

Habitability dynamics of Pacific Islands in a changing climate

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Statement of Originality

This is to certify that, to the best of my knowledge, the content of this thesis is my own work. This thesis has not been submitted for any degree or other purposes.

I certify that the intellectual content of this thesis is the product of my own work, and all the assistance received in preparing this thesis and sources have been acknowledged.

Emily Nabong

Ethics Approvals

The research in this thesis received ethical approval from the University of Sydney's Human Research Ethics Committee (HREC) under the following project titles and approval numbers:

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I attest that I am the lead and corresponding author for the manuscripts included in this thesis. For work within this manuscript that has been published, I ask that citations reference journal publications rather than this thesis when applicable.

Emily Nabong (PhD Candidate, thesis author)

As supervisor for the candidature upon which this thesis is based, I can confirm that the authorship attribution statements above are correct.

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Abstract

Islands and atolls in the Pacific face heightened climate risk due to low elevations and limited resources. The question of (unin)habitability in these locations is often simplified to characteristics of hazard exposure, reinforcing assumptions of inevitable mass migration. This thesis builds on existing research, challenging the idea of linear causality between hazard exposure and habitability by examining habitability's dynamic and multi-faceted nature in the Pacific. This investigation builds to the thesis's overarching objective of informing effective adaptation policy by understanding the holistic and interconnected impacts of climate change on habitability outcomes.

The compounding and cascading effects of climate change add complexity in untangling how impacts influence habitability perceptions and migration decisions. I began this work by systematically identifying the multi-causal factors that affect climate-affected populations' decisions to leave or remain in place. I then engaged two sets of experts to contextualise these findings by hazard type and to the specific geography of Pacific atolls, using the country of Kiribati as a case study location. Participatory model building activities were used to understand habitability needs and migration decision-making in Kiribati, resulting in a systems map of habitability. The work in this thesis culminates in a locally derived system dynamics stock and flow model of the social-ecological system in Kiribati, analysed over the next century.

With this thesis, I contribute to both to the theoretical body of knowledge on climate change and habitability, while also offering practical insights to governments and development and aid groups. From my global synthesis of climate migration decision-making and further contextualisation between hazards and geographical contexts, I advance theory by causally mapping relationships within and between climate impacts, uninhabitability, and displacement to understand how factors combine and cascade to cause outcomes. The system dynamics model, developed in partnership with local partners, provides a novel operationalisation of habitability to quantifiably measure changes over time and provide insights into key drivers of those changes. Using these system analyses, I was able to identify intervention points that could be effective in supporting communities to adapt to climate change in the Pacific.

This thesis emphasises co-produced knowledge with research partners, answering calls for a grounded understanding of habitability from perspective of those with localised knowledge and experience. The novelty of this work lies in the identification of key drivers of habitability in Kiribati and examination of how these core feedback loops shift in dominance in the coming decades. The results of this work have practical implications for the strategic adaptation planning in the Pacific and can be used to further informed, evidence-based policy development.

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Acronyms

CLD	Causal Loop Diagram
IPCC	Intergovernmental Panel on Climate Change
IQR	Interquartile Range
LTM	Loops that Matter
NELM	New Economics of Labor Migration
NGO	Non-governmental Organisation
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PTA	Purposive Text Analysis
QCT	Qualitative Choice Theory
RCP	Representative Concentration Pathway
RQ	Research Question
SFS Model	Stock and Flow Simulation Model
SSP	Shared Socioeconomic Pathway

Glossary of Key Terms

Dynamic Hypothesis	A theorised causal explanation for why a system behaves as it does
Factor	Any element, variable, or concept that directly, or indirectly affects a system
Feedback Loop	Cycles where factors influence and loop back onto themselves <i>Balancing</i> – A cycle where factors in the system counteract to create stable behaviour <i>Reinforcing</i> – A cycle where there are no intervening factors to limit the perpetual growth or decline of a system
Habitability ‘Pillars’	Dimensions that contribute to what makes a place habitable
I-Kiribati	A person or group from the country of Kiribati
Leverage Point	A place, or factor, in a system where intervention could cause far-reaching effects [also referred to as target variables and intervention points]
Mental Model	An individual’s, or group’s, mental conceptualisation of reality
Polarity	Refers to relationship typology and can be positive (+) where factors move in the same direction, or negative (-) where factors move in opposite directions
Reference Mode	The observed behaviour of key variables in a system over time with bifurcation of possible pathways that are either hoped for or feared to come about
Shared Socioeconomic Pathway (SSP)	SSP 1 “Sustainability” An optimistic pathway based on sustainable and inclusive development SSP 2 “Middle of the Road” A business-as-usual pathway where behaviour is similar to current and historic trends SSP 3 “Regional Rivalry” Nations focus on individual needs, such as energy, at the expense of others. This pathway sees little international cooperation for global climate issues SSP 5 “Fossil-fueled Development” A pathway of high technological achievement driven by increased fossil fuel reliance
Stella Architect	System dynamics modelling software
α	Baseline utility unique to each location
β	Weighting for term in utility function; calculated from participatory system mapping workshop

Chapter 1

Introduction

1.1. Introduction

Activists from small-island states around the world urge policymakers to take seriously their calls of “1.5 to stay alive”. This is in reference to the degree of warming that they advocated for as the target in the Paris Climate Agreement and, though any degree of warming is harmful, is looked upon as a threshold after which the effects of climate change would become extremely dangerous. According to Climate Action Tracker’s (2024) current temperature estimate, our global policies are presently on track to achieve 2.7°C of warming relative to pre-industrial global temperature averages. Resulting from this path of warming, a co-chair of the Intergovernmental Panel on Climate Change’s (IPCC) latest assessment report forecasts that, “With climate change, some parts of the planet will become uninhabitable” (Rice, 2022). Around the world, the potential for habitability loss would have major implications for human rights (Maldonado et al., 2013), demographic shifts (Horton et al., 2021), and cultural upheavals (Adger et al., 2013).

In this thesis, I employ systems thinking and system dynamics modelling to explore the idea of (unin)habitability in the context of climate change and what this may mean for communities that are highly exposed to climate impacts, such as those living on islands and atolls in the Pacific. The future (unin)habitability of Pacific islands and atolls has been a growing topic, with researchers debating the likelihood of impacts overwhelming communities’ abilities to cope and the potential for mass displacement (Farbotko, 2023; Farbotko & Campbell, 2022; McLean & Kench, 2015; Mortreux et al., 2023; Storlazzi et al., 2018). This research aims to investigate habitability from a localised lens and inform policy recommendations from a systems perspective to confront the impacts of climate change in atolls.

1.1.1. Climate Change and Atolls

The attention that small island states, and atolls in particular, receive in discussions of climate impacts is related to their unique geographic and geologic features that make them especially susceptible to climate hazards (IPCC, 2022b). Atolls are ring-shaped mid-ocean reefs that surround lagoons (Woodroffe & Biribo, 2011). The majority (57%) of world’s 598 atolls are located in the Pacific (Andréfouët & Paul, 2023). In atolls, low elevations coupled with impacts of sea level rise, such as erosion, salinisation, and increased wave height create concerns for future land loss and freshwater contamination (Barnett & Adger, 2003). Water resources for atolls are primarily sourced from limited groundwater that is susceptible to contamination from saltwater intrusion caused from wave over-topping and over-abstraction (Barnett & Adger, 2003; Post et al., 2018; White & Falkland, 2010). In addition, increasing ocean temperatures have led to shifting and declining reef fish populations, affecting atolls which are historically heavily dependent on marine and coastal livelihoods (White et al., 2018).

Coastal settlements in atolls’ limited land areas are exposed to hazards exacerbated by climate change such as coastal flooding, which is likely to continue to damage and degrade infrastructure (Duvat et al., 2021). In many atolls, degraded soil quality and declining fisheries production have led to a heavy reliance on imported foods (Troubat & Sharp, 2021). Likewise, climate change is expected to increasingly create difficulties for nature-based livelihoods and further strain local economies (Barnett & Adger, 2003; Spencer et al., 2024). These economic challenges compound with geographic remoteness which limits global connectivity and heightens economic vulnerability for many atoll nations. These, and other challenges stemming from climate change in atoll nations, give rise to arguments of potential uninhabitability and have

led some governments to prepare migration pathways as a safeguard for their people (McAdam, 2023; McNamara, 2015).

1.1.2. Linking Migration and Habitability

While there is often a predisposition to draw connection between climate change and migration, current discourses increasingly recognise the multidimensionality of both people’s perceptions of habitability as well as their decisions surrounding (im)mobility (Black et al., 2011; Farbotko, 2023; Maretti et al., 2019; McNamara et al., 2018; Merschroth et al., 2024; Stege, 2018; Sterly et al., 2025; Xu et al., 2020). Studies which have attempted to forecast the number of future climate migrants by exposure to hazards, and implied uninhabitability, have received criticism as environmentally deterministic, oversimplifying the complex nuance of human decisions and behaviour (Ebrahimi & Ossewaarde, 2019; Koubi et al., 2016).

Horton et al. (2021) defines habitability as composing of three dimensions: basic human survival, livelihood security, and society’s capacity to manage environmental risks. This definition highlights how habitability is influenced not only by environmental conditions, but also local abilities to adapt (Gilmore et al., 2024). Consequently, differentiated levels of coping capacity – at individual, household, and community levels – may lead to varying (im)mobility outcomes in the face of increasing climate events. Similarly, individual perceptions lead to heterogenous, and sometimes unintuitive, views of habitability even amongst populations within the same location (Merschroth et al., 2024). O’Byrne (2023) further makes the case against assumed migration from hazard exposure by providing examples of counterintuitive decision-making, like instances of increased immigration from places with perceived high habitability and choices to stay in hazard-prone places against warnings and advice.

Examples of voluntary immobility are common in the Pacific, where sense of place and belonging are strongly tied to ancestral land (Constable, 2017; Nunn & Campbell, 2020). In this context, the intersections of climate change, habitability loss, and decisions of (im)mobility are highly complex (Sterly et al., 2025). In initial conceptualisations of this thesis, I framed my research around the idea of “What (combination of) factors make people leave?” to explore future migration trends. However, following consultations with local research partners in the Pacific, and a better understanding and recognition of the importance and nuance of place attachment, my research focus shifted towards the question of, “What is needed to support people to stay?” While both questions are important, reframing has allowed me to better align my work to the preferences of my local partners in viewing migration as a last resort.

1.2. Research Context: Kiribati

The geographic focus of this research is on Kiribati, a small-island developing state in the Pacific (Figure 1-1). Kiribati is comprised of 32 atolls and 1 coral island within an expansive ocean area of over 3.5 million square kilometres (DFAT, 2024). The country is comprised of three island groups: the Gilbert Islands, the Phoenix Islands, and the Line Islands. The capital of Kiribati is South Tarawa, located in the Gilbert Island chain.



Figure 1-1 Map of Kiribati (Source: Encyclopedia Britannica, Inc)

South Tarawa and Kiritimati Island, located in the Line Islands, are the only two urban centres in the country. The total population of Kiribati, as of the 2020 Census, was 119,438 people with 59% residing in either South Tarawa (52.8%) or Kiritimati Island (6.2%) (SPC, 2022). Urban centres, such as South Tarawa have experienced high population growth, increasing 149% in the last 30 years (SPC, 2022). The monthly median household income for urban areas is \$1,248 AUD and \$864 AUD for rural areas (SPC, 2021). Twenty-two percent of the population is estimated to live below the poverty line and more than 40% of the population was estimated to experience moderate to severe food insecurity, with each statistic higher in urban areas (FAO, 2021). The main economic livelihood in Kiribati is retail work (25%) followed by agriculture (17%), which is higher in rural areas (SPC, 2021). In South Tarawa, public administration and education also make up a large proportion of the workforce.

Infant and childhood mortality is high (41 and 21 deaths respectively per 1000 live births) and likely related to water quality challenges (ADB, 2021; Kiribati National Statistics Office, 2019). Seventy-two percent of households nationally are not connected to a water supply line (SPC, 2021). Further, more than 17% do not

have access to improved drinking water sources and nearly 40% do not use improved sanitation facilities, with 33% nationally practicing open defecation (Kiribati National Statistics Office, 2019). Sanitation and hygiene challenges are likely to continue as climate change intensifies water insecurity with periods of prolonged droughts and more frequent inundation events leading to the salinisation of groundwater (ADB, 2021). Kiribati is also likely to experience other climate impacts such as rainfall variability, increasing air and ocean temperatures, and ocean acidification (CSIRO, 2011). These hazards compound with constraining pressures such as limited land area, low elevation, and overcrowding to lead to high levels of vulnerability (McIver et al., 2014).

These future challenges have drawn significant attention from global media who speculate on the future of Kiribati's people, culture, and land (Brennan, 2024; CNN, 2014; Ives, 2016; National Geographic, 2015; Srinivasan, 2024). Research, likewise, has raised questions of the uninhabitability of Kiribati, and other atolls in the near future (Storlazzi et al., 2018). With these forecasts in mind, Kiribati is a prime context in which to examine the impacts of climate change on habitability.

1.3. Rationale

The thorough examination of possible habitability outcomes for Pacific atolls, like Kiribati, is practically and theoretically valuable. Practically, by mapping the interconnectivity of climate impacts and social-ecological systems at risk, this work can assist in the development of targeted strategies that foresee cascading effects and limit unintended negative consequences. Social-ecological systems refers to coupled human and natural systems and all of their interconnections and interactions (Biggs et al., 2021; Preiser et al., 2018). Social-ecological systems recognise that the deep interdependencies between humans and nature is such that 'the delineation between social and natural systems is artificial and arbitrary' (Berkes & Folke, 2000). This work aims to identify which dimensions of habitability are dominant in Kiribati's social-ecological system at different points in the future to support strategic adaptation planning.

The theoretical contributions of this work are in the novel combination of participatory systems thinking with quantifiable approaches to advance scientific understanding of how habitability is conceptualised and operationalised. By framing habitability in a way that comprehensively recognises the highly complex interlinkages between human and environmental systems I offer a more holistic approach for addressing future climate challenges.

I argue that to understand how climate change may alter the landscape of habitability in Kiribati, we must recognise habitability as a multidimensional concept. I began in Chapter 2 with a global synthesis on the factors that drive people to leave in the context of climate change as well as the anchoring factors and barriers that lead them to stay. While focused on migration, this comprehensive list of factors provides insights into the influences of what makes a place habitable and leads people to stay or leave. I then contextualise these global results through consultations with two groups in Chapter 3 – academic experts and local experts with lived experience of climate change in Kiribati. The results of contextualisation showed differences in perspectives and highlighted the need for local engagement when conceptualising migration and habitability. The locally grounded results, supplemented by global insights, were then used as the basis for developing a system dynamics model, presented in Chapter 4, capable of simulating various dimensions of habitability for the social-ecological system in Kiribati to understand how habitability

outcomes may unfold in the next century, presented in Chapter 5. A summary of the gaps, questions, and methods for each thesis chapter is presented in Table 1-1.

Table 1-1 Summary of thesis gaps, research questions, and methods

Overarching Thesis Aim			
To inform effective adaptation policy by understanding the holistic and interconnected impacts of climate change on habitability outcomes			
	Gaps	Research Questions (RQs)	Outputs
Chapter 2	A need to synthesise the multi-causal pathways that directly and indirectly lead to migration in the context of climate change	<p>RQ1. Within the existing literature, what are the decision-making factors that influence migration for households affected by climate change?</p> <p>RQ2. How do these decision-making factors interact to create climate (non)migration?</p>	<ul style="list-style-type: none"> • Compilation of factors found to directly and indirectly affect climate migration decision-making • Causal mapping of factor relationships
Chapter 3	Limited knowledge on how the understandings of climate change, migration, and habitability complexities change between hazards and the expertise of experts	<p>RQ1. What are the relationships between factors that influence climate change migration?</p> <p>RQ2. What are the differences in casual relationships between migration factors for different hazards influenced by climate change?</p> <p>RQ3. How does the structure of a climate migration system differ between global and local perspectives?</p>	<ul style="list-style-type: none"> • Contextualisation of factors and relationships including through: <ul style="list-style-type: none"> – System maps – Factor rankings – Factor characterisations
Chapters 4 & 5	Lack of understanding of how the current social-ecological system structure in Kiribati may lead to habitability outcomes in the future	<p>RQ1. How might habitability change in Kiribati within this century?</p> <p>RQ2. What is the system structure that drives habitability in Kiribati?</p> <p>RQ3. What outcomes might this system lead to in the future?</p>	<ul style="list-style-type: none"> • Map of system structure • Identification of habitability dimension dominance over time • Analysis of system behaviour trends

1.4. Research Methods Overview

To answer the questions addressed in this thesis, a mixed-methods approach incorporating various forms of participatory systems-based methodologies were employed. The overall approach in this thesis was aligned to fit the recommendations of the standard system dynamics modelling process (Hines & Lyneis, 2007; Sterman, 2000), beginning with problem articulation, the development of a dynamic hypothesis, simulation model, testing, and policy formulation and evaluation. The modelling process is shown in Figure 1-2 along with thesis data collection and analysis methodologies that contributed to the overall model process.

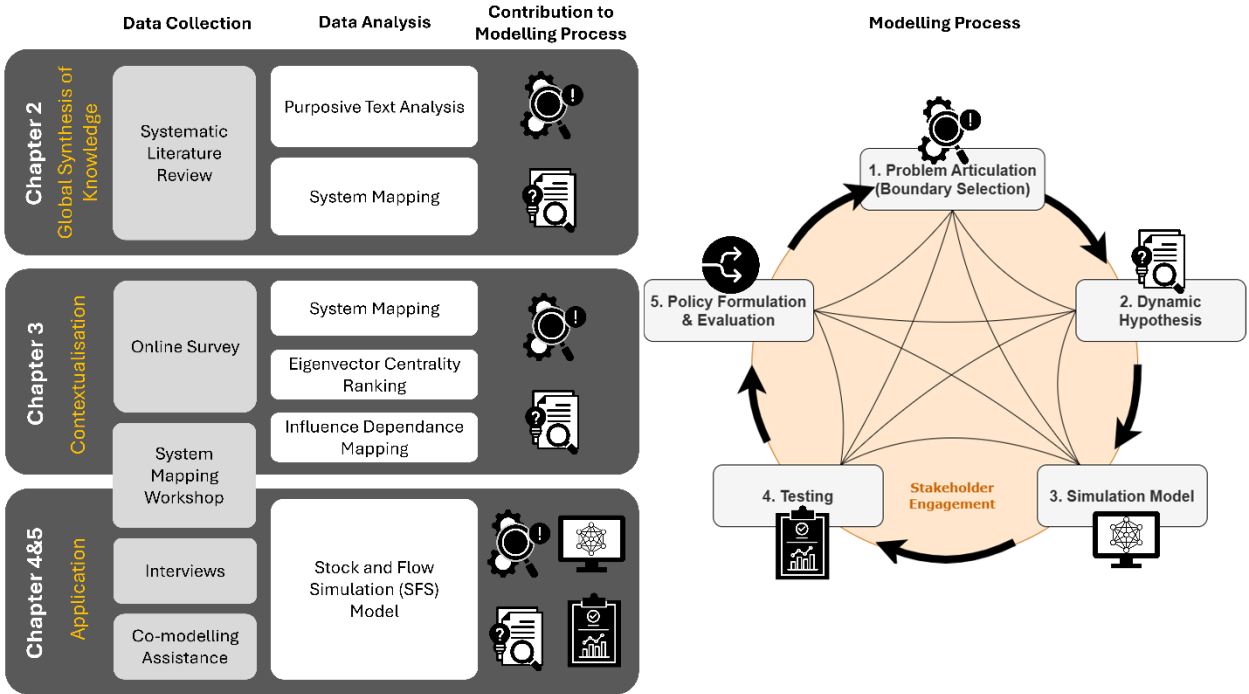


Figure 1-2 Summary of thesis methodology

1.4.1. Data Collection and Analysis

The knowledge base of this thesis was informed from a variety of sources using multiple data collection and analysis methodologies. I first began this work by synthesising current literature on the topic of climate migration, presented in Chapter 2. This global review of literature provided the foundation from which I began to build an understanding of climate, habitability, and migration systems. My systematic literature review followed standard practice as recommended by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). In the 206 articles reviewed, purposive text analysis was used to deductively code factors and relationships shaping migration under climate change (Kim & Andersen, 2012). In total, 21 distinct factors were identified as contributing to, or hindering, migration. In my analysis, I not only identified links between factors and migration, but also between factors. In this way I could develop a system map to tell a complete story. From these interconnected linkages, 155 feedback loops- cycles where factors influence and loop back onto

themselves- were identified related to migration (Nabong et al., 2023). At the completion of the global literature review I developed a nascent idea of the problem (problem articulation) and formed a preliminary mental model of the factors and interactions contributing to the problem (dynamic hypothesis).

