Banana crops are distributed across tropical and sub-tropical areas of the planet, being a very important crop both nutritionally and economically. Optimal temperatures for banana growth are around 27°C (range between 20-30^{0}C) with optimum temperatures varying across regions (e.g. 20.1^{0}C for Brazil and 30.4^{0}C for Africa; (Van den Bergh, 2012; Varma and Bebber, 2019). Optimal annual rainfall range is between 900-1,700 mm (Van den Bergh, 2012). Small increases in temperature seem to be beneficial for banana crops, with annual yields increasing since the 1960s as a result of warming temperatures (Varma and Bebber, 2019). However, this trend is not expected to continue beyond 2050 as global yield gains could be dampened or disappear under the climate scenarios for Representative Concentration Pathways 4.5 and 8.5 (Varma and Bebber, 2019).

Pineapple **(Ananas comosus)**

Pineapples grow in tropical and sub-tropical areas across the world. Temperature is the most important climatic factor affecting its productivity with optimum temperatures of 32°(day) and 20°C (night). For every 1°C above or below, the optimum growth rates decrease by about 6 per cent (The State of Queensland, 2022). Rainfall should more than 750mm per year and be well distributed throughout the year, growing in areas with annual rainfall as high as to 4,000mm (Williams et al., 2017). The pineapple plant is highly water use efficient and therefore well adapted to arid conditions although their growth is sensitive to climate (Williams et al., 2017). Pineapples are also sensitive to saline water making it also susceptible to soil ground water and soil salinisation due to sea level rise.

Sea cucumbers

See above for Makin Island.

Lobster

The lobsters caught in the Solomon Islands are from the genus Panulirus and include *P. penicillatus, P.versicolor, P. femoristiga* and two other relatively rare species (*P. ornatus* and the slipper lobster; (Kile, 2000). They grow in optimal sea surface temperatures of between 25-29°C (Plaganyi et al., 2018). Norman-Lopez et al. (2013) assessed growth of rock lobsters in all life history stages (larval, juvenile and adults) and found they are at high risk due principally to a likely increase in sea temperatures. This effect was assessed as being mostly positive based on experimental studies demonstrating the enhancement of growth by warmer sea surface temperatures up to 30°C (Dennis et al., 1997; Skewes et al., 1997). Medium risks contained both positive and negative effects. Positive effects were associated with an increase in larval growth due to projected increases in primary production (Brown et al., 2010), and faster adult growth and bigger lobsters resulting in an increase in adult reproduction. Negative effects were associated with increased larval and juvenile mortality related to higher sea surface temperatures and detrimental effects on the juvenile lobsters' seagrass habitats. Plagányi et al. (2018) developed a model for Torres Strait (Australia) which estimated a fairly steep increase in mortality of lobsters as sea surface temperature increased above the likely optimum of 29°C.

Seagrapes

See above for Makin Island.

*Skipjack tuna (*Katsuwonus pelamis*)*

See above for Makin Island.

Reef fish

See above for Makin Island.

Mangroves

See above for Makin Island.

Tilapia

See above for Makin Island.