In Chapter 3, I built from this global understanding of climate migration by soliciting expert perspectives to provide further insights into how these relationships change by context. I began my contextualisation of global findings through an online survey where I asked 32 academic experts in the field of climate migration to evaluate how these relationships change in the context of different climate hazards (Nabong et al., 2022). I then conducted interviews (n=7) and a system mapping workshop (n=21) with local experts with lived experience of climate impacts in Kiribati to understand how these relationships are further refined through the perspectives of those with lived experience. Local experts who participated in these discussions were able to provide valuable insights from their experiences working on climate-related initiatives in Kiribati. The data from both expert sets was analysed through system mapping, eigenvector centrality rankings, and influence and dependence mapping. This combination of analysis tools allowed me to visualise the relationships and identify top factors in each of the respective climate-habitability systems. By analysing the factors' influence and dependence in the different hazard and geographic contexts, I was also able to determine leverage points in the systems. From this work, I continued to refine my articulation of the problem and dynamic hypothesis through greater understanding gained from localised knowledge and expertise of the system.

My thesis culminates in the quantitative analysis of Kiribati's social-ecological system and how its structure leads to habitability outcomes in the future (with model methodology in Chapter 4 and results in Chapter 5). Towards this aim, a system dynamics stock and flow simulation model was developed based on the foundation built in the previous two chapters. Throughout the process of model development, local knowledge was continually sought and embedded through interviews, co-modelling assistance, as well as the system workshop results. At the completion of the stock and flow model development, robustness and soundness checks were used to build confidence that the model simulated behaviour realistic to historical data and the expectations of local experts (testing). I analysed the model through an evaluation of the key feedback loops, loops that drove the model behaviour, over time. In Chapter 4 I discuss how these key loops align with current conditions and decisions in Kiribati, as well as established pillars of habitability, and their influence on model behaviour (e.g. demographic trends, resource availability). Chapter 5 offers useful insights into how the dynamics of habitability changes over time and how this understanding can be used to strategise tailored adaptation solutions to meet future needs. With this model, I lay the groundwork for future policy evaluations to test the effects of proposed adaptation solutions.

1.4.2. Iterative Modelling Process

As new knowledge and understanding was gained, it was necessary to reassess prior model process steps. The problem articulation and dynamic hypothesis were iteratively developed and revised as new information was gleaned through each step of data collection and analyses. The revision of my problem articulation from "What (combination of) factors make people leave?" to "What is needed to support people to stay?" is an example of iterative adjustments. These changes throughout the thesis highlight the model's strengths of adaptability and ability to stay aligned with new information. In the chapters following, I detail further how each of these methods and processes were combined and built upon to address the overall aim

of informing effective adaptation policy through the increased understanding habitability outcomes in the context of climate change.

1.5. Thesis Format

This thesis follows a journal article format where each chapter is a stand-alone piece – a conventional format in engineering disciplines. As such, there may be minor overlap of concepts and research context. Chapter 2 has been published in *WIREs Climate Change* and is presented as it was accepted for publication. Chapter 3 is primarily based on an article published in *Climatic Change* where I discussed how climate migration systems are shaped by academic experts’ mental models. For this thesis, Chapter 3 was further expanded to incorporate the mental models of local experts from Kiribati. This addition was useful and necessary to compare the system of climate change, migration, and habitability between academic and local experts. Chapter 4 integrated the learnings from Chapters 2 and 3 and presents the methods for the system dynamics stock and flow model, which I refer to as the *Stock and Flow Simulation Model*, “SFS Model”. The results of the SFS Model are presented in Chapter 5, a stand-alone chapter in preparation for publication. The format of Chapter 5, including length, separated methods, and a focus on results, is aligned to the criteria of its intended journal outlet and intended to be read in conjunction with Chapter 4. The implications of the findings, cross-cutting themes, limitations, and contributions of the thesis are presented in Chapter 6.

A cumulative list of references for all chapters is compiled and included at the end of the thesis. Supporting information for each chapter is then presented as appendices following the reference list. Appendix I presents the factor definitions for concepts that were discussed in the participatory interviews and system mapping workshop in Kiribati. Appendix II is the interview guide used to structure the interviews with the local experts. Appendix III provides the results of the participatory system mapping workshop as an impact matrix. Appendix IV shows the layout of the SFS Model in the Stella Architect software and Appendix V provides the model documentation (variable lists, equations, assumptions, etc.). Appendix VI is supplementary results of Chapter 5’s Loops that Matter analysis, including habitability pillar categorisation and dominance scores.

Chapter 2

*Decision-making factor interactions influencing
climate migration:
A systems-based systematic review*

“Research is formalized curiosity. It is poking and prying with a purpose”

Zora Neale Hurston, writer

2.1. Introduction

In 2020, more than thirty million new people became displaced as a result of weather-related disasters (IDMC, 2021). As the impacts of climate change increase, global population movement will also continue to experience larger shifts in people on the move (Shukla et al., 2019). Although there is a relationship between climate change and mobility, it does not necessarily follow that those affected by climate hazards will move (Duijndam et al., 2022; Stojanov et al., 2014; Wisner et al., 2004; Zander et al., 2016). Migration relating to climate change results from multi-faceted decision-making and the confluence of multiple factors (Black, 2001; Oliver-Smith, 2012; Xu et al., 2020; Zander et al., 2016). While past studies have contributed significantly to the identification of decision-making factors that drive migration (Parrish et al., 2020; Piguet, 2012), a gap remains in understanding exactly how these factors interact to lead to migration (Bates-Eamer, 2019; Piguet, 2022; Willett & Sears, 2020).

In this study we address these gaps and advance understanding of migration processes through a comprehensive systematic literature review of the decision-making factors of climate migration and their interactions, asking the questions:

- (1) Within existing literature, what are the decision-making factors that influence migration for households affected by climate change?
- (2) How do these decision-making factors interact to create climate (non)migration?

To answer these questions, we begin by presenting a brief background on migration relating to climate change, relevant terminology, and existing climate mobility frameworks in the literature. We then detail our systematic literature review which identified 21 factors influencing migration decision-making, and the interactions between these factors, from 206 studies. We then used causal loop diagramming to map and analyse the interaction of these factors. Through the identification of top feedback loops in the climate migration literature, this study lays the groundwork for policy makers and future researchers to understand the systemic and dynamic drivers of climate-change induced migration so that the consequences of climate change may be better anticipated.

2.2. Background

Population movement due to environmental challenges is not a new phenomenon (Stojanov et al., 2014). Historical migration practices are deeply embedded into many cultures and act as risk management strategies to cope with periods of environmental hardship (Farbotko et al., 2018; Opeskin & MacDermott, 2009). Residents of seasonally dry environments, for example, employ circular migration in order to diversify livelihood opportunities during non-growing periods (Milan & Ho, 2014; Shi et al., 2019; Willett & Sears, 2020). Recently we have seen examples of climate migration in hazard-prone locations such as

California, USA (Casey, 2022) as residents looked to escape future wildfires. Although most of the global population remains relatively sedentary (McAuliffe et al., 2020), mobile and mix-mobility lifestyles are also a significant aspect of global population dynamics (Kelman, 2019) leading many scholars to argue that migration relating to climate change doesn't imply instability, but is a recognised resiliency strategy (Wiegel et al., 2019).

However, while environmental and climate changes are known to catalyse migration, identifying and classifying instances of climate migration can be unclear. Due to inconsistent migration movement, including episodes of movement and non-movement, as well compounded migration stimuli, difficulties arise in delineating classifications of people on the move. Especially when coupled with other drivers, many scholars argue that environmental or climate migrants are difficult to separate from other migrants, such as those moving on economic grounds (Boas et al., 2019; Oliver-Smith, 2012). The classification and terminology used for those whose movement is related to climate change is a debated subject in which there is a marked lack of consensus. Renaud et al. (2011) offers typologies such as environmentally-motivated, environmentally-forced, and environmental emergency migrants to classify such populations, while the International Organisation for Migration (IOM) (2019) simply uses environmental or climate migrants. In contrast, Boas et al. (2019) recommends moving away from the term "migration" altogether in favour of climate mobilities to capture more diversity in the duration, direction, and multi-causality of movement. The terms "environmental or climate refugee" have also quickly fallen out of favour. While used in the past, these terms are now widely agreed to be technically incorrect as environmental justification is not given within the 1951 Convention Relating to the Status of Refugee's definition of refugees. Many also argue that "refugee" deceptively implies mono-causal movement and denies agency of those affected by climate change (Bettini, 2013; Constable, 2017; Olwig & Gough, 2013). Using the knowledge and learning from literature, we provide a summary of operationalised definitions used in this study to describe mobility, migration, factors, and migrants in Table 2-1.

Along with the evolution of terminology, conceptual frameworks of migration have also evolved to better include the agency and autonomy for those affected by climate change. McLeman and Smit (2006) developed an algorithmic flowchart style model to determine migration response to climate change, accounting for a community's capacity for adaptation. Later, Black et al. (2011) proposed a conceptual framework identifying five main families of drivers which affect migration decision-making: economic, political, social, demographic, and environmental. As the impacts of climate change become more apparent, existing vulnerabilities within these five families are multiplied and contribute to how mobility decisions unfold (Harper, 2021). Later work, such as that of Parrish et al. (2020), has since expanded Black et al.'s (2011) framework into new conceptual models showing driver dynamics over time, space, and society. Subsequent case studies have applied these frameworks to specific hazards and cultural contexts to help explain migration decision-making (Ayeb-Karlsson et al., 2016; Hauer, 2017; Khavarian-Garmsir et al., 2019; Parnell & Walawege, 2011).

Table 2-1 Operationalisation of terms in climate migration literature

Mobility	The ability to move freely and easily. This is the umbrella term for movement and includes a spectrum of varying degrees of agency (e.g. forced displacement, migration, voluntary tourism) (Thornton et al., 2019; Warner, 2012).
Migration	The process of moving within or across borders, temporarily, seasonally, or permanently. Migration falls along the continuum between forced and voluntary mobility (Piguet, 2018). Migration in this text is shorthand for what is more rightfully termed ‘migration influenced by climate change’ (Foresight, 2011).
Factors	We use ‘factors’ synonymously with drivers. Similar to how climate is not a direct linkage to migration, the presence of the factors identified does not necessarily imply movement and may only influence the decision-making of climate affected households or individuals.
Migrants	The term, ‘migrants’ in this text refers specifically to those whose movement is related to climate change. As the articles in this review focus on slow-onset climate hazards, we highlight the agency of individuals in responding to these gradual changes as opposed to individuals forcibly displaced by rapid-onset hazards. For more reading on migrant typologies refer to Renaud (2011).

In addition to the growing theoretical contributions and empirical case studies of climate migration, many authors have also sought to advance the field of climate migration studies through rigorous syntheses and meta-analyses of existing research. It is amongst these reviews that we look to situate our work. Previous reviews have offered enumerations of both direct and indirect factors influencing migration (Beine & Jeusette, 2019; Borderon et al., 2019; Priodarshini & Mallick, 2021), with many categorising these factors into themes similar to Black et al.’s (2011) conceptual frame (Beine & Jeusette, 2019; Berlemann & Steinhardt, 2017; Kaczan & Orgill-Meyer, 2020; Šedová et al., 2021; Veronis et al., 2018). Some reviews have focused on methodological practices in this field of research (Fussell et al., 2014; Piguet, 2022; Safra de Campos et al., 2016), while others limit to geographic areas (Borderon et al., 2019; Kaczan & Orgill-Meyer, 2020; Priodarshini & Mallick, 2021), mobility type (Miller & Vu, 2021; Obokata et al., 2014; Veronis et al., 2018), or specific climate hazard (Duijndam et al., 2022).

In this work, we are closely aligned with Beine and Jeusette (2019) who used statistical analyses to identify positive and negative relationships between factors influencing climate migration. Similarly, we used qualitative coding to highlight positive and negative linkages in literature while taking a new and progressive step of analysing these linkages through causal loop diagramming. While interactions between influencing factors and migration are well acknowledged in past reports and literature (Foresight, 2011), we present explicit interactions not only between identified factors and migration but also between the factors themselves. Through this, we can analyse both direct causal relationships but also indirect relationships between factors may contribute to non(migration).

2.3. Methods

We conducted a systematic literature review to identify the interaction of factors influencing climate migration. We first discuss our process for the selection of relevant literature and the identification of

migration factors and their interactions. Then, we describe how we mapped and analysed migration factor interactions using purposive text analysis and causal loop diagramming.

2.3.1. Systematic Literature Review

A systematic literature review was employed to document the current state of knowledge on migration factors relating to climate change and how these interactions lead to migration decision-making. While long used in health research, systematic reviews are gaining attention within the field of climate change in order to summarise and aggregate existing knowledge on specific topics (Berrang-Ford et al., 2015; Ford et al., 2011). Our systematic literature review was adapted from Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) and consisted of identification, screening, and eligibility review of articles (Page et al., 2021). A keyword search was used within Scopus, following the example of the IPCC which used this database in its review of scientific literature (IPCC, 2014). In comparison to other often used databases, Scopus was selected to capture the multi-disciplinary nature of literature where migration scholarship is situated (Gusenbauer & Haddaway, 2020), offering higher coverage than Web of Science and a higher result consistency than Google Scholar (Falagas et al., 2008; Mongeon & Paul-Hus, 2016). Using a Population, Exposure, Outcome (PEO) format, modified from the Population, Intervention, Comparison, Outcome (PICO) search strategy, keywords were selected for search terms (Table 2-1). The PEO search strategy allowed us to clarify and define our search terms based on population, exposure, and outcomes set in our research question. The search covered the use of these terms in document titles, abstracts, and keywords. A Boolean “or” operator was used for any of the terms within the population, exposure, and outcome categories, while “and” operators were used across these groups. Wild card search strings (*) were added to terms that had several expected terms, such as ‘climate change’ or ‘climatic changes’. The search was limited to peer-reviewed journal articles written in English, with all dates included up until May 2021. As primary empirical data was the focus of the search, review and meta-analysis articles were excluded. The initial search yielded 665 articles.

Table 2-2 Search terms for climate change migration

Human (Population)	Climate Change (Exposure)	Movement (Outcome)
human*	“clima* chang*”	migrat*
person*	“global warming”	displace*
people*		relocate*

Article abstracts were then preliminary screened using the following exclusion criteria:

- Non-contemporary climate migration (migration before 1970)
- Non-human migration (flora, fauna)
- Short-term mobility (i.e. daily mobility, movement in which dwelling remains consistent per week)
- Mobility not related to climate change (e.g. displacement from infrastructure projects)
- Displacement from rapid-onset hazards (tsunamis, typhoons, etc.)
- Adaptation project-related migration (e.g. displacement from Reduced Emissions from Deforestation and Forest Degradation (REDD+) initiatives)

Screening consistency was validated by the third author through an independent review of inclusion for 50 randomly selected abstracts. Following the abstract screening, 240 articles remained. An additional 34 articles were excluded after full text review showed them to be not relevant using the same exclusion criteria above, leaving a total of 206 articles used for analysis. Documents were then imported to Nvivo software for analysis of causality between factors influencing climate change migration to model factor interactions and dynamics.

2.3.2. Purposive Text Analysis

Casual factor interaction themes were deductively coded based on Black et al.’s (2011) conceptual framework with factors categorised according to ‘Economic’, ‘Political’, ‘Social’, ‘Demographic’, and ‘Environmental’ families. Each causal factor interaction took the form of a pairwise connection; one factor influencing the other. In this analysis, only pairwise connections identified directly in each article’s results were coded to avoid duplicate coding and skews to frequency data. This means that discussions of others’ work which identified pairwise connections were not included in the coding. This coding methodology called purposive text analysis (PTA) has been used in other system dynamics studies such as in Kim and Anderson (2012) for transcript data and Valcourt et al. (2020) for workshop interviews to build models of factor interactions. Examples are provided in Table 2-2 to show how causal statements in the literature were coded to form pairwise interactions.

Table 2-3 Example of purposive text analysis (PTA)

“There has been significant depletion and degradation of natural resources in some Pacific countries because of population pressures and over-exploitation.” (Opeskin & MacDermott, 2009)

Cause Factor		Effect Factor
Population growth	→	Resource depletion
Population growth	→	Environmental degradation

*“Autonomous adaptation measures in flood-prone areas in the city of Belem have become a good instrument to enable low-income populations to stay in central parts of the city.” (Szlafsztein & de Araújo, 2021) **

Cause Factor		Effect Factor
In Situ Adaptation	→	Migration

*This example shows a negative causal relationship where in situ adaptation leads to a decrease in migration.

In the first PTA example, Opeskin & MacDermott (2009) identify that population pressures have led to depletion natural resources. As such, the entire phrase was highlighted and added to the coding theme of

“population growth → resource depletion”. The quote also mentions population growth’s effect on environmental degradation and was likewise added to the coding theme of “population growth → environmental degradation”. In the second quote, we provide an example of how in situ adaptation was recognised to affect migration. Although the relationship is negative, the quote was still coded to the relevant factors, while the polarity of the connection was assessed later using the polarity of the majority of codes for each pairwise connection. For each of the factors identified, a coding dictionary was maintained to ensure consistent identification of themes across the included studies.

The process of systematically coding pairwise factor interactions allowed for the development of an aggregated model of factor interactions, described in the next section. Although article excerpts were coded into pairwise factors to show relationships (e.g. “population growth → resource depletion”), each individual factor was categorised as ‘Economic’, ‘Political’, ‘Social’, ‘Demographic’, or ‘Environmental’. A full list of factors identified in literature as well as how they were defined for the coding is shown in Table 2-3 (page 20).

2.3.3. Modelling Factor Interactions with Causal Loop Diagramming

Following the coding of pairwise factor interactions found in the literature, the identified connections were then analysed using a form of qualitative system dynamics modelling known as causal loop diagramming (CLD). Causal loop diagrams are an approach to study complex systems that have interdependence, mutual interaction, and circular causality known as feedback loops, with a goal of building theoretical understanding on systems leverage points for policy improvements (Richardson, 2020). In this study, we aggregate pairwise interactions between factors identified using PTA (addressing RQ1 and RQ2) to develop a CLD to analyse the feedback loops driving climate migration (addressing RQ2).





The systems insights gained from CLDs are derived from the combination of simple model components – *pairwise interaction* between factors (presented as arrows), *interaction polarity* (presented as + or -), and *feedback loops*. Interaction polarity allows for the characterisation of dynamics within each pairwise connection, where a positive polarity (+) implies a direct influence (i.e., if Factor A increases, Factor B increases, or vice versa), and negative polarity (-) implies an inverse influence (i.e., if Factor A increases, Factor B decreases, or vice versa). The combination of pairwise interactions with interaction polarity (positive or negative) in a CLD enables the identification and characterisation of feedback loops representing circular causality between two or more factors. A feedback loop can be characterised as *reinforcing*, causing an exponential increase in system behaviour, or *balancing*, causing a goal-seeking or stabilising system behaviour (Sterman, 2000). Reinforcing loops are characterised within a CLD by an even or zero sum of negative polarities, while balancing loops are characterised by an odd sum of negative polarities. The combined output of pairwise interactions, polarities, and characterised loops allows for the hypothesis on the dynamic drivers of a complex and non-linear problem, emerging from reinforcing and balancing loops interacting in concert. Please refer to Table 2-4 for more information on understanding a CLD.

While CLDs can identify and characterise feedback loops driving a complex problem, they cannot ascertain which feedback loop dominates system outcomes, as all pairwise interactions are assumed to have the same strength (Luna-Reyes & Andersen, 2003; Richardson, 1995). In order to identify the dominant loops within

the CLD emerging from our analyses, we added interaction strength based on the frequency a pairwise interaction was mentioned in the literature and used these strengths to evaluate factor influence. It is important to note that though the frequency of factor interaction occurrence in literature does highlight strength of evidence for connections, it does not necessarily point to importance in the overall climate-migration system. For this reason, we classified the strength of factor links into four categories: weak, moderate, strong, and very strong (corresponding to values of 1-4). The middle 50% of factor links, represented as Interquartile Range (IQR), were defined as having moderate strength as the value difference within this range was minimal. The lowest quartile of factor interactions was assigned as weak connections, while the highest quartile was defined as strong connections. Any factor pair that was more than 1.5 times the IQR above the upper quartile was classified as very strong.

Table 2-4 Reading a climate migration causal loop diagram



Symbol	Meaning	Example
 Pairwise Interactions	Denoted by an arrow pointed from the causing factor to the effected factor. The thickness of the arrow connection is based on the factor pair's frequency of occurrence in literature, on a 1-4 scale.	The top left link shows that <i>political stability</i> affects <i>migration</i> .
	The factors' circle sizes are directly proportional to their eigenvector centrality value (i.e. it's relative importance in the system).	Eigenvector centrality values for <i>migration</i> , <i>financial capital</i> , and <i>political stability</i> are 1.00, 0.42, and 0.26, respectively.
- / + Polarity	Denoted as (+) or (-), where a positive polarity (+) implies a direct influence and negative polarity (-) implies an inverse influence.	In the presence of <i>political stability</i> , households are less likely to migrate (i.e. there will be a decrease in <i>migration</i>).
 Reinforcing	Reinforcing loops can be identified as having an even or zero sum of negative polarities. These loops lead to exponential increase or decrease, continually compounding change in the system.	In the presence of <i>political stability</i> , households are less like to migrate. The less incoming migrants in a community, the likelihood for <i>political stability</i> increases.
 Balancing	Balancing loops can be identified as having an odd sum of negative polarities. These loops cause a goal-seeking or stabilising system behaviour.	As a household's <i>financial capital</i> increases, their likelihood of <i>migration</i> also increases. However, through <i>migration</i> , relocation costs and higher costs of living in destination locations leads to decreases in <i>financial capital</i> .

Vensim, a system dynamics modelling software, was used to consolidate the pairwise interactions identified with PTA into a single CLD used to identify feedback loops. As with all complex systems, factors within the climate migration system are deeply intertwined and well understood through a systems feedback loop approach. In our analysis, we focused on the feedback loops that ‘passed through’ the factor *migration*. This enabled us to directly evaluate the dynamic processes within the diagram that influenced migration. These loops ranged from two to seven factors in length.

2.4. Scoring and Ranking Feedback Loops

Eigenvector centrality values were computed for each factor within the CLD, and loop scores were calculated as the normalised summation of eigenvector values for each factor within the loop. Eigenvector centrality is a measure of a factor’s influence in a system or ‘network’, where influence is calculated based on its connection to other influential factors (Borgatti, 2005), scored on a range of 0 (extremely low) to 1 (extremely high). This metric was used because it highlights not only a factor’s individual connections to adjacent factors, but its relative importance in the whole system. The calculation of an eigenvector centrality scores requires multiple calculation iterations to arrive at a dominant eigenvector score for factors in the network. We calculated eigenvector scores based on the weighted and directed network (the CLD) using the ‘igraph’ package in R (Csardi & Nepusz, 2006).

Although a metric typically used in social network analysis, Murphy and Jones (2021) propose the integration of eigenvector centrality into systemic design as an indicator of potential leverage points in the system. In this study, we used eigenvector centrality values to score loops to evaluate loop dominance within the context of the whole system of factor interactions. Loop scores were based on the average eigenvector centrality values for factors included in the loop. For example, a loop with three factors having eigenvector centrality scores of 0.8, 0.5, and 0.7, respectively, would result in a loop score of 0.67. Loops were ranked by their scores to determine the dominant loop for each length (number of factors in the loop). By highlighting the top loop for each length, we show a progression of how factors are folded into varying dynamic layers as analysis of the system becomes more complex.

2.5. Results and Discussion

We first provide a condensed summary of main themes found through the systematic literature review. Next, we present a comprehensive list of migration decision-making factors from the literature (addressing RQ1). Through our use of systems analysis, we then show the interactions between migration factors and identify the dominant feedback loops within the CLD (addressing RQ2) driving climate migration systems.

2.5.1. Emerging Themes in Climate Migration Literature

There has been rapid growth of climate migration literature over the past three decades, as shown in Figure 2-1 with tallies of the annual publication counts on literature focused on the climate-migration nexus. Prior to 2010 we found few studies that explicitly examined migration decision-making processes to climate change and a ten-fold increase in articles published in the decade between 2010-2020. This evolution is well detailed by Piguet (2013) who posits a number of reasons for the noted lack of environmental mention in migration studies in the 1900’s and its current resurgence. In his work, Piguet suggests the current uptick may relate to the politicization and securitisation of climate migration (Boas, 2015), increasing natural

hazards driving displacement, and growing climate change anxiety, among others. Fussell et al. (2014) also suggest that improved data collection methods and analysis tools may have contributed to this increase.

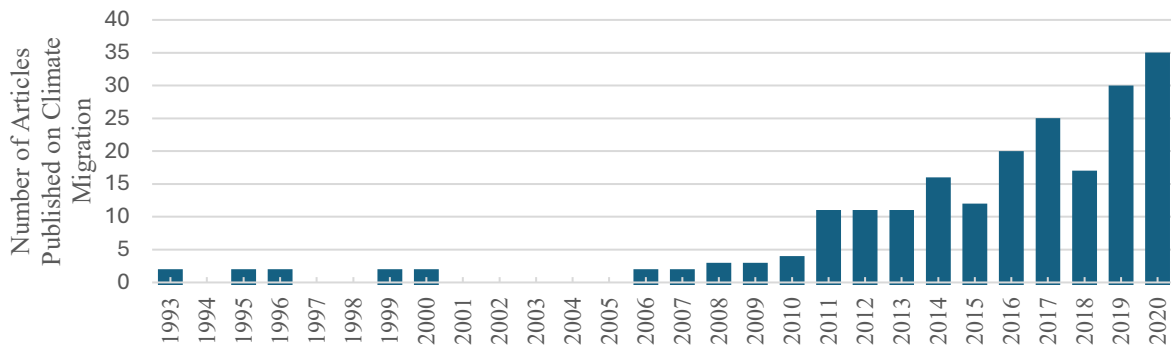


Figure 2-1 Study dates for climate change migration publications (n=206)

Of the 206 total articles examined, 34% (n=70) took a global approach using aggregated global data or a theoretical framing, 15% (n=30) had focuses on Bangladesh, and 3% (n=6) in both India and Mexico. In Figure 2-2, we provide a heat map showing darker colours for countries with high reference counts in climate migration literature. The focus of environmental migration literature on low and middle-income countries has been previously documented in other reviews (Obokata et al., 2014; Piguet et al., 2018). In their review, Piguet et al. (2018) suggest that this uneven geography may be explained by an attitude of immunity held by high-income countries, leading to research and funding focused more on countries perceived to have less adaptive capacity. Other suggested reasonings for the research geography distribution include the attraction to high risk regions, stereotypical racialisation of “climate refugees” to low-income country populations (Piguet et al., 2018), and a built-up fear that incoming migrants from low-income countries will lead to security threats in high-income countries (Boas, 2015).

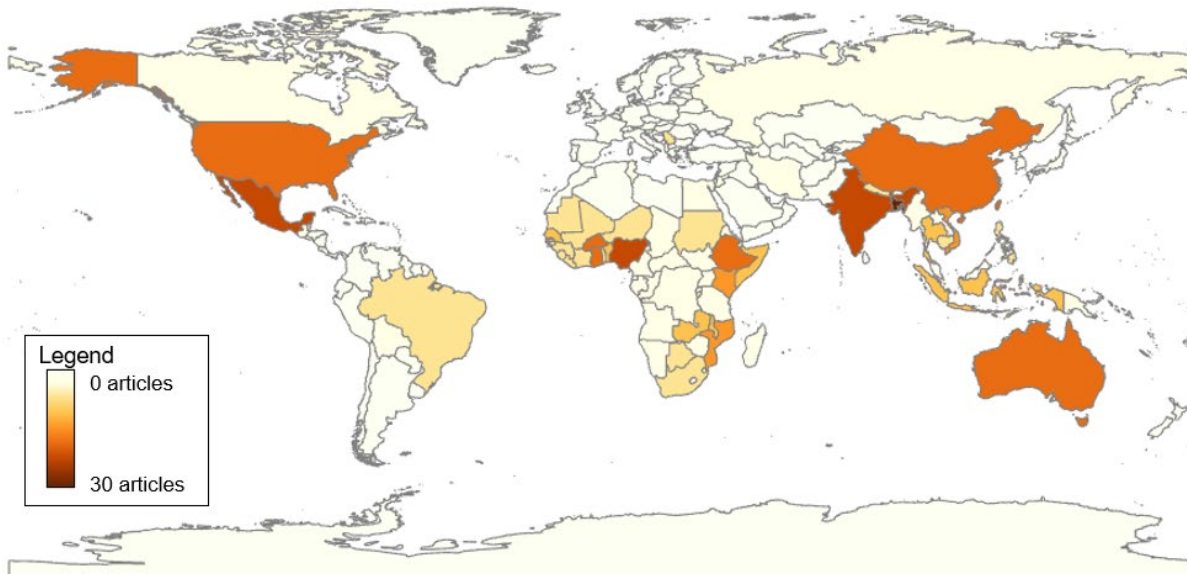


Figure 2-2 Heat map of climate change migration articles by country (n=206 excluding 70 articles with global focus)

2.5.2. Identifying Leading Migration Decision Factors

We found 21 leading factors discussed in scholarship that influence migration relating to climate change. These factors were categorised into ‘Personal & Household Characteristics/ Intervening Facilitators and Barriers’, ‘Demographic’, ‘Economic’, ‘Environmental’, ‘Political’, and ‘Social’ based on Black’s (2011) classification of migration factors (Table 2-3).

Table 2-5: Migration factors

Categorisation	Migration Factor	Definition
Personal & Household Characteristics/ Intervening Facilitators and Barriers	In Situ Adaptation	In-place individual, household, or community level adaptation
	Place Attachment	Emotional ties to the land, culture, or society
	Aid Programs	Programs offering monetary or in-kind assistance for livelihoods, shelter, or adaptation
	Risk Perception	Belief in ability to cope through stressor (through adaptation, assets, past experience, or divine protection), denial of hazard reality, resignation towards environmental decline
	Fear and Anxiety	Reluctance to move because of misgivings about migration process or destination location
Demographic	Health	Physical/ mental wellbeing, lack of disease
	Population	Group of individuals in distinct community
Economic	Livelihood	Income-generating activities; jobs;
	Financial Capital	Money available (including remittances); assets (equipment, vehicles, livestock, land tenure, etc.) that can be sold
	Cost of living	Monetary cost for rent/housing, regular food costs
Environmental	Resource Security	Availability of resources needed for habitation (water, timber, etc.)
	Food Security	Access to and availability of food to maintain health
	Environmental Degradation	Deterioration of air, soil, or water quality
Political	Political Stability	Stable political infrastructure; lack of conflict (between citizens or citizen-government); lack of resource conflicts
	Physical Infrastructure	Houses, community buildings, roads, utilities
	Legal Policies	Immigration policies that restrict or promote migration
Social	Social Capital	Social networks
	Social Services	Health infrastructure (healthcare and sanitation systems), education services, community amenities
	Social Norms	Social expectations for migration (gender specific migration norms, migration for marriage, etc); Perceived acceptance, hostility, and immorality in destination
	Social Inequality	Uneven distribution of resources in a society

Personal Security	The absence of threats to personal harm, including theft, exploitation, abuse, and murder
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2.5.3. Climate Migration Factor Interactions

Using the interactions identified through literature, the next step in our study was to consolidate the relationships into a climate migration system. The 21 identified factors, as well as their relationships between each other, are presented as a CLD in Figure 2-3. As shown in, the CLD presents the interaction of factors within the climate migration system where link size is based on the the strength of relationship (1-4 quartile value), the factor and font size is based on the on the eigenvector centrality of the factor, and the factor color is based on the factor category.

Analysis of the climate migration CLD in Vensim revealed 155 unique feedback loops which included the *migration* factor. Within these loops, the top 10 factors with the highest factor occurrences are shown in Table 2-4 along with their respective eigenvector centrality score. *Financial capital*, *food security*, and *livelihood* were the most frequently occurring factors within these feedback loops.

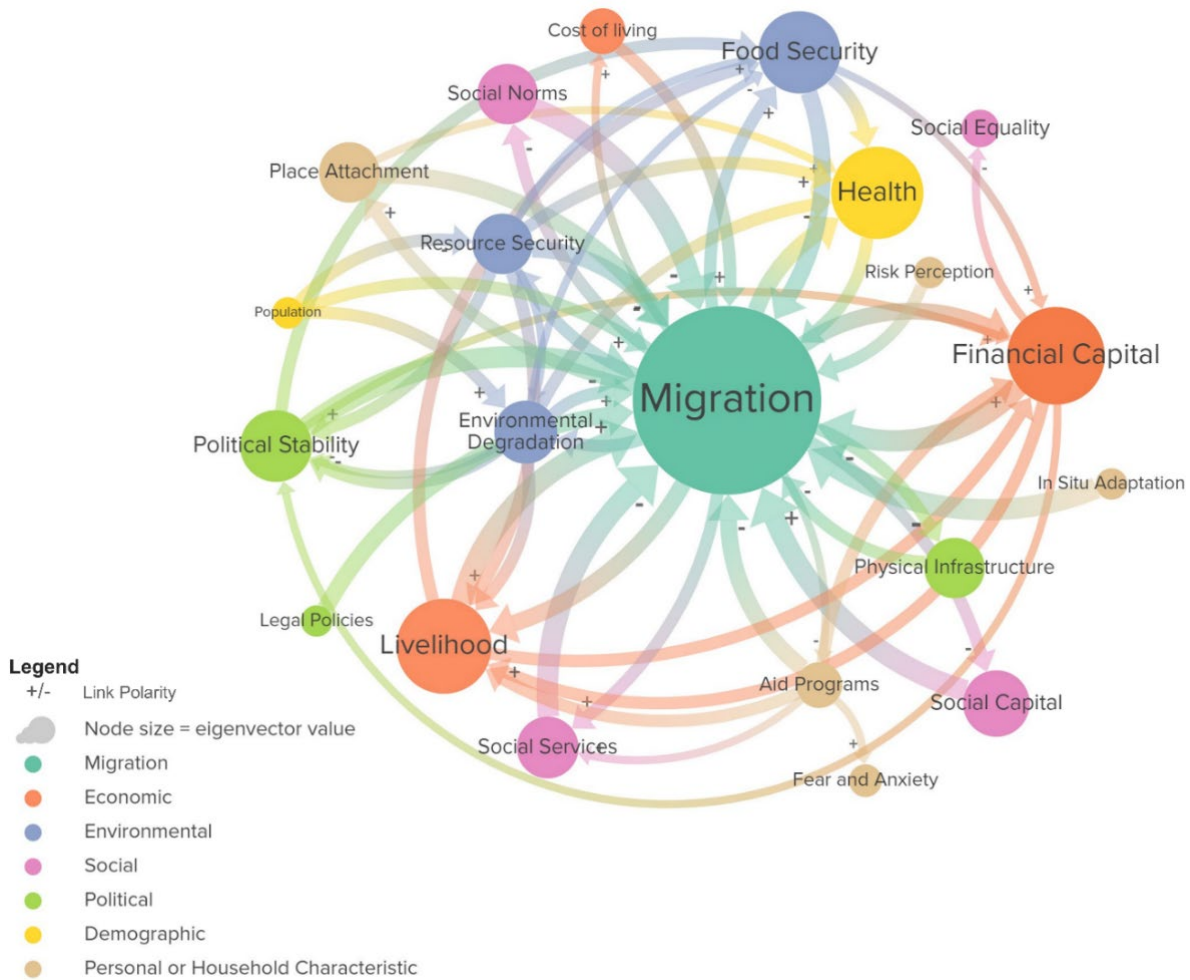


Figure 2-3 Climate change migration system causal loop diagram

Table 2-6: Frequency of top 10 factor occurrences in feedback loops

Factor	Frequency of Occurrence	Eigenvector Centrality Score
Financial Capital	104	0.537
Food Security	95	0.493
Livelihood	81	0.463
Political Stability	74	0.419
Environmental Degradation	60	0.257
Resource Security	60	0.211
Health	31	0.456
Social Capital	25	0.318
Aid Programs	21	0.209

While the frequency of a factor’s occurrence in the 155 feedback loops shows that it is a core factor in the climate migration system, the eigenvector centrality score shows its importance relative to other high influential factors in the system. For example, *resource security* has a more frequent occurrence in the feedback loops than *health* but we can see that *health* has a higher eigenvector centrality score implying that while *health* is more connected throughout the system, *resource security* is a more acute driver of migration.

2.5.4. Climate Migration System Feedback Loops

In addition to ranking the most commonly occurring factors in the migration-focused loops we also ranked loops based on their overall loop score. Loop score was based on the average of eigenvector centrality values for factors included in each loop. In order to not overvalue loops with smaller lengths, and as a way to let the top feedback loops capture the nuance of climate migration, we show the top feedback loop(s) of each loop length in Figure 2-4. Some loop lengths had multiple feedback loops with the same eigenvector loop score, but only one was selected as a visual in Figure 2-4 for clarity. In these instances, each variation shared the same factor combinations in varying sequential order.

Through examining the growth of the top feedback loops, from two factor loops to eight factor loops, a pattern emerges showing *migration* and *financial capital* as the epicentre of dominant loop behaviour, adding one new factor as the loop length increase. Starting with a feedback loop of *migration* and *financial capital*, the factors added in order of increasing loop length were *livelihood*, *food security*, *health*, *political stability*, *environmental degradation*, and *resource security*. These loops illustrate the most significant interactions and dynamics leading to climate migration, as identified in climate migration literature.

A key finding is the interaction between *migration* and *financial capital* as the anchor for subsequent series of influential loops. Although some studies share cases of movement spurred by lack of financial capital (Bernzen et al., 2019; Dreier & Sow, 2015; Shi et al., 2019), more often studies highlight that those with stable finances are the ones who will move (Constable, 2017; Kartiki, 2011; Logan et al., 2016).

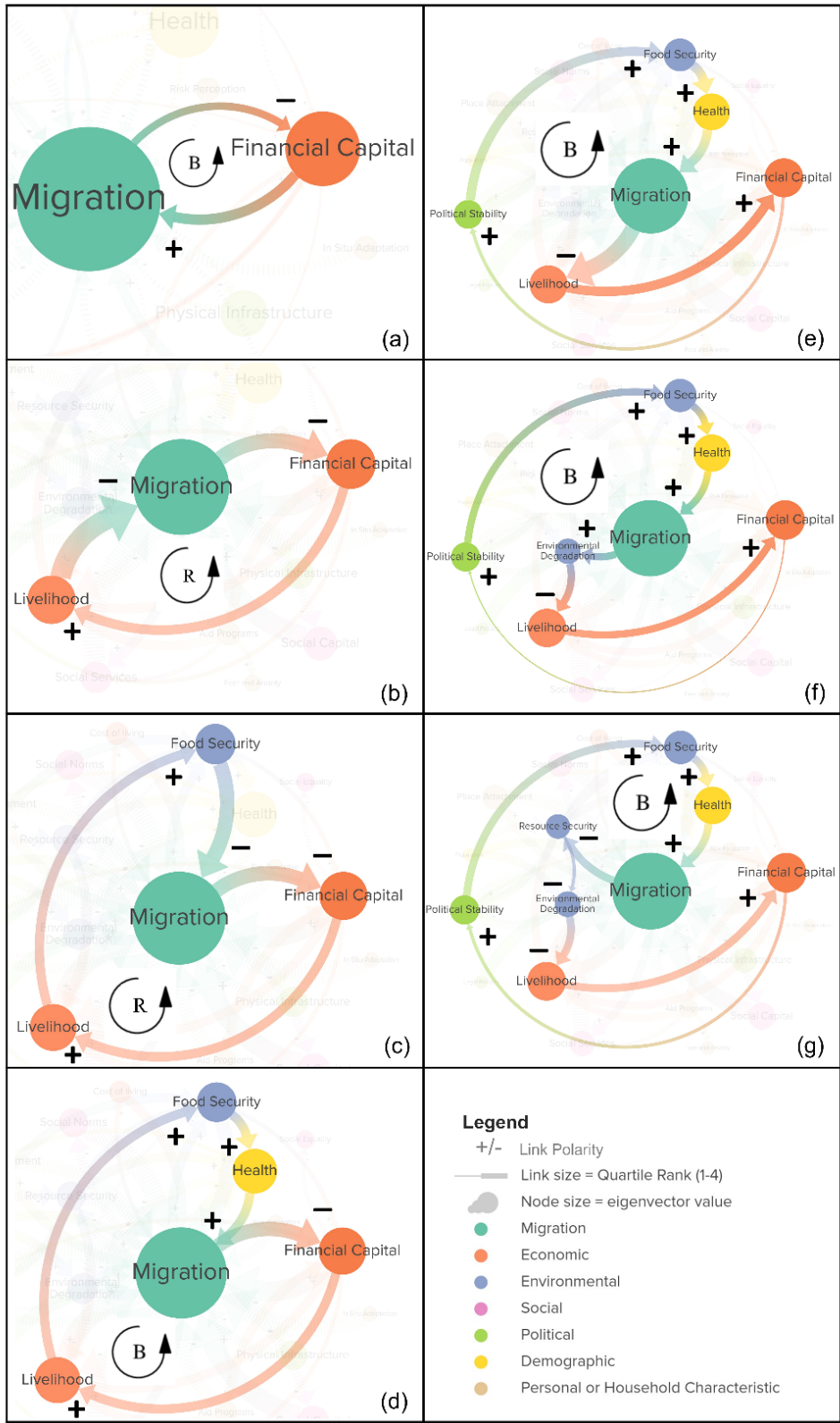


Figure 2-4 Top feedback loops in the climate migration system (per feedback loop length)

This result was also found in Borderon et al.'s (2019, p. 528) systematic review of empirical evidence in Africa which concluded, "...even though climate change will increase population exposure to environmental hazards, high levels of poverty mean that a large part of African populations do not have sufficient resources to be mobile."

A notable aspect of our coding scheme was the inclusion of remittances under *financial capital*. As one member of a household moves away and sends back money, the liquidity constraints of other household members are relieved, making them more likely to have the financial capacity to move as well (Bernzen et al., 2019). This point is, however, contested in literature where some studies have also found that instead of encouraging future migration (Kleemans, 2015; Tan, 2017; Tiwari & Winters, 2019), remittances may also be used for strengthening a family to remain in their home location (Calero et al., 2009; Das Sharma et al., 2020; Shi et al., 2019). Indeed, many families choose to have a member migrate in order to diversify income and stabilise their finances against future climate shocks (Sakdapolrak et al., 2016; Scheffran et al., 2012). Post-migration, transition costs as well as higher costs of living in destination locations were reasons that literature pointed to decreases in financial capital after migration (Barua et al., 2017; Haque et al., 2020; Mallick & Sultana, 2017). The story that this loop (Figure 2-4a) implies is that as a household gains enough financial capital to choose to move, their capacity to move in the future is lessened because of the costs of their initial movement. In summary, this loop (Figure 2-4a) supports arguments for liquidity constraints effects on migration, showing that individuals will migrate as this constraint is relieved and will have at least an initial negative financial shock after migrating.

The next factor added into the loops is *livelihood*. In the literature, opportunities for more secure livelihoods were a strong motivating factor for migration (Chen & Caldeira, 2020; Davis et al., 2018; Kolmannskog, 2010). As traditional livelihoods are strained under climate change, many people will venture into urban areas looking for work (Abah & Petja, 2016; Schwerdtle et al., 2021). Both failed livelihoods in origin locations as well as opportunities for more stable livelihoods in destination locations were strongly cited as motivating factors for migration. A significant criticism towards the idea of "climate migrants" is that it is difficult to separate climate-influenced migrants from those who are economically motivated (Kartiki, 2011; Lonergan, 1998). We however point to the clear link that as climate change increases, communities will experience shifts in their natural environments and major disruptions to traditional livelihoods leading to increases in migration. The latest IPCC report also confirms with high confidence that deteriorating economic conditions and livelihoods are main pathways towards climate-induced migration (IPCC, 2022c).

Food security was the next factor to appear in four-length loops. For this loop length there were three loops that had the same loop score, each showing various sequences of factors in relation to migration. All three of these loops tell variations of the same theme that as livelihoods suffer, particularly those based in agriculture, a household or individual's food security decreases (Kartiki, 2011) and their likelihood of migration increases. For example, Milan and Ho (2014) show how changes in rainfall patterns effect livelihoods in Peru, leading food insecure households to employ migration as a coping strategy. Similarly, *health* is introduced as an intermediary factor in Figure 4(d). *Food Insecurity* is directly related to poor health outcomes (Meze-Hausken, 2000; Rakib et al., 2019), while illness decreases the ability to migrate (Morrissey, 2013; Parrish et al., 2020).

The next factor added in loops of lengths six, seven, and eight are *political stability*, *environmental degradation*, and *resource security*, respectively. There is abundant literature documenting how political instability and conflict lead to migration (Abah & Petja, 2016; Atapattu, 2020; Owain & Maslin, 2018; Smith, 2007). In literature, cases show how increasing intensity and frequency of hazards, such as drought and desertification, lead to *environmental degradation* (Missirian & Schlenker, 2017). As the environment degrades, food insecurity rises and conflicts over resources such as water are likely (Levy & Sidel, 2014; Reuveny & Moore, 2009). The combination of these and other factors contribute to decisions to migrate. Likewise, as new populations enter destination communities there is a likelihood for ethnic and resource tensions as pressures increase on infrastructure (Kamta et al., 2021; Kartiki, 2011; Nunn & Campbell, 2020).

Out of these top loops, only two of the seven (Figures 2-4b and 2-4c) exhibit reinforcing behaviour while the rest are balancing loops. This means that the feedback between *migration*, *financial capital*, *livelihood*, and *food security* will lead to perpetuating behaviour in the system. Practically, this shows that communities whose livelihoods are negatively affected may have difficulties settling in a new location if they employ migration as an adaptation strategy. A case study in Bangladesh supports this with evidence of migrants with limited skill sets experiencing difficulty finding jobs at urban centres, as well as women losing access to their traditional livelihood options (Kartiki, 2011). This should be a point of focus for policy planners in aiding climate-resilient livelihoods in climate affected locations or supporting livelihood training programs in destination locations for incoming migrants.

The remaining balancing loops (Figures 2-4a, 2-4d, 2-4e, 2-4f, 2-4g) show a stabilisation of the climate migration system. This means that the combination of factors within these loops combine to limit the “growth” of migration. Alternatively, if climate-related migration continues to increase this could point to other mechanisms (factors) at play that were not included in this analysis. A second alternative would be that *financial capital*, *livelihood*, and *food security* are indeed the dominant factors influencing *migration*, while the others are more incidental.

While this study successfully identifies factors and interactions influencing climate change from within climate migration literature, more work is needed to understand these interactions in a fuller context of migration literature. Although some factor pairs may have had low frequency counts in this study, we do not suggest that there are weak or non-existent relationships, but rather that there was a lack of explicit mention of these relationships in climate migration literature. In the future we recommend researchers dive into these relationships with expanded scope to develop a clearer understanding of how factors interact. This study highlights gaps in climate migration literature where no linkages were coded such how ‘Social’ and ‘Environmental’ factors interact. The suitability of migration as a climate change adaptation strategy is highly context specific and will be unique to each individual and household. While this study presents a general, global view of the climate migration system, geographically specific case studies are also needed to understand the nuance of particular societies and cultures. In addition, this research develops a map of relationships within climate migration systems that can be furthered with future research. In particular, the results of this research lend well to future system dynamics modelling, where the addition of unique demographic data can help to determine context specific consequences of factor build-up or reduction over time (Fussell et al., 2014).

2.6. Limitations

We reiterate that the results of this research reflect the findings from the state of current literature on the topic of climate migration. Although these results are useful for gaining an idea of the interconnection and complexities within the climate migration system, they are also subject to the inherent biases found within scientific research at large. In our work, we acknowledge the English language bias of the articles selected for review and the disproportionate authorship from high-income, western countries (see Piguet et al. (2018) for a discussion on the uneven geographies of environmental migration research). As such, we lack important and relevant insights from experts originating from the lower income countries which are highly vulnerable to impacts of climate change.

2.7. Conclusion

In this study, we set out to identify the factors that influence climate migration in literature (RQ1) and how these factors interact to lead to migration or non-migration (RQ2). To date, there has yet to be a thorough, comprehensive review of climate migration literature to specifically identify key factors and interactions that lead to climate migration decision-making. Through this study, we provide not only an updated view of the current state of literature in the field but also a novel systems-based approach for the synthesis of interactions and feedback loops.

In our review of literature, we presented a breakdown of publications by year and country setting and identified 21 factors that contribute to migration decision-making under climate change. Our work extends previous meta-analyses and syntheses which have also sought to identify factors affecting climate and environmental migration (Hoffmann et al., 2020; Parrish et al., 2020; Sedova & Kalkuhl, 2020), emphasising a new and more dynamic view of migration systems. For instance, in their meta-analysis, Hoffmann et al. (2020, p. 910) concluded by stating, “environmental change can influence migration through several other channels” and identified urbanisation, labour market conditions, conflicts, and health, among the factors playing a role in triggering migration. While this study agrees with the intermediary relationships between environmental change and migration, the conceptualisation of “channels” of influence still denote a linear causal thinking. We, meanwhile, expand upon previous studies such as these to emphasise feedback loops within systems, rather than chains of causality. Using purposive text analysis and causal loop diagramming as a means to map of the pairwise interactions in literature allowed us to visually explore the interconnection of the identified factors. A major output of this research is the development of a climate migration causal loop diagram which can be used to visualise the multitude of interactions with system (Figure 2-3).

The use of systems thinking, and causal loop diagramming, is a new approach to analysing and displaying the known interconnection and complexities in the field of climate migration. Notably, in this study we not only include direct causal relationships between specific factors and migration but also relationships between factors. This is an important aspect of systems thinking that allows us to better understand how tweaks and perturbations to any part of the system causes repercussions directly and indirectly to migration decision-making. Using this visualisation aid, cascading effects can be more easily understood and predicted by policy makers and planners, thereby minimising future unintended consequences. We specifically recommend policy makers to reference these causal connections when determining

development strategies in climate-affected areas so that down-stream effects on migration and other key areas can be better understood. In this way, we compliment meta-syntheses, such as Schwerdtle et al. (2020), in helping to better understand ensuing effects and possibly prioritise policy recommendations for aiding health in human mobility. In our analysis of the top feedback loops within the climate migration system causal loop diagram we highlight that particular emphasis for policy and practice needs to be made on ‘Economic’ factors, such as *financial capital* and *livelihood* to assist climate-affected communities. Likewise, the relationship of how livelihood struggles lead to food insecurity is another point where planners should direct their attention.

In addition to its practical use, the results of this study are also useful to further understandings within the literature of climate migration. Obokata et al. (2014) calls researchers to include greater context in key areas (economic, demographic, social, political, and environmental) to increase our understanding of the interplay between these factors and migration. We likewise recommend the continued and increased collection of empirical data to contextualise these identified relationships to specific geographic or hazard settings. In this way, future studies may address the limitations associated with the global nature of this study.

In the future, the results of this study may also be useful in the development of more empirically or quantitatively derived systems models. From here, we recommend the exploration of temporal dynamics between these factors to determine how factor importance and relationship shift over time. Hoffman et al. (2020) likewise points to the need to consider time by noting that certain factors may only affect migration after specific threshold points have been reached or passed.

As the impacts of climate change are expected to increase in the coming decades, so too can we expect the mechanisms of the climate migration system to be amplified. In the future, studies may be needed to validate and revise these relationships at a localised level. While the results are generalised across geographic locations and hazard types, we still offer valuable insight into factor interactions that are useful for policy and aid planners.

Chapter 3

Contextualisation of causal relationships and leverages points in climate migration systems through expert mental models

“I ask world leaders to take us all along on your ride. We won’t slow you down. We’ll help you win the most important race of all. The race to save humanity.”

Kathy Jetnil-Kijiner, Poet, Climate Activist

3.1. Introduction

Migration is set to accelerate due to climate change, with an estimated 216 million total internal climate migrants by 2050 (Clement et al., 2021). However, the estimation of climate migrants is often a controversial topic as some experts argue the difficulty in pinning climate change as the primary cause of migration (Black et al., 2011; Curtis et al., 2015). Unlike migration estimates based on mono-causal hazard exposure modelling (Kam et al., 2021; Myers, 2002; Robinson et al., 2020), current research incorporates a complex array of direct and indirect non-climatic factors that influence how migration decisions are made (Maretti et al., 2019; McLeman, 2013; Menjívar et al., 2019; Pei et al., 2016). We use the term climate migration to describe scenarios of migration that have been directly or indirectly affected by climate change. This shorthand is used to differentiate between other types of migration (e.g. economically motivated), but does not prescribe a linear relationship between climate change and migration (Kabir et al., 2018). In this study, we aim to further the discourse on the multi-faceted nature of climate migration by examining how principal influencing factors interact to lead to climate migration and how these interactions may be viewed differently between academic experts and experts with lived experience.

Although researchers work to identify the relationships between socio-economic and political factors to migration (Parrish et al., 2020), these connections are often not identified by climate-affected individuals themselves (Mortreux & Barnett, 2009). Studies have found that when directly asked, many climate-affected individuals rarely state climate change or related environmental hazards as reasons for migration (Kelman et al., 2019; Speelman et al., 2017; van der Geest et al., 2020). While climate-affected individuals may recognise the impacts of climate change on their health, livelihoods, and other aspects of their daily lives (van der Geest et al., 2020), climate is not often cited as reason for movement. The unclear relationship between climate change, socio-economic political factors, and migration points to a need to understand the system from multiple perspectives and draw underlying connections more explicitly. In this study, we employ a systems approach to address gaps in understanding the relationships and feedback mechanisms between demographic, economic, environmental, political, and social factors and migration (Black et al., 2011; Jokisch et al., 2019; Sakdapolrak et al., 2016; Schwerdtle et al., 2021; Willett & Sears, 2020). The delineation of underlying and often unintuitive relationships is needed for policymakers when identifying climate resiliency and adaptation policy strategies, whether to support migration or in situ adaptation.

We present climate migration systems as multidimensional, interconnected, and dynamic interactions of macro-, meso-, and micro-level factors, exacerbated by climate change impacts, that lead to (im)mobility. While there exists a global climate migration system, culminating from decisions and movements worldwide, we build from Mabogunje (1970, p. 3) who states, “a system with its environment constitutes the universe of phenomena which is of interest in a given context” and contend for the existence of localised

climate migration systems broken down by unique characteristics (i.e. geographic location, group ethnicity, hazard type). To this end, we build from factors identified in Chapter 2 as influencing migration decision-making and contextualise them through data collected from two separate expert groups: academic experts from around the globe and local experts who experience climate impacts in Kiribati. Kiribati was selected as a case study for this research because it is frequently cited as a country where climate migration is likely. We surveyed both academic experts and those with lived experience (local experts) to better understand how mental models of climate migration systems change between global and local levels of perspective. While academic experts offer a higher-level view of global climate impacts, experts with lived experience in Kiribati offer a grounded truth for the realities of climate change.

As such, we positioned that the best way to capture the most comprehensive representations of these systems is to draw on the knowledge and expertise of both sets of experts. To this end, our first research question asks of both expert sets [RQ1]: What are the relationships between factors that influence climate change migration? As used in this study, factors reference decision-making influences that climate-affected individuals and households weigh when deciding whether to migrate. Factors are also often called "drivers" of migration (Black et al., 2011). While conceptually the same, we choose "factors" of climate migration to reinforce the decision-making power of the climate-affected individuals and households in choosing to migrate or not. This question was interrogated with academic experts through an online survey while a participatory system mapping workshop was used to discuss factor relationship with the local experts in Kiribati. From the relationships of factors, we were able to build a system map to conceptualise how each factor affects others while using additional analysis techniques to determine key relationships.

When analysing climate migration, the nexus of natural hazards, cultures, and geographies shape decision-making of climate-affected individuals (Kabir et al., 2018). The Intergovernmental Panel on Climate Change (IPCC) warns that as the global temperature rises, we can expect changes in the frequency or severity in a range of natural hazards (IPCC, 2018). Each hazard type (e.g. drought, sea level rise) will exploit different vulnerabilities within climate-affected communities, thus approaches to resiliency and adaptation should be likewise tailored. With this in mind, our second research question [RQ2] asks: What are the differences in causal relationships between migration factors for different hazards influenced by climate change? Through the comparison of causal relationships in multiple natural hazard contexts, we aimed to determine how specific factors, and their relationships, shift in importance and roles within migration systems. This question was answered through survey data of academic experts while experts with lived experience assessed causal relationships with the lens of their own combination of climate hazards in Kiribati. By answering Research Questions 1 and 2 for both sets of experts, we also present a brief comparative analysis to answer the question of [RQ3]: How does the structure of a climate migration system change between global and local perspectives? The analysis of both data sets leads us to the identification of leverage points for policy and migration planners looking to support climate-affected populations. The causal relationships identified in this chapter also provide the foundations of causal feedback used to develop the core model structure of Chapter 4.

3.2. Background

Literature on the topic of migration relating to climate change has risen remarkably in the past decade (Piguet, 2022). This uptick can be at least partially attributed to the publication of major works such the

Foresight (2011) and Groundswell (Riguad et al., 2018) reports, following the landmark Cancun Adaptation Framework (2010), which formalised our understanding of migration, displacement, and relocation. Although growing, the field of climate migration studies is still relatively nascent and in contention on various terminology and concepts.

One such point of debate is whether migration should be encouraged as a means of adaptation (Adger & Adams, 2013; McLeman & Smit, 2006; Piguet et al., 2011) or viewed as a last resort policy (Ingham et al., 2019). For many climate-affected communities, there is a high preference for remaining in place (Campbell, 2014; Kartiki, 2011). The decision to prioritise safe migration or in situ adaptation will significantly change the climate strategies employed. For instance, seawalls (Tomlinson & Jackson, 2019) and climate-adaptive livelihoods (Akhtar et al., 2022; Cooper & Wheeler, 2015) are common adaptation measures that local and regional governments encourage to help residents combat the impacts of climate change and remain in place. Meanwhile, governments focused on encouraging migration as adaptation may promote education or livelihood opportunities elsewhere, such as Kiribati's "Migrate with Dignity" labour migration scheme (McNamara, 2015). Whether policy makers intend to encourage migration as adaptation or support in situ adaptation strategies to improve climate resiliency in place, we aim to uncover critical relationships to inform policy implementation. To better understand the holistic effects of such strategies on the climate migration system, we employ systems thinking to evaluate their potential impacts on migration.

3.2.1. Conceptualising the Complexities of Climate Migration

The complexities of climate migration are evident in the deeply interwoven relationships between factors influencing decision-making. A central point to the idea of migration is agency retention – the ability of affected populations to make their own decisions. In this way, we differentiate migration from displacement, a mobilities reaction linked most often to rapid-onset hazards (Black et al., 2013).

Our study draws from the conceptual climate migration framework put forward by Foresight (2011). The Foresight framework identifies five key categories of drivers (factors) that influence climate migration: environmental, political, demographic, economic, and social while climate change acts as an external force that exacerbates existing vulnerabilities within the five categories. Rather than climate change acting as the sole driver, it is more accurate to say that climate migration is caused by the compounded effects of socio-economic and political factors, aggravated by climate change until affected populations no longer find it in their best interest to stay (McLeman et al., 2021). Previous works can be referenced to see how others have sought to identify the factors in an effort to better understand their relationships to climate change and migration, such as Cai et al.'s (2016) analysis of agriculture's role in climate migration and Whitley et al.'s (2018) exploration of individuals' mental models to explore climate migration decision-making processes.

The Foresight climate migration conceptual model is theoretically grounded in a combination of neoclassical and push-pull theory, among others (de Sherbinin et al., 2022). Neoclassical migration theory states that movement is predominantly driven by labour demand differentials between geographic locations, thus leading to migration in search of wages (Massey et al., 1993). This framework has largely been overtaken by the New Economics of Labor Migration (NELM) which accounts for more diverse household economic needs when migrating (de Sherbinin et al., 2022; Fussell et al., 2014). While aspirations for economic gains in tandem with climate change impacts makes it difficult to differentiate between climate

migrants and economically-motivated migrants, economic factors are nonetheless an important aspect in climate-affected individuals' decision-making (Oliver-Smith, 2012), making NELM an appropriate stepping stone in our understanding of climate migration. We also draw largely from push-pull theory in this research which incorporates NELM in identifying economic factors (e.g. low wages) and other non-economic factors (e.g. persecution) that repel individuals from an area and attract them to another location (e.g. job opportunities) (Khalid & Urbański, 2021). In our survey of experts, we focus specifically on push factors and how they relate to migration, as well as to other push factors.

While the push-pull theory of migration is a useful framework for understanding climate migration decisions, we also recognise that for many climate-affected populations across the globe, the idea of climate migration is viewed as a last resort option (Berlemann & Steinhardt, 2017; Ingham et al., 2019). In Kiribati, as well as many Pacific Island nations, place attachment, identity, community, and culture are woven into the land in a way that makes the consideration of leaving untenable for some (Constable, 2017; McMichael et al., 2021; Oakes, 2019; Zickgraf, 2019). In 2016, the newly elected government of Kiribati realigned its climate focus on ways to support citizens to stay and adapt within the country. As such, when working with local experts in Kiribati, workshop prompts inversed the questions of “What makes people leave?” to rather, “What do people need in order to stay?” From these discussions, we share insights from local experts in Kiribati on what they perceive as necessary for habitability and how future climate realities may affect these needs.

3.2.2. Mental Models

While our development and analysis of this research is framed from the Foresight framework, others may understand and conceptualise climate migration through a different lens. de Sherbinin et al. (2022) note the potential pitfall of restricting focus on singular framework, stating that the utilisation of one theory or framework can lead to oversight in other critical relationships. To avoid the potential omission of important aspects in climate migration systems, we proposed an aggregation of viewpoints from experts in climate migration research and experts with lived experience in Kiribati. By aggregating multiple perceptions, bringing interdisciplinary and lived experience and knowledge, we offer a convergence of conceptualising of the climate migration system (Boumans & Martini, 2014). We present these expert-informed climate migration systems to address current gaps in literature stemming from discipline and framework siloed understanding and analysis.

Central to this effort of combining multiple viewpoints is the utilisation of experts' mental models. As Jones et al. (2011) succinctly states, *"Mental models are cognitive representations of external reality"*. Mental models are how processes and phenomena are simplified in our minds to be later called back or applied to similar experiences. Mental models are widely used in system dynamics for their ability to represent cause and effect dynamics (Doyle & Ford, 1998) and have been previously used to inform climate migration (Whitley et al., 2018). Mental models are moulded and informed through lived experiences, and we contend that by aggregating experts' perceptions, we can avoid the pitfalls that result from conceptualising the climate migration system from a singular viewpoint. In this study, gathering the mental models of experts allows us to build a convergence on causal understanding of how the climate migration system unfold while also identifying differences in perspectives (Moray, 1998).

3.3. Methods

This study used expert perceptions of the causal relationships between factors influencing climate migration as the primary source of data. These perceptions – or mental models – were elicited through a global online survey and a participatory workshop with experts in Kiribati. Both mental model elicitation methods aimed to identify key migration factors and explore causal relationships and overall system structures. The survey of academic experts was extended to identify the differences between natural hazard context (sea level rise, drought, flooding, and erosion) while the workshop discussions with local experts provided insights into the specific context of Kiribati. In Figure 3-1, we provide an overview of the method sequence used in this study before discussing each in more detail below.

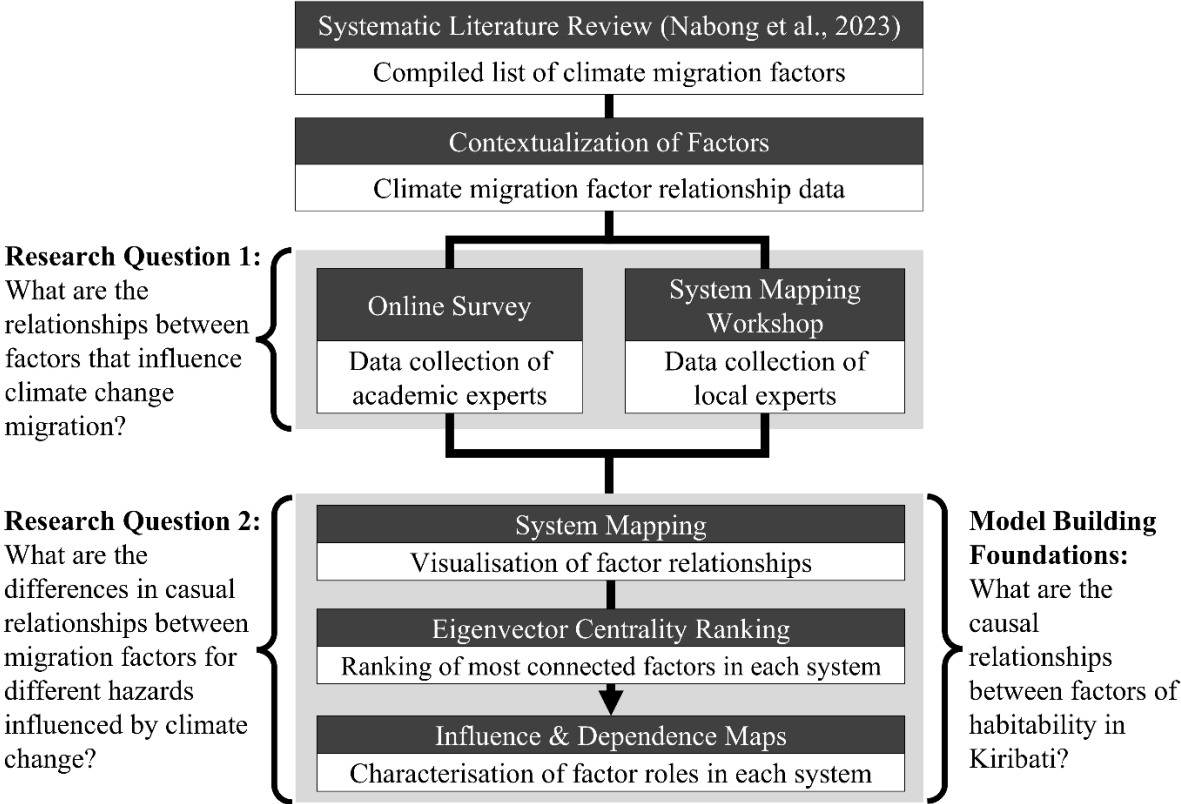


Figure 3-1 Methodological design of steps and associated outputs

3.3.1. Data Collection

3.3.1.1. Survey of Academic Experts

We collected data through a survey of academic experts conducted from December 2021 to January 2022. As mental models are informed and developed through experience, understanding the background of expert contributors provides meaningful context for how factor relationships were evaluated. Experts were identified from a previous systematic literature review where climate migration factors were synthesised (*Chapter 2*; Nabong et al., 2023), using authorship on one or more peer-reviewed journal publications on

the topic of climate migration indexed in the Scopus database as the criteria for expertise. We also used snowball sampling to allow survey participants to nominate others with expertise in the field of climate migration. Nominated experts were reviewed by the research team to determine inclusion criteria was met (publication on a climate migration topic) before being invited to participate. Seven additional experts were contacted from peer recommendations. In total, surveys were sent out to a total of 590 participants of which we received 32 responses (5%).

Within the survey, the experts were asked to share perceptions of relationships between a given list of factors influencing climate migration decision-making. These factors were identified in Nabong et al. (2023; *Chapter 2*) where we produced a list of 21 factors and interactions found as influencing decision-making in climate migration literature. To keep the length of the survey compact, we ranked the factors identified in literature by eigenvector centrality scores and used only the top 10, shown in Table 3-1. Eigenvector centrality values of the factors were calculated from their frequency in coded pairwise relationships in literature. Eigenvector centrality is a metric to measure the connectedness of each factor to other central factors in the system (Knoke & Yang, 2008). This centrality metric was used to prioritise climate migration factors based on their level of interconnectivity, so that factor importance and top causal relationships could be explored in greater depth.

We began our survey by collecting basic demographic information including institutional affiliation and position, years of experience, country of residence, and geographic focus of research. Additionally, prior to beginning their responses on factor relationships, participants were asked to choose the climatic hazard that they had the most experience with and respond to the factor relationships with that specific hazard context in mind. In this way, experts could keep a consistent context in mind throughout the survey allowing us to analyse structural differences in factor relationships between hazards. The top four hazards chosen by the experts (sea level rise, drought, flooding, and erosion) were used in our comparative analysis along with the generalised climate migration system ("aggregate"). Through the disaggregation of survey data by hazard, we recommend targeted policies for specific hazard contexts.

Experts were asked to evaluate the polarity and strength of factors links using pairwise comparisons. The definitions of each factor were provided to respondents to maintain consistency for response comparison with the option to provide feedback or their own definitions. Polarity of factor interactions was gauged by having participants fill in the blank of "Factor A _____ Factor B" with either *increases/ improves*, *decreases/ degrades*, *both increases and decreases*, or *no relationship*. Polarity allows us to infer shifts in factor strength over time, whether increasing as another factor increases in strength or prominence (+) or decreases when another factor increases in strength or prominence (-).

Table 3-1 Definition of climate migration factors as used in the survey of academic experts with rationale and eigenvector centrality rankings

Ranking of Factors by Eigenvector Centrality Scores (Chapter 2)	Climate Migration Factor	Definition
1	Financial Capital	Money available to an individual or household or assets that can be sold
2	Food Security	Access to sufficient, safe, and nutritious food that meets an individual's food preferences and dietary needs for an active and healthy life
3	Livelihoods	The assets, the activities, and the access to these that together determine the living gaining by the individual or household
4	Health	The physical and mental well-being of an individual
5	Political Stability	Ability of a political system to survive through crises without internal warfare
6	Social Capital	The networks of relationships among people who live and work in a particular society
7	Social Services	Government services provided for the benefit of the community's well-being
8	Resource Security	The ability of an individual or household to secure access to their current level of natural resource demand
9	Physical Infrastructure	Private and public built environment assets
10	Migration	Movement of an individual or household from one place to another

The strength of that relationship was then evaluated using a 5-point Likert scale of unclear, very weak, weak, strong, very strong. For example, one might choose to say that *livelihoods* increase *health* with a strong relationship. The systematic elicitation of expert perceptions on pairwise factor relationships allowed us to reveal their mental models on the climate migration system for particular hazard contexts.

Through the aggregation of the thirty-two experts' mental models, we developed a collective representation of a generalised climate migration system. We also develop hazard specific climate migration systems by disaggregating the survey responses from experts' selected hazard experience. The responses from experts of each hazard context resulted in impact matrices containing strength values for all possible relationships. Scholars point to the need to account for particular nuances (e.g. geography, culture) to fully understand migration decision-making (Kabir et al., 2018; McLeman & Smit, 2006). By comparing the hazard-specific climate migration systems we can better understand contextual climate migration decision-making.

3.3.1.2. System Mapping Workshop With Local Experts

Prior to the workshop with local experts of climate impacts in Kiribati, scoping discussions were initiated in October 2023 to ensure conceptual alignment of the identified problem (i.e. climate change's effect on

habitability) with I-Kiribati local leaders (n=7). Individuals were selected for discussion because of their expertise in climate change impacts in Kiribati, both through lived experience with climate hazards in Kiribati and their leadership in local climate initiatives. Scoping discussion participants were from non-governmental organisations (NGOs) focused on climate change, and some with experience leading climate initiatives in local organisations not primarily focused on climate change (e.g. women's groups). Discussions were conducted in English and lasted around one hour each. The scoping discussions followed an interview guide and were centred around the idea of understanding the key factors that are important, and perceived as necessary, for maintaining habitability in Kiribati.

In these discussions, the participants were provided a list of 18 potential factors of habitability which were previously compiled from a global study which synthesised reasons why people have decided to move in relation to climate change (*Chapter 2*; Nabong et al., 2023). The factor list and definitions that were provided can be found in Appendix I and the full interview guide in Appendix II. Participants were asked to consider the relevancy of each factor to Kiribati and rank the top 5 most important factors they felt are needed to maintain a habitable living environment (i.e. what, if missing, would make them want to leave their homes?). Factors were given a score of 5 for highest priority (*Rank 1*) choices, 4 for *Rank 2*, 3 for *Rank 3*, 2 for *Rank 4*, 1 for *Rank 5* choices, and 0 for unselected choices. The top factors of habitability were then calculated using the sum of ranking scores for each factor to determine the top 10 key factors to include for a subsequent workshop.

To understand how each identified factor contributes to long-term habitability, it was necessary to take a holistic and multi-sectoral systems approach (Mirchi et al., 2012; Rich et al., 2018). Using the ranked factors from the scoping discussions, a participatory system mapping workshop was held in November 2023 to identify causal consequences from climate impacts and possible adaptation measures, for a total of 3 weeks in Kiribati for data collection. In this participatory method, participants contributed to the development of a system dynamics model by sharing their mental models of climate impacts in Kiribati, the aggregation of which formed the core feedback structure of the stock and flow model which will be described in Chapter 4. A participatory system mapping method was selected to reflect the actual lived experiences of I-Kiribati residents, rather than interpreted realities from literature.

The workshop was approximately four hours in length and brought together local leaders in South Tarawa, Kiribati who were interested in participating on the topic of climate change adaptation and resiliency. Participants were targeted and invited because of their past involvement and leadership in climate-related initiatives in Kiribati. This group of 21 people included members of local climate NGOs, church groups, youth activist groups and other civil society groups. All participants were I-Kiribati, with the exception of one American who was volunteering with the local youth organisation. The workshop was approximately four hours in length and was conducted in I-Kiribati, with a translator for full group discussion and local facilitators for small group facilitation. There were five small groups in the workshop, with a minimum of 4 participants per group, and assigned specific factors to evaluate as the leading factor. For example, if a group was tasked with discussing *financial capital* as a lead factor, they would evaluate how *financial capital* affected *food security*, how *financial capital* affected *livelihoods*, and so on until they had discussed its relationship to all factors.

For each pair of factors, participants were asked to agree on the polarity and strength of each relationship. This approach was similar to that for the academic expert surveys where the polarity of factor interactions was gauged by having participants fill in the blank of "Factor A _____ Factor B" with either *increases/improves*, *decreases/degrades*, or *no relationship*. Participants then judged the strength of the relationship between "No Relationship" (strength score of 0), "Weak" relationships in cases that are rare but possible (score of 1), "Regular" when the causal relationship is common but not guaranteed (score of 2), and a "Strong" relationships when the causal relationship identified is guaranteed to always happen (score of 3). Notetakers for each group recorded the reasoning behind each polarity and strength decision. There were no noted disagreements in groups' discussions of factor pairings.

3.3.2. Data Analysis

To analyse the climate migration systems for each hazard and Kiribati-specific context, we used three complimentary structural and network analysis techniques for structurally evaluating mental model data for academic and local experts: systems maps, eigenvector centrality, and influence mapping which were used to evaluate factors' interconnections, interconnectedness, role characterisation, respectively. Below we describe these analyses in more detail.

3.3.2.1. Systems Maps – Evaluating Factor Relationships

We began our exploration of the climate migration systems through system mapping. System mapping is a tool used to visualise relationships and feedback loops between factors in a system (Ford, 1999). System mapping is useful in interconnected systems by showing not only linear cause and effects, but also pathways and dynamic interactions between factors (Cradock-Henry et al., 2020; Kunze et al., 2016). System mapping has been used in this way in a variety of related fields, such as climate change (Cradock-Henry et al., 2020) and sustainable livelihoods (Banson et al., 2015). From the survey of academic experts, the system maps in our study resulted from the hazard impact matrices and visually represent the mental models of study experts for the aggregate climate migration system as well as each hazard context. For the local experts, the system map was generated after combining all group data into one single impact matrix to describe the climate impact system in Kiribati. We used the online platform Kumu to create and analyse the systems maps (Kumu, 2022).

For the academic expert results, the inputs of the systems maps were based on the factor relationships' polarity and strength data from the survey of experts. The mode of the relationship polarity was used as a consensus measure to reflect the general perceptions of the experts. The strength of each factor relationship was taken as the weighted sum of expert responses where unclear, very weak, weak, strong, and very strong were weighted as 0, 1, 2, 3, and 4, respectively. Using the weighted sum of relationships' strength allowed us to compare and contrast each relationship's strength with more granularity and is an acceptable approach for evaluating non-parametric Likert data (Jamieson, 2004).

We calculated the summed strength for each pairwise factor relationship for experts (n=32) as:

$$Strength_n = \left((Unclear_{n_i} \times 0) + (Very\ Weak_{n_j} \times 1) + (Weak_{n_k} \times 2) + (Strong_{n_l} \times 3) + (Very\ Strong_{n_m} \times 4) \right)$$

where n is the total number of experts in each hazard context and n_i , n_j , n_k , n_l , and n_m are the number of responses for unclear, very weak, weak, strong, and very strong, respectively. Although system maps are typically non-weighted, in this study we follow Murphy and Jones's (2021) methodology called leverage analysis. With this technique, we combine the dynamic insights of system mapping with the quantitative analysis offered through network analysis. By assigning weights to each factor in the system map, we identify leverage points from both a dynamic and structural standpoint. Through the system maps, we show a visual representation of the factors' connectedness; both direct links between two factors and pathways between multiple factors. Academic experts were asked about the relationship between each of the 10 factors bi-directionally, for a total of 90 pairwise relationships. Relationships were excluded from the system maps if the resulting polarity mode was "no relationship".

The data within the hazard impact matrices was additionally filtered to only strong and very strong relationships. Strong and very strong relationships, as perceived by academic experts, are indicative of stable causal relationships within the climate migration system. We performed a network density analysis of these filtered relationships to compare how the drivers of climate migration vary between systems. Network density was calculated by counting the number of strong and very strong relationships perceived in each climate migration system and dividing by the total potential relationships (90 potential relationships).

For local expert data, system mapping was generated from the polarity and strength data collected for each causal relationship, with causal linkages identified as "No Relationships" omitted from the map. A network density analysis was also performed by dividing the number of "strong" relationships (with scores of 3) by the total potential relationships for the workshop (112 potential relationships).

3.3.2.2. Eigenvector Centrality – Evaluating and Ranking Factor Connectedness

While system mapping allows for the visualisation of key relationships through link strength, a quantitative comparison is useful for finding key factors. For the academic expert data, we calculated the weighted eigenvector centrality score of each factor based on the weighted sum strength score described in the previous section, while for the local expert data the eigenvector centrality was based on the given strength scores from the workshop participants. As eigenvector centrality is used to measure interconnectivity, we produced a ranked list of the factors' connectivity for each climate migration system, as perceived by experts. By evaluating each factor on their connectedness to other important factors (as measured by the eigenvector score), we can highlight when factors potential to drive climate migration system outcomes. We also provide a comparative analysis between academic and local expert rankings to highlight the differences between global and local mental models.

3.3.2.3. Influence Maps – Characterising Factor Roles

Once key factors were identified through weighted eigenvector centrality scores, we further characterised their roles in each system with an approach from Godet (1994) called ‘influence maps’. Using the matrices of weighted sum values for the relationships' strengths, the influence and dependence scores for each factor were calculated, normalised, then plotted on a two-dimensional influence vs. dependence chart. Factor influence is calculated as the sum of influence (arrows) from one factor on the other factors, while factor dependence is the sum of influences from all the factors on a particular factor (Arcade et al., 1999). Factor influence and dependence are plotted on an influence map, which was broken into four quadrants to help categorise the roles of each factor, described below in Figure 3-2. The plotted position, along with the quadrant characteristics, helps us to understand the role of the factors in the climate migration system.

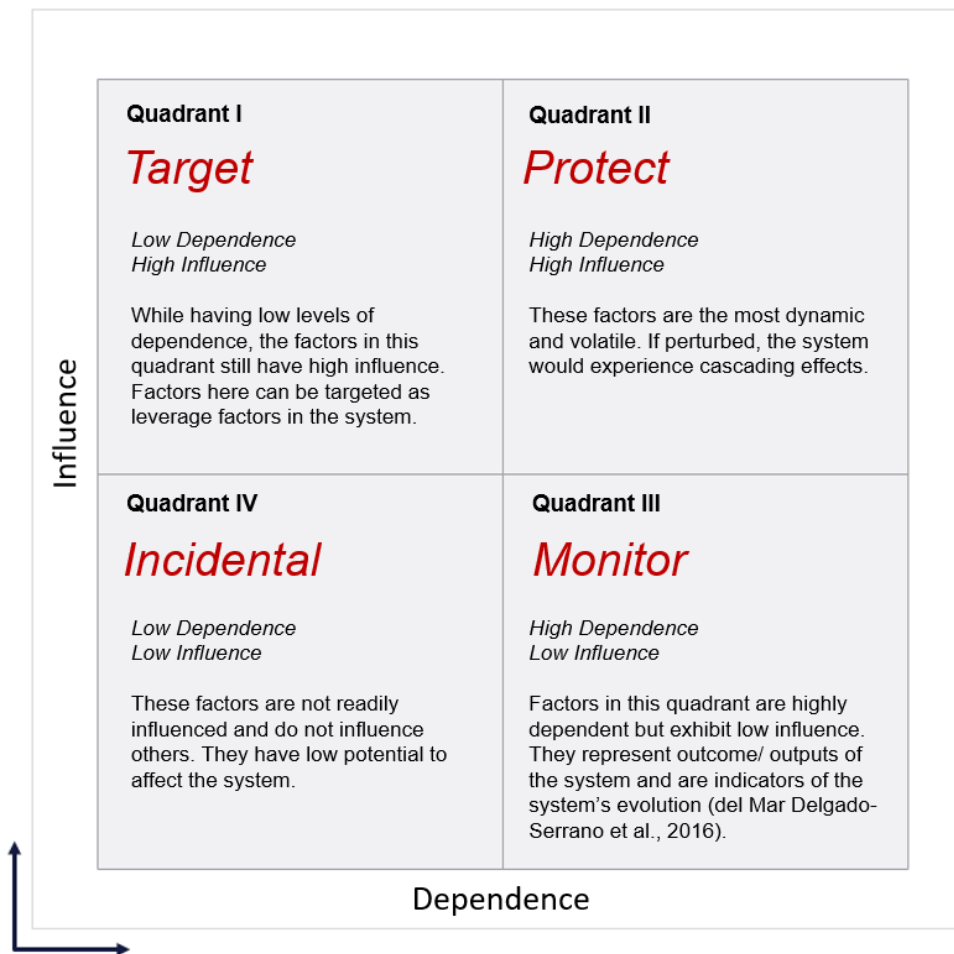


Figure 3-2 Description of an influence map

While eigenvector centrality scores measure overall connectedness, influence maps allow us to distinguish whether a factor's relationship role is more dependent or influential. Factors plotted in Quadrants I and II are of particular interest when evaluating factor roles due to their high levels of influence. This means that perturbations to these factors would cause rippling effects throughout the system. When developing policy

strategies, factors should be targeted from Quadrant I. A low dependence score is preferable when seeking to identify which factors might serve as system leverage points, given their lower vulnerability to influence from other factors, and any unintended consequences that could result. Mapping of factor dependence and influence has been used in similar contexts, such as natural resource management (del Mar Delgado-Serrano et al., 2016) and rural water systems (Valcourt et al., 2020), where researchers look to classify factors' roles in a system.

Similar to the eigenvector analysis, a comparison was also made between local and academic experts' influence map results. By identifying structural similarities and differences in each expert set's mental models, as presented through comparative eigenvector ranking and influence maps, we explore how building models from localised perceptions versus more global, non-grounded understandings can add additional contextualised understanding.

3.4. Results and Discussion

In this section the results and discussion are presented for the climate migration and habitability systems from the academic and local experts' mental models. Section 4.1 will present the findings from the academic experts and Section 4.2 will present the local experts as compared to the results of academic experts.

3.4.1. Academic Experts' Mental Models

Our survey solicitation generated 32 responses from experts in the field of climate migration. The majority (n=29) of experts self-described their roles as researchers at academic or research institutions. Other experts self-reported roles in non-governmental organisations (NGO) (n=3), government (n=1), and multi-lateral organisations (n=1). Two experts selected that they were both engaged at an academic or research institution as well as in the NGO sector. The experience of the experts varied from 20+ years (n=10), 10-14 years (n=9), 5-9 years (n=8), 15-19 years (n=3), and 1-4 years (n=2). Collectively, the 32 experts who participated in the survey have published 1,298 journal articles which have been cited 49,658 times, according to Scopus data. Accounting for the range of experience, the median number of articles published by the surveyed experts was 16 with a median citation count of 272. Although the survey was sent to a geographically diverse group, the experts who responded were from high-income countries, with only one individual who was from a middle-income country. Many experts selected having a global focus in their research (n=9). Bangladesh (n=9) and the U.S.A. (n=5) had the highest rates of respondents reporting country-specific research expertise. Experts noted that their primary hazard experience related to sea level rise (n=9), drought (n=6), flooding (n=6), coastal and river erosion (n=5), land and forest degradation (n=3), salinisation (n=2), or heat waves (n=1).

The results of the survey capture experts' mental models of causal relationships between factors influencing climate change migration [RQ1]. Here we present aggregated results (n=32) for all experts while highlighting the four most prevalent hazard experience among surveyed experts: sea level rise, drought, flooding, and erosion. The remaining hazards were still included in the aggregated results, but not highlighted due to low response numbers. By disaggregating the data by hazard experience, we sought to understand differences in generalised (aggregated) conceptualisations and hazard-specific factor

relationships [RQ2]. In the following sections we discuss how system mapping, factor ranking, and factor characterisation help us to understand the leverage points in each climate migration system.

3.4.1.1. Systems Maps – Evaluating Factor Relationships

We begin our analysis of the survey results by visualising the factor relationships in system maps. Systems maps were created for the aggregate system of climate migration from all experts' mental models and four climate migration systems specifically reflecting scenarios of sea level rise, drought, flooding, and erosion. In these maps we identify how factors affect each other and at what strength, as indicated by polarity notation and link width. We present a system map in Figure 3-3 of the aggregate climate migration system showing the factor relationships as perceived by all the surveyed experts. This map shows general trends of how each factor is perceived to impact the others in the system. In Figure 3-3, the polarity is denoted by "+" or "-" symbols at the end of each link, as well as blue and red colouring respectively. Positive (+) links show relationships where the factor at the tail leads to an increase or improvement in the secondary factor. Negative (-) links show relationships where the first factor leads to decreases or degradation of the secondary factor. Link polarity offers insight into how factors might change over time. Relationships that experts perceived as being capable of both increases AND decreases are coloured grey. For clarity, factors will be indicated in *italics* for the remainder of the chapter.

One main takeaway from Figure 3-3 is the polarity of the factors' relationships towards *migration*. With the exceptions of *financial capital* and *social capital*, all other factors have a negative relationship with *migration*. This implies that the increased presence of *livelihoods*, *health*, *physical infrastructure*, *food security*, *political stability*, *resource security*, and *social services* potentially leads to decreases in *migration*. This point is supported by one participant who stated, "If people have secure livelihoods they are more likely to withstand climate change impacts and will not leave their place of origin (reduce migration). Most people want to remain (and adapt) in place." Another expert commented, "...In a resource dependent island community, there will be linkages between resources and livelihoods, health etc. People would be reluctant to move away from resources (e.g. proximity to fishing grounds)..."

In contrast, the system map shows a positive relationship between *financial capital* and *migration* (i.e. increases in *financial capital* leads to an increase in *migration*). This relationship is strongly supported in literature, where scholars state that financial capacity has a significant role in determining the ability of an individual or household to move (Cai et al., 2016; Grecequet et al., 2017; Kartiki, 2011). However, a relatively new topic of research also explores cases where individuals are motivated to migrate, but lack the resources to do so, leading to "trapped populations" (Nawrotzki & DeWaard, 2018; Suckall et al., 2017). This point is further supported by a comment from one expert who shared, "Contrary to popular belief, greater economic resources and opportunities facilitate migration. Many of the poor hunker down in response to adversity and, when they do, it is out of desperation".

When a relationship is viewed to have both a positive or negative effect at different times, such as in the complicated relationship between financial capital and migration, it is often the case that there are missing intermediary variables to explain the change in polarity. As shown in Chapter 2 (Figure 2-4a and Figure 2-4b), when the intermediary variable of *livelihoods* is added, the polarity effect of *financial capital* on

migration switches. The results from this survey of academic experts highlight the need for future studies to focus on intermediary factors when teasing out the relationship between *financial capital* and *migration*.

We found that the presence of strong *social capital* helps to increase *migration* by offering a continuation of kinship ties and transitional assistance (Nawrotzki et al., 2013; Smith, 2007; van der Geest et al., 2020). However, one expert also argued that "Social capital levels [strength] may be less important than the configuration of networks. Dense but closed networks (as in tribal societies) have a different impact than more diffuse "-1 tie" networks (as in modern civil societies)." Prioritising community togetherness rather than strengthening diasporic ties is an important point for policy makers looking to strengthen social capital in climate-affected communities.

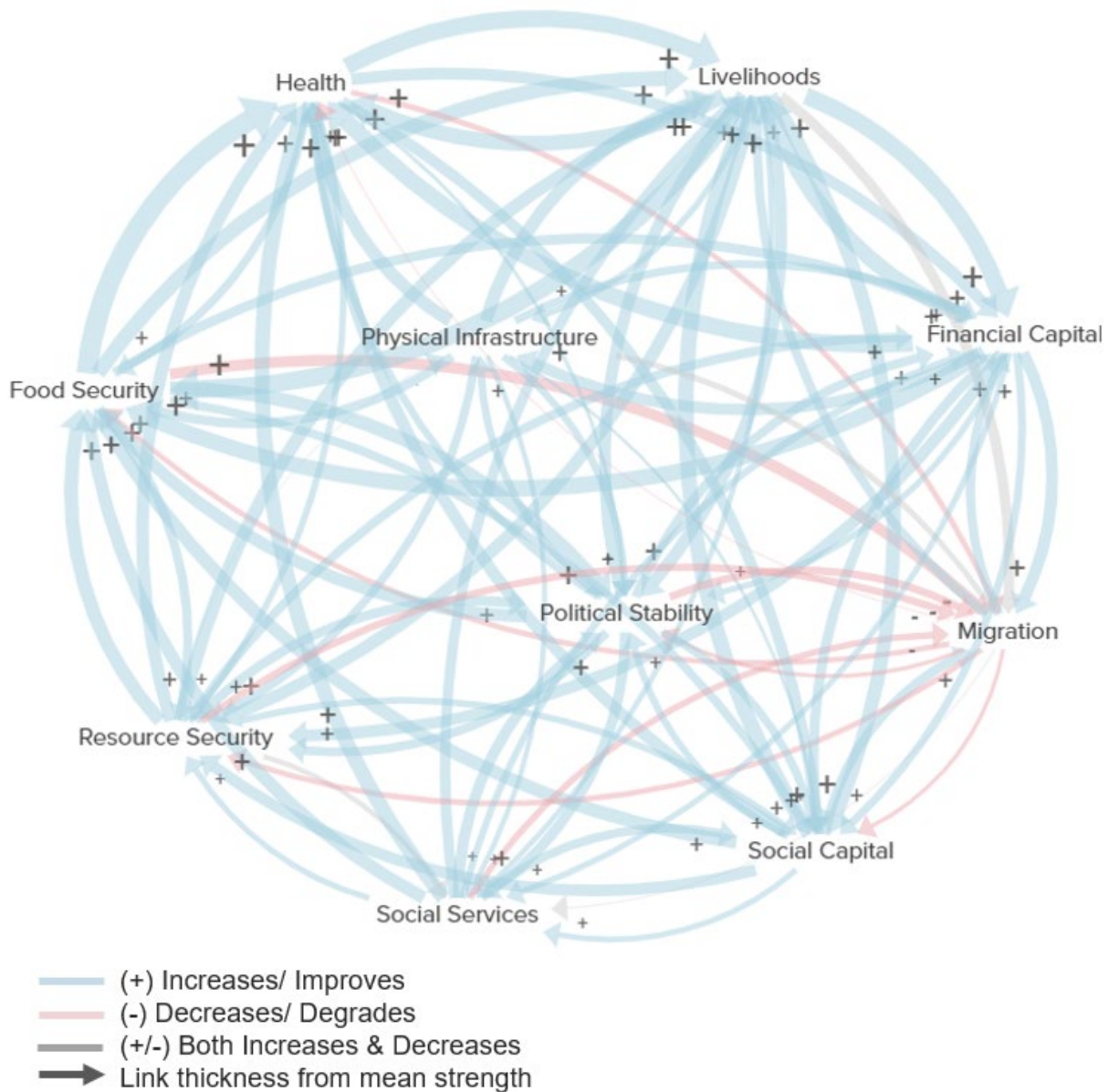


Figure 3-3 System map from academic experts' aggregated mental model (results aggregated from all hazard contexts)

After disaggregating the survey data by hazard type and filtering to only include strong and very strong relationships, we compared the network density between the four-hazard system. A higher density within these systems points to higher interconnectedness and complexity, adding difficulty in determining the best intervention points for policy. The densest system of strong relationships was erosion (77%), followed by flooding (49%), drought (30%), and sea level rise (23%). A possibility for these density differences is that experts with experience in sea level rise and drought were more capable discerning nuance in their selection of strength due to a higher-level experience in and understanding of the system. All expert respondents who contributed to the sea level rise system had over 10 years of experience, with the majority over 15 years. In contrast, the majority of the experts contributing to the erosion system had less than 10 years of experience.

3.4.1.2. Eigenvector Centrality – Evaluating and Ranking Factor Connectivity

In our system maps, we can visually compare and contrast the interaction between factors for different hazard contexts. With eigenvector centrality scores we can systematically and quantitatively identify which factors are the most highly connected. In Figure 3-4 we show the ranking of the factors' connectedness within their respective systems based on their weighted eigenvector centrality scores. In this figure the initial colour gradient was set from the factor rankings in the aggregate system and factor colours were carried through to the other climate migration system contexts to show a comparison on how ranking shifts.

Rank	Aggregated (n=32)	Sea level rise (n=9)	Droughts (n=6)	Flooding (n=6)	Erosion (n=5)	Rank
1	Livelihoods	Livelihoods	Livelihoods	Livelihoods	Livelihoods	1
2	Health	Food Security	Financial Capital	Health	Health	2
3	Food Security	Health	Food Security	Food Security	Migration	3
4	Financial Capital	Social Capital	Health	Political Stability	Food Security	4
5	Migration	Financial Capital	Resource Security	Resource Security	Financial Capital	5
6	Political Stability	Political Stability	Migration	Financial Capital	Resource Security	6
7	Social Capital	Resource Security	Political Stability	Social Capital	Social Capital	7
8	Resource Security	Migration	Social Capital	Migration	Social Services	8
9	Social Services	Physical Infrastructure	Social Services	Social Services	Physical Infrastructure	9
10	Physical Infrastructure	Social Services	Physical Infrastructure	Physical Infrastructure	Political Stability	10

Figure 3-4 Eigenvector centrality ranking of climate migration systems

Figure 3-4 shows that *livelihoods*, *health*, and *food security* are consistently among the most connected factors throughout all five climate migration systems. Other notable factors are *social capital*, *financial capital*, *migration*, and *political stability* which increase in connectivity depending on the hazard context. *Social capital* ranked as seventh in the aggregated scores and hovers around this position in drought, flooding, and erosion contexts. In scenarios of sea level rise, however, *social capital* has an upward shift in rank to fourth. From literature and expert comments, it is unclear why *social capital* is more highly connected in this hazard context and is perhaps an avenue for future studies. *Financial capital* shows highest centrality in the context of drought. Much research centred on migration relating to drought has a strong focus on the impacts to agriculture and other water sensitive livelihoods likely explaining this shift (Missirian & Schlenker, 2017; Nawrotzki et al., 2013; van der Geest et al., 2020). Lastly, we found that *political stability* shows a high interconnectivity in the context of flooding. This shows that experts perceive *political stability* as a more central factor to affecting (im)mobility in scenarios of flooding than other

hazards. As a factor, *migration* is ranked highest in the context of erosion meaning it is highly connected within that system. *Migration*'s high connectivity has two possible explanations: (1) that singular factors are more likely to catalyse migration compared to other hazards that may require multiple compounding factors to reach a migration tipping point or (2) migration is likely to cause direct impacts.

3.4.1.3. Influence Maps – Characterising Factor Roles

To better understand the connectivity scores and characterise factors' roles, we mapped their relative dependence and influence in each climate migration system. Weighted summations of pairwise strength, as perceived by the surveyed experts, were used to generate normalised dependence and influence scores which were plotted as circles on an influence map. Starting with the aggregated data for each factor (circle outlined in black), we can see how the factors' dependence and influence shift per hazard context (Figure 3-5).

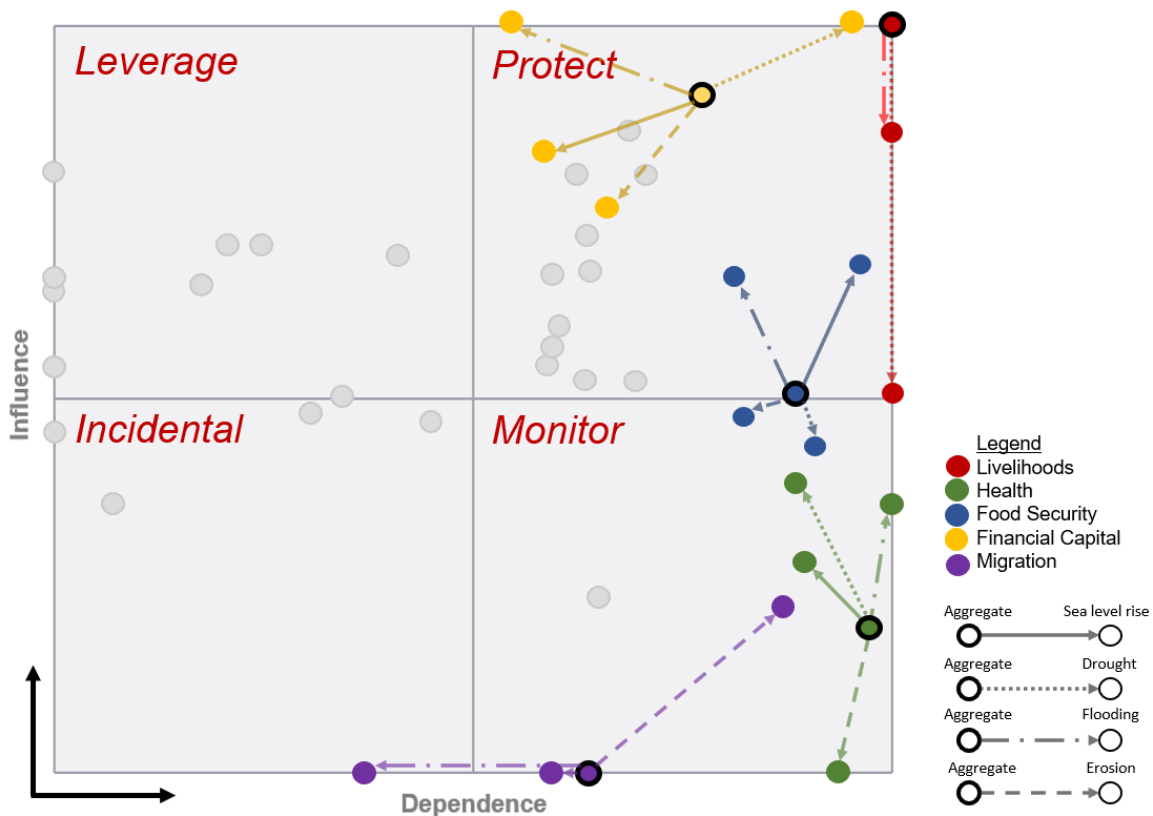


Figure 3-5 Climate migration system influence map within four hazards contexts

In this map, we show the top five factors as ranked by the eigenvector centrality scores in the aggregated climate migration system results. These factors and their respective eigenvector centrality scores were *livelihoods* (1.00), *health* (0.98), *food security* (0.93), *financial capital* (0.87), and *migration* (0.79). Beginning with the aggregated climate migration system, we can see that three of the top factors are contained within the top right quadrant. These factors display high levels of dependence and influence in the system, meaning that they may be easily perturbed and influenced by other factors, in turn causing

significant ripples across the other factors in the system. This makes these factors highly dynamic and potentially volatile. In contrast, *migration* and *health* are located in Quadrant III and can be thought of as outcome factors. This implies that changes in other factors greatly affect whether an individual may migrate, but *migration* does not have a significant effect on how the other factors change after migration. We note that it is unclear whether this is a true representation or an indication that there is not a strong research focus on the consequences climate migration.

The dependence of *health* on other factors is well noted in literature, such as the relationship of *food security* on *health* (Carney & Krause, 2020; Rakib et al., 2019). Experts also shared examples of *health*'s high dependency saying, "The social gradient of health means that people with better financial capital/higher SES have better health. The opposite is also true - low SES generally associated with poorer health" and "Social capital is considered a social determinant of health. As social capital increases, generally, so does health." However, there is relatively little mention of how changes in *health* affect other factors in climate migration literature nor is there any strong influencing relationships identified by experts.

Figure 3-5 is also a useful visualisation to consider how the role of factors shifts in different hazard contexts. For example, we see that in the context of drought, *livelihoods* becomes less volatile and more of an outcome factor. We also see *financial capital* become less dependent and more stable in all hazards except drought. *Migration* experiences a similar shift in decreased dependency in all hazards except erosion. Evaluating the shifts in factor roles is an important strategy for determining prioritisation of interventions between different hazard contexts.

As these examples show, a highly connected factor may not necessarily be an ideal leverage point for policy makers looking to affect the climate migration system. To find factors suitable for adjustments, we look to Quadrant 1 in the upper-left of the map. As shared in Figure 3-2, factors located in Quadrant 1 display high influence over other factors in the system with minimal influence from other factors. These qualities make them ideal for policy makers looking to make changes to the system. In Figure 3-6 we present the leverage points (from Quadrant 1) for each hazard system and tie together our results. Using the system maps of each hazard, we highlight the leverage factors that policy makers should target in each system. We also highlight the pathways leading to and from the leverage points to determine which factors would be next affected if leverage factors were targeted. We see that *physical infrastructure* is identified as a leverage point in many of the systems, as well as *social services*, *social capital*, and *political stability*. Notably, the sea level rise climate migration system did not produce any leverage points. The lack of leverage points does not indicate the absence of potential interventions, but rather that interventions should reflect a constellation of policy actions, targeting multiple factors in tandem. As a highly complex system, there is a need for deeper understanding into the interactions between factors in the context of sea level rise.

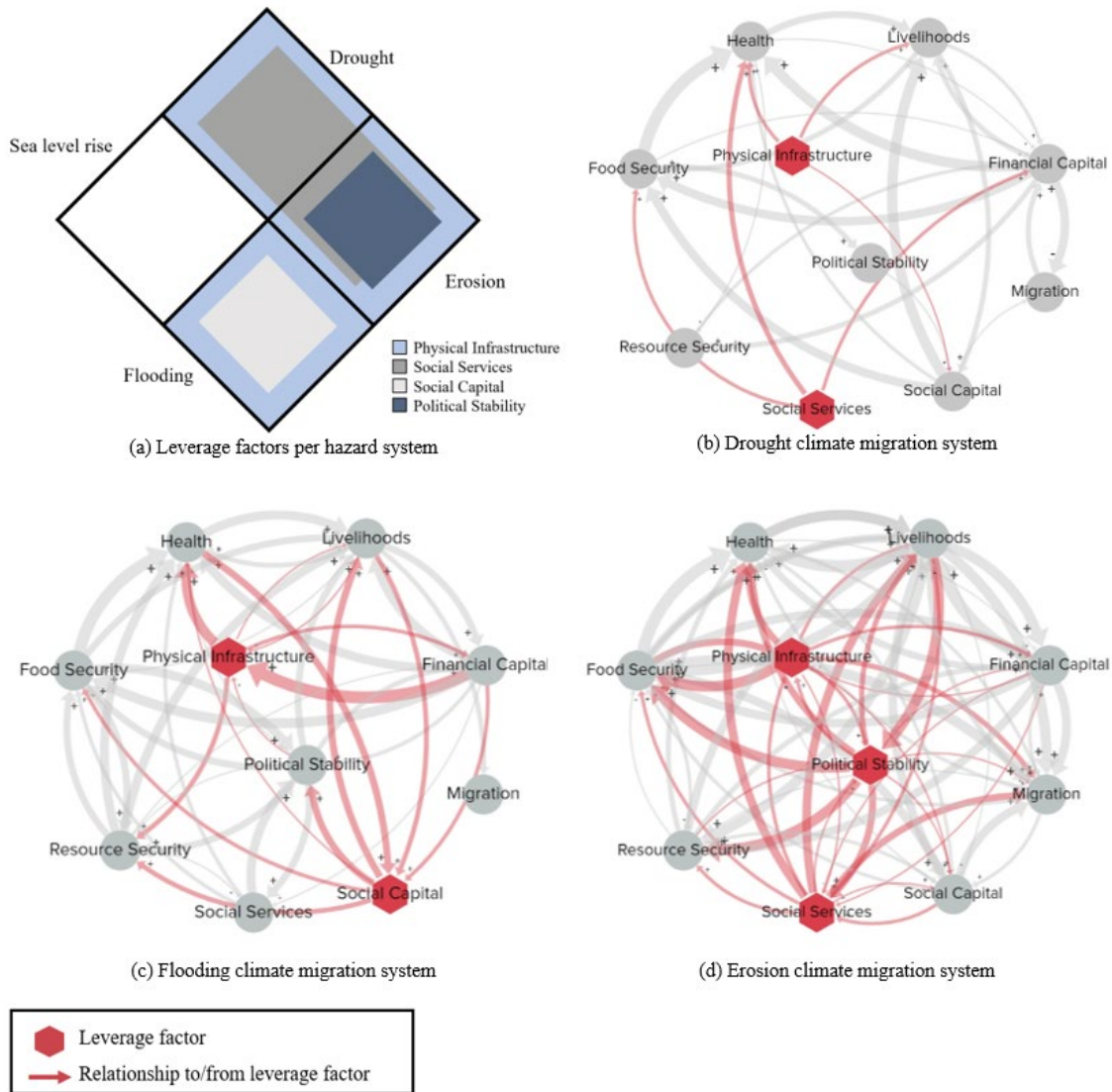


Figure 3-6 System maps with highlighted leverage points and relationships per hazard

We additionally recommend prioritising leverage points with pathways leading to highly influential factors (top two quadrants in Figure 3-5) so that we can create the greatest impact on *migration* (outcome variable in Figure 3-5). For example, in the context of drought we see that *social services* can lead to increases in *livelihoods*, leading to an increase in *food security*, and a decrease in *migration*. Practically, this can be seen in real cases such as the Philippine government’s distribution of rice seedlings to increase agricultural livelihoods and thus food security (Gomez, 2022). While realistically *food security* does not prevent *migration*, it creates a lower likelihood than situations of food insecurity.

In each climate migration system, all leverage points have a positive (+) causal relationship with effected factors, and each are linked with at least one highly influential factor to create widespread impact through the system. We posit that these characteristics make *physical infrastructure*, *social services*, *social capital*, and *political stability* appropriate targets for policy interventions.

3.4.2. Local Experts' Mental Models

The following sections show the results of the participatory systems mapping workshop with local experts in Kiribati. Discussions with local experts began initially with scoping discussions to determine the relevancy of the problem and identified habitability factors to residents in Kiribati, while also ranking the importance of the factors. Resulting from these scoping discussions, factors used in the subsequent participatory system mapping workshop differed from those assessed in the online survey by academic experts. The results of the participants' ranking of habitability priorities in the scoping discussions are shown in Table 3-2. The top factors show what is needed for Kiribati to maintain habitability, or in some cases what would lead to uninhabitability if missing. Unranked factors do not necessarily denote lack of necessity for habitability, only that participants did not view it as an issue for Kiribati (e.g. *security, political stability, social equality*). Though definitions were provided to create a shared understanding among participants, some factors were understood and discussed in a way different to the original definition. Notes taken during workshop discussions provided details on how factors were interpreted, and subsequent factor name use was changed to reflect the interpretation. In particular, *community* was interpreted as the quantity of people living in an area, rather than the social ties, and was re-termed as *population*. Discussions on *resource security* focused primarily on water and was re-termed as *water availability*.

Table 3-2 Ranking of habitability factors from interviews with local experts

Rank	Factor	Definition	Score [^]
1	Land	Physical land in Kiribati (also relates to the emotional and social ties to land, culture, and society)*	16
2	Resource Availability	Availability of natural resources (usually referenced as water availability)*	15
3	Environmental Degradation	Quality of air, soil, or water getting worse (usually referenced as water becoming salinised or otherwise unusable for drinking or washing)*	14
4	Transport (Road, Wharf)	Transportation infrastructure was specifically pulled out from 'Physical Infrastructure' in the initial factor list*	13
5	Social Services	Most participants viewed social services primarily as education opportunities and access to health care*	12
6	Food Security	Access to and availability of food to maintain health	8
7	Cost of Living	Cost of rent/housing, regular food costs, household expenses	7
8	Community	In the factor rankings, community referred to the social networks between family, friends, etc.. In the focus group, community was interpreted as quantity of people (population)*	6
9	Utilities (energy, telecommunications)	Utilities were specifically pulled out from 'Physical Infrastructure' in the initial factor list*	3
10	Future Safety	Perception of Kiribati's future habitability*	3
11	Livelihoods	Income-generating activities; jobs	3
12	Remittances	Money sent from overseas	3
13	Health	Physical and mental health	2
-	Aid Programs	Programs that offer monetary or in-kind assistance	0

-	Assets	Physical things that are owned and worth money	0
-	Security	Safety from unlawful activity	0
-	Physical Infrastructure (shelter)	Houses and residences	0
-	Political Stability	Stable political system, lack of political conflict	0
-	Social Equality	Even distribution of resources in society	0

*factor definition revised (from initial definition in Appendix I) to match interpretation of participants

^scoring is the summation of scoping discussion participants' (n=7) rankings where top priority factors (Rank 1) were given a score of 5, 4 for Rank 2, 3 for Rank 3, 2 for Rank 4, 1 for Rank 5 choices, and 0 for unselected choices

3.4.2.1. System Maps – Evaluating Factor Relationships

The system map of the local experts' combined mental model is shown in Figure 3-7. The network density of the local experts' system map was calculated to be 44%, meaning that nearly half of the potential relationships in the system were identified as “Strong”. This density result is higher than the network density of the aggregated system from the academic experts (18%) and in the middle among systems disaggregated by hazard type (77% for erosion, 49% for flooding, 30% for drought, and 23% for sea level rise).

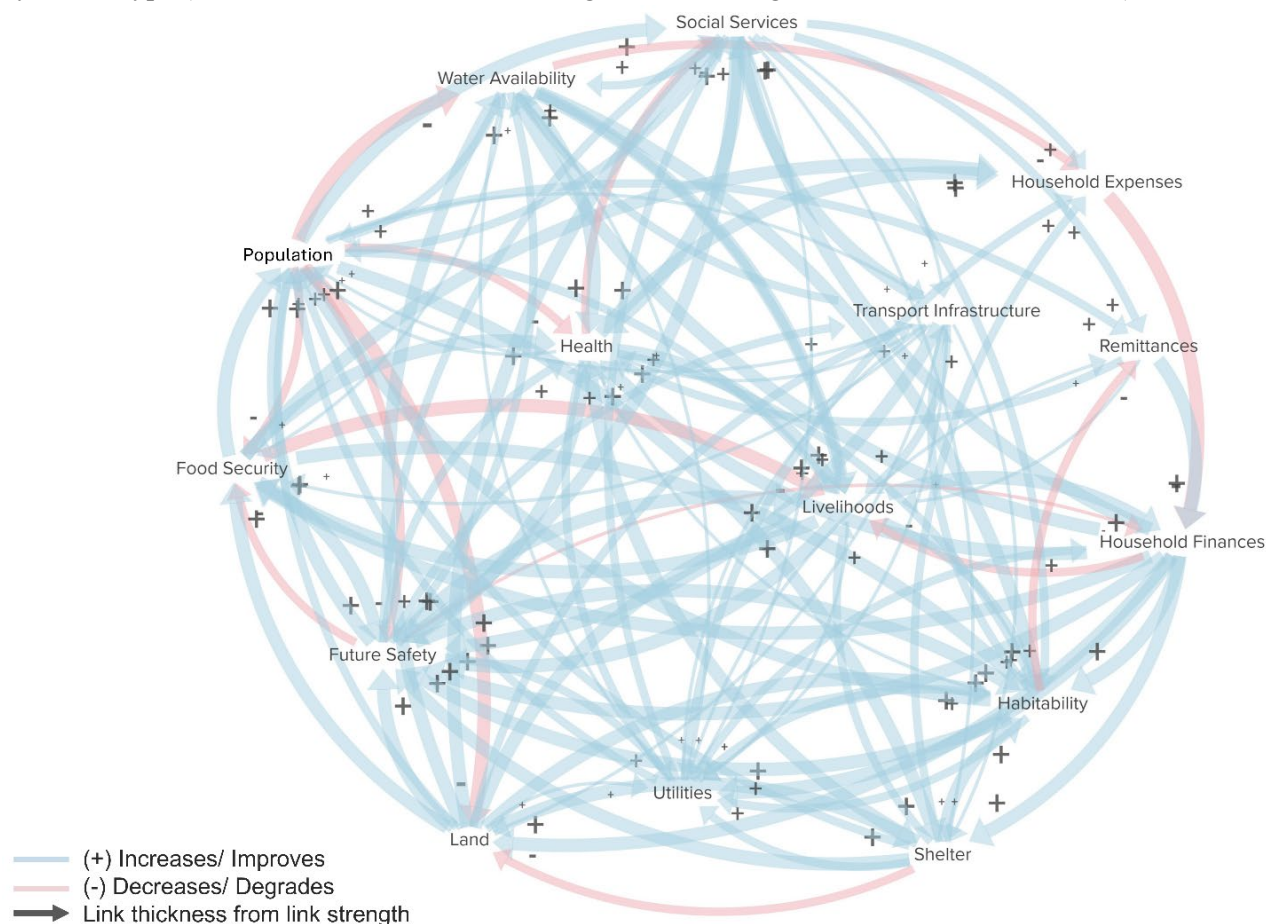


Figure 3-7 System map from participatory systems mapping workshop

One point to highlight from this map is the negative effects stemming from *population* (previously named ‘Community’). In the workshop, notes from the exercise indicate that *population* was conceptualised as an amount of people, rather than a social concept of community. When evaluating relationships, participants discussed the consequences of continued population growth leading to a loss of *land, water availability, food security, health, and future security*. As one group noted when discussing *future security*, “More people within a limited space would mean a dire future if the population grows over time”. Another significant relationship from this map is the negative relationship between *financial capital* and *livelihood* where participants shared, “We won’t need jobs if we already got money in our hands”. This insight points to the importance of remittances and other non-livelihood-based income as determinants in people’s interest to work.

3.4.2.2. Eigenvector Centrality – Evaluating and Ranking Factor Connectivity

The factors from the participatory systems mapping workshop were ranked according to their eigenvector centrality scores to identify the most highly connected factors in the system (Figure 3-8). *Future safety* ranked as the most highly connected factor in the system indicating that there many factors that affect whether the participants would view Kiribati as a safe place to stay in the future and that their perceptions of future safety influence decisions that they make now. On the other end, *land* was ranked as having the lowest connectivity in the system. However, a low ranking does not mean that *land* is unimportant in the system. As eigenvector centrality scores are calculated from both a combination of the factor’s influence and dependence on other factors, a lack of either can affect the ranking. *Land*, for example, was discussed as influencing a multitude of other factors in the system but actions from other factors do not often affect *land*. In the next section, we will break down the influence and dependence of each factor to better understand their roles in the system.

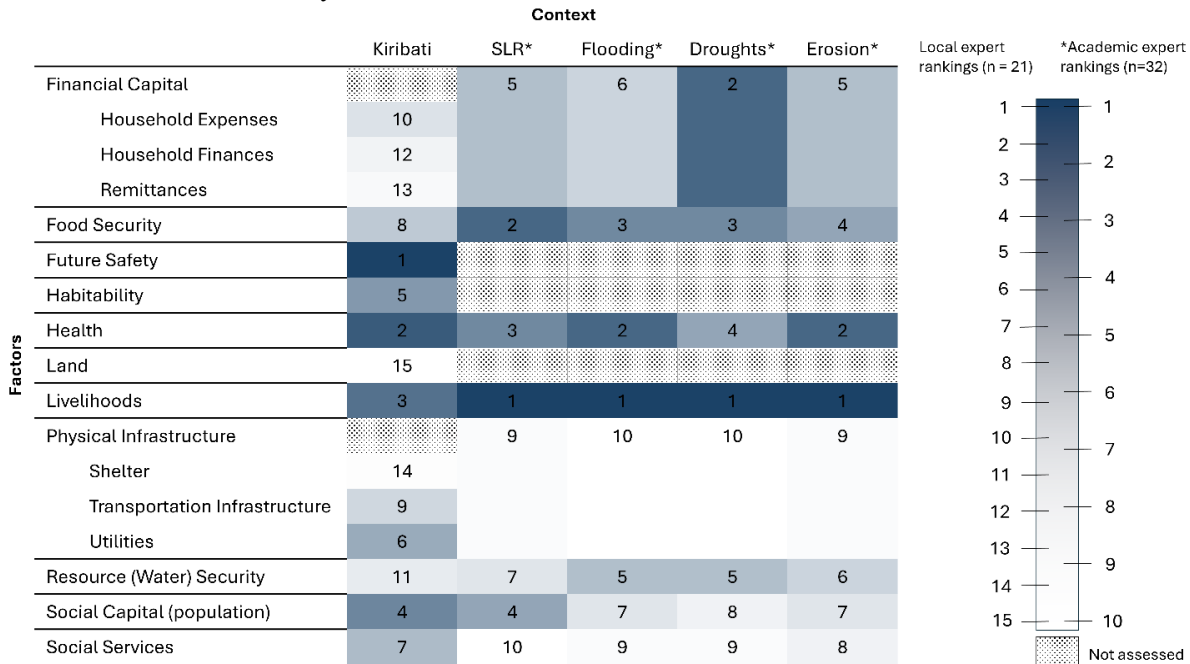


Figure 3-8 Eigenvector centrality ranking of habitability factors from local expert workshop compared to rankings from academic expert survey. Variables not assessed for each group marked with black.

In comparing the results of the local participatory workshop and the global online survey, we found similarities and variances in factor eigenvector rankings. In all academic expert hazard systems, *livelihoods* was identified as a top factor in the system. While not the top factor for local experts, it is still highly ranked. There is also similarity between expert sets for *health*, which was consistently ranked as a highly connected factor. Points of difference include the perceived connectivity of factors like *financial capital*, *food security*, and *resource security*, which were ranked lower for local experts. Low connectivity does not indicate low importance in the system, only that participants may have perceived them as out of their control of change, or as less influential in the system. These perceptions are explored further in Section 4.2.3.

3.4.2.3. Influence Maps – Characterising Factor Roles

Using the normalised strength scores collected from the workshop, the factors were plotted on an influence map to determine the factor roles in the system (Figure 3-9). The most volatile factors in the system are population and future safety (Quadrant II). Both factors have high levels of influence and dependence, meaning that many things may affect Kiribati’s population size and perceptions of safety in the future. In contrast to future safety, which reflects people’s perceptions of their future ability to live safely in Kiribati (specifically in the context of climate change), the factor habitability is conceptualised as the idea of Kiribati’s current state of liveability. In the system, habitability has a similarly high dependence level as future safety, but lower influence over other factors. This result shows that people’s decisions to adapt or act now may be influenced by their perceptions of how much potential there is remaining to sustain or improve their areas of residence.

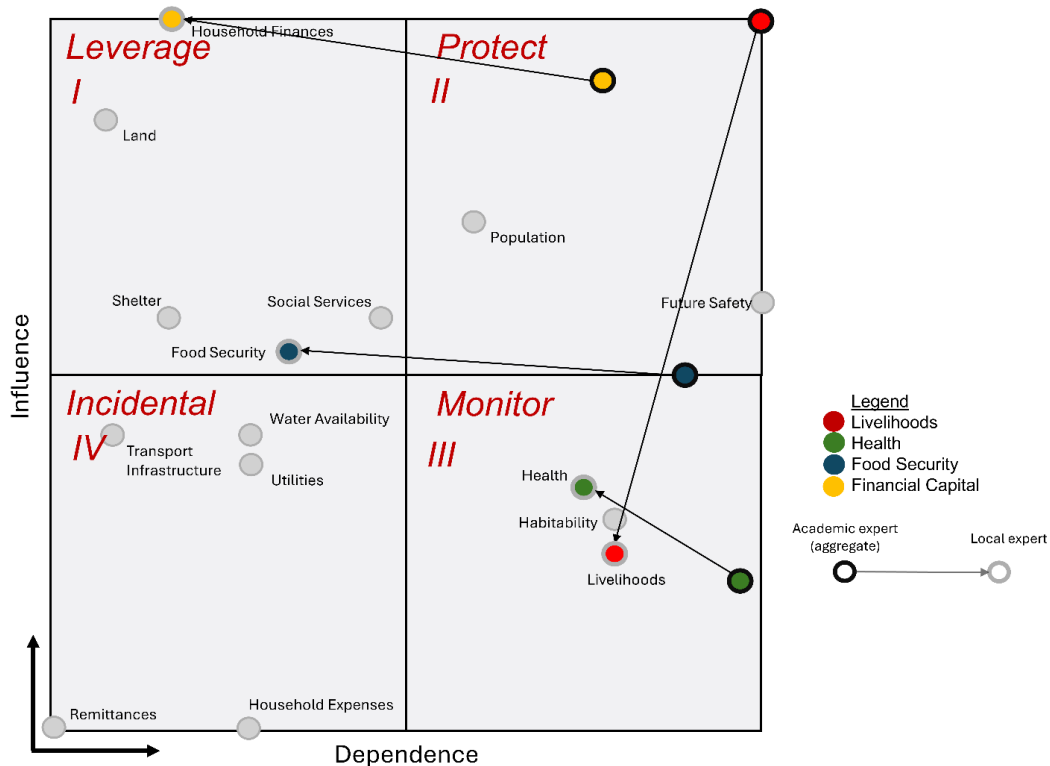


Figure 3-9 Influence map comparing mental models of local and academic experts

Outcome variables (Quadrant III) are *health, livelihoods, and habitability*. These are factors that are highly influenced by others, but when changed do not have large influence in other parts of the system. In Chapter 4, we investigate outcome variables further by analysing their respective feedback loops, mapping their relationships with other factors. Variables in Quadrant I are referred to as target variables, or leverage points, showing low levels of dependency and high influence. These variables are ideal to target when creating leverage in the system because it is easier to isolate and control what is affecting it while also having a high impact throughout the system. Leverage factors identified from the local results are *household finances, land, shelter, social services, and food security*.

In comparing the mental models of the academic and local experts, we selected the same top factors as Figure 3-5 to highlight. In all four highlighted factors, there is a shift in perceptions between the expert groups where local experts tended to view the factors as less dependent and slightly more influential, except for *livelihoods*. In the example of *food security*, this factor has a marked high dependence rating among academic experts and mid-to-low level dependence among local experts. In the context of South Tarawa, where we conducted the system mapping workshop, a large portion of food is imported, explaining why they do not perceive as many factors as influencing the food availability. This difference shows how gathering information and mental models from a local context can enable the development of a deeper understanding of a system, offering salient insights that are specifically suited to that context.

3.4.3. Implications and Limitations

Our findings from the academic experts' analysis expand the current knowledge of causal relationships within climate migration without suggesting their preferred use in either encouraging migration or supporting in situ adaptation. Policy planning for climate-affected populations should always be made in consultation with those affected, as highlighted by the differences between system structure between expert sets.

We recognise the view of climate migration as an adaptation strategy and present these leverage points as strategies that governments can pursue to ease the transition of movement. For example, investments in the leverage point, *physical infrastructure*, in destination locations is a critical need as population sizes grow (Kelman et al., 2019). Many scholars share cases of the inability of infrastructure in destination locations to support incoming flows leading to housing crises (McLeman, 2018) and deleterious health outcomes (Haque et al., 2020; Schwerdtle et al., 2021), among other consequences. Likewise, increasing *social services* such as government agriculture assistance during drought has been found to affect the number of migrants (Whitley et al., 2018).

On the other hand, we also acknowledge that continued habitation of home and ancestral lands is often a preferred option for climate-affected populations (Constable, 2017; Dreier & Sow, 2015; Zickgraf, 2019) and the encouragement of migration as adaptation unjustly shifts the burden of adapting to climate change on individuals rather than the government actors at fault (Baldwin, 2014; Bettini, 2014; Sakdapolrak et al., 2016). These leverage points can also be adapted to in situ adaptation strategies such as investing in *physical infrastructure* to mitigate the effects of climate change. Efforts to build social cohesion and community may also increase climate resiliency, as demonstrated in previous research that shows increased intergroup cooperation and generosity during hazards (De Juan & Hänze, 2021).

Kiribati is an example of such a place where climate migration is viewed as a last resort option, and for some not an option at all. As the selected case study for future research, it was imperative to supplement the data of academic experts' mental models with the localised mental models of experts in the Kiribati context. The differences between the academic experts' system and that of the local experts highlights the importance of contextualising research for specific localities using the mental models of those with lived experience in the system. By better understanding the underlying structure of the Kiribati-specific system, we can build a quantitative system dynamics model (stock-and-flow simulation model, SFS Model) to analyse the subsequent behaviour over time.

Although this research provides valuable insights into the causal relationships with climate migration and habitability systems, we acknowledge several limitations. While our survey responses reached a notable variety of experts, the number of non-responses points to a large number of perspectives still missing. To reach a convergence on the truest representation of a climate migration system, the ideal contributors would be from a diverse range of technical and geographical expertise. The climate migration systems produced from the online survey were primarily built from the mental models of academic experts from high-income countries. The predominance of responses from high-income countries suggests that their perspectives may be shaped by, at best, experience from fieldwork, rather than the lived experience of someone from the area of study. Survey results from respondents with lived experience would have provided deeper insights into the relationships in question.

This geographic skew of respondents is likely because the invited participants were from the authorship list of Chapter 2's systematic literature review. Authors from the low- and middle-income countries are historically underrepresented in environmental migration research (Piguet et al., 2018). In the future, perspectives from low- and middle-income countries should be explicitly sought to strengthen the accuracy of globally oriented migration systems. Furthermore, to elevate the climate systems models from convergence of experts' mental models to a consensus on factors, factor interactions and interaction strengths, we recommend an iterative feedback approach such as the Delphi method conducted either remotely or within a focus group format.

We also acknowledge the limitations associated with insights produced from generalised climate migration systems. Even with the disaggregation of expert responses by hazard experience we still lack the nuance that geography and culture add to each unique climate-affected community. While the most reliable method for ascertaining the truest representation of an area's climate migration system is through a detailed case study specific to that site, we posit that there is still a theory-building benefit to a generalised view of the collective climate migration system and hazard specific climate migration systems. The further contextualisation of factors through a participatory systems mapping workshop in Kiribati did help to address this concern, though a similar limitation still exists in that local experts were recruited only from the capital, South Tarawa. We acknowledge that there is significant regional nuance between the urban centre of South Tarawa and other outer islands that could have been better captured with a more diverse participation across regions in Kiribati.

3.5. Conclusion

In this study we answer the questions of how climate migration factors interact (RQ1), how these interactions change in different hazard contexts (RQ2), and how system structure changes between global and local perspectives (RQ3). While system mapping, eigenvector ranking, and dependence and influence maps show factors' relationship to climate migration, it is the use of all three methods in tandem that best inform understanding of complex systems. Working together, we used the system mapping to visualise causal relationships through individual linkages and as an entire system, the eigenvector centrality rankings to determine the most connected factors, and the influence maps to characterise the roles of factors in hazard-specific climate migration systems.

Our findings from the analysis of academic experts' mental models identify *physical infrastructure*, *social services*, *social capital*, and *political stability* as intervention points when looking to increase the resiliency in drought, flooding, and erosion climate migration systems. These recommended target factors have positive causal relationships with *livelihoods*, *health*, and *food security*, factors which were found to be the most highly connected with the aggregated climate migration system. As such, targeting the identified leverage points will elicit positive cascading effects through the whole system. These effects can be forecasted through the causal relationships shown in our system maps (Figure 3-6). We also highlight the sea level rise climate migration system as high complex and interconnected where further research is needed to determine best strategies for intervention.

The impacts of climate change will be felt differently across the globe, down to the most granular scale depending on individual and household vulnerabilities and capabilities, and finer scale contextualisation is necessary to better understand the nuance of each localised system. In the analysis of local experts' mental model, we aimed to better contextualise understanding of climate change's impact in Kiribati through targeted scoping discussions and a participatory system mapping workshop. Results from a group developed system map lays the groundwork for future analysis of the climate socio-environmental system in Kiribati using quantitative system dynamics modelling.

By presenting results formed from the convergence of multiple experts' mental models of climate migration systems, we capture a more accurate representation of reality than could be created through the lens of an individual expert. The differences between the two expert sets also highlights the importance of engaging with local experts and stakeholders when developing an understanding of a system. Our findings, rooted in systems thinking approaches, contribute to the growing body of work which seek to better understand the dynamic interactions between factors influencing climate migration and habitability.

Chapter 4

*Methodology for
stock and flow simulation model*

“The future can’t be predicted, but it can be envisioned and brought lovingly into being. Systems can’t be controlled, but they can be designed and redesigned. We can’t surge forward with certainty into a world of no surprises, but we can expect surprises and learn from them and even profit from them. We can’t impose our will upon a system. We can listen to what the system tells us, and discover how its properties and our values can work together to bring forth something much better than could ever be produced by our will alone.

We can’t control systems or figure them out. But we can dance with them!”

Donella Meadows

4.1. Introduction

In this chapter, we present the methods for the development of our system dynamics model of habitability under climate change in Kiribati, built from the theoretical frameworks in Chapter 2 and contextualised system structure and leverage points in Chapter 3. This chapter is intended as a standalone presentation of the methodology, while the next chapter presents the model results and discussion. Below, we begin with a brief background of systems thinking approaches as well as justification for using system dynamics to understand the complex problem of climate change impacts on habitability. We then present the development of the system dynamics model of habitability in Kiribati according to the standard system dynamics model building process (Hines & Lyneis, 2007; Sterman, 2000, p. 86).

In this research, a system dynamics approach was chosen to understand the interactions and feedback between climate change, Kiribati’s social-ecological system, and people’s migration decision-making as a response to shifts in habitability (Forrester, 1975; Sterman, 2000). Habitability, a location’s suitability to be lived in, is multidimensional, comprised of bio-physical and cultural factors, and subject to change over time (Gemenne et al., 2021; Merschroth et al., 2024; Stege, 2018). As such, system dynamics modelling is well-suited for understanding and modelling this complex system.

System dynamics allows for the integration of a variety of factors to understand non-linear, dynamic behaviour over time (Rich et al., 2018). It is based on the idea that understanding the structure of a system and the interacting factors will help to uncover current and future behaviour (Meadows, 2008). Rather than being a predictive forecasting tool, system dynamics’ usefulness lies in its ability to discover trends arising from system structure and is particularly valuable in policy development and scenario planning (Sterman, 2000). Moreover, systems thinking is useful in assessing long-term system behaviour, helping to avoid maladaptive short-sighted decision-making (Woodruff et al., 2018). My research thus utilised a system dynamics model to explore the complex interplay of climate change effects, habitability, and the potential for ensuant effects, such as migration, in Kiribati. The goal of this work is to inform sustainable adaptation planning by offering long-term insights into system interconnections.

4.2. System Dynamics Model Overview

The system dynamics model developed was a stock and flow simulation (SFS) model which will be referred to subsequently as the ‘SFS Model’. The model developed in this research follows Lyneis & Hines’s (2007) “The Standard Method” for system dynamics modelling. These steps are supported and supplemented with guidance from Sterman’s, “Steps of the modelling process” (2000, p. 86). The overall process and steps are detailed in Figure 4-1. While the steps are presented in a sequence, model development is an iterative process (as described in Chapter 1 – Figure 1-2).

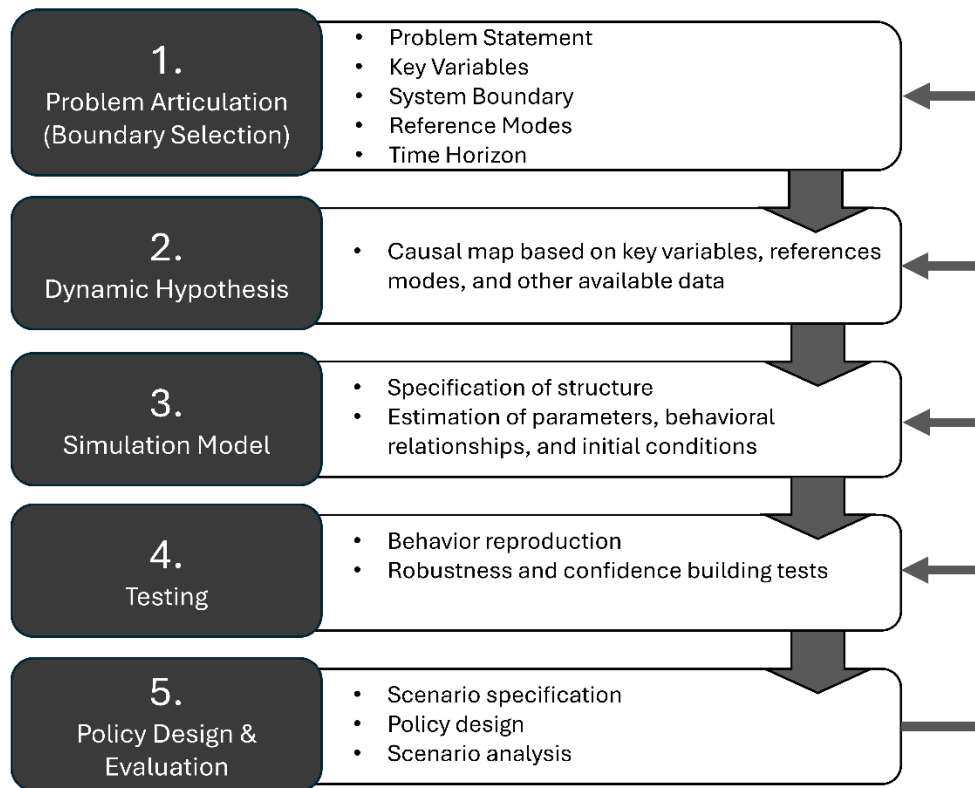


Figure 4-1 Modelling process overview, adapted from Sterman (2000) and Hines & Lyneis (2007)

The model process described in the sections below follow the structure and sequence of the steps and sub-steps shown in Figure 4-1. In this thesis, the SFS model was analysed to determine driving dynamics in the current social-ecological structure, without additional scenario analysis (Step 5 of Figure 4-1). This work does, however, provide a foundation for future research on policy design and evaluation in collaboration with local experts.

4.2.1. Problem Articulation

The future habitability of climate-affected regions is a growing point of discussion as the world continues to follow unsustainable emissions pathways. In this study, a system dynamics approach was used to operationalise habitability, as multi-faceted and affected by the combination of multiple influences

(Gemenne et al., 2021). A stock and flow model was developed to better understand the dynamics of how climate change is, and will, affect habitability in the Pacific. The purpose of this model is to investigate how the utility, as understood from the combination of multiple dimensions of habitability, of staying in or leaving Kiribati changes in light of future climate impacts. In Chapter 5, we discuss how the structure and simulated dynamics of Kiribati's social-ecological system informs future trends in habitability. The model was built with the intention of providing a base template from which national government and local community organisations can test various climate adaptation measures prior to implementation and better understand the potential dynamics of proposed policy interventions.

4.2.1.1. Problem Statement

The Intergovernmental Panel on Climate Change (IPCC) reports that Pacific atolls, such as Kiribati, are likely to experience severe impacts of climate change such as land loss, saltwater intrusion, and warming temperature (IPCC, 2022b). One study has pointed to such impacts as insurmountable and forecasts uninhabitability for atolls (Storlazzi et al., 2018). In this work, we explore the concept of habitability from a locally grounded understanding to simulate how climate change may impact Kiribati in the future.

The island of South Tarawa currently has 15.76 km² of land and the freshwater lens has an estimated yield of 2,000 m³ per day (ADB, 2021). Based on the 2020 census count for South Tarawa, this amount can supply ~32 litres (~0.03 m³) per person day for the 63,072 residents (SPC, 2022), falling short of the World Health Organization's recommendation of 50 – 100 litres of water per person per day for basic living needs. As climate-driven sea level rise impacts intensify, such as land loss and saltwater intrusion, Kiribati is likely to face increased environmental strains on these already-limited resources. We analyse these climate projections – through precipitation changes, temperature rises, and sea level rise – in conjunction with non-environmental dimensions derived from local knowledge to determine the key drivers of habitability in Kiribati over the next century.

4.2.1.2. Key Variables

To determine the variables used within the SFS model, a systematic review of literature was first conducted to identify drivers of migration decision-making globally in relation to climate change (Chapter 2; Nabong et al., 2023). Twenty-one factors were identified as contributing to people's decisions to move, often as compounding motivators. In the case of climate migration, decisions to migrate stem from residents' perceptions of their location's current and future habitability (Campbell, 2014; Gemenne & Blocher, 2017).

Farbotko and Campbell (2022) emphasise that, "habitability is culturally and socially experienced and open to multiple truth claims". To this end, initial scoping discussions with representatives from seven local climate-related non-governmental organisations were used to discuss the relevancy and nuance of the 21 factors from the systematic literature review within the context of Kiribati, as well as rank key variables for habitability in Kiribati. Please refer back to Chapter 3, Section 4.2 for more details on the ranking methodology and results. In total, 15 factors were identified from literature and confirmed by participants to be relevant to habitability in Kiribati, shown in Table 4-1. These factors were then used as discussion points in the participatory system mapping workshop.

Table 4-1 Key habitability variables identified from scoping discussions

Factor	Definition
Land	Land and property that is owned or held. This also includes emotional value associated with the land
Water Availability	Availability of clean water for drinking or use
Transport	Safe and accessible roads and wharfs
Social Services	Health services (hospitals), education services, community amenities available at the community level
Food Security	Access to and availability of food to maintain health
Household Expenses	Regular cost of rent/housing, regular food costs, etc.
Household Finances	The amount of money a household has access to (ie. Income, remittances, etc.)
Community	Family, friends, neighbours, and other social networks (understood as number of people)
Health	Physical and mental health of individuals
Utilities	Available energy and telecommunications services at the community level
Future Safety	Idea that Kiribati will be liveable for many generations
Livelihoods	Income and sustenance-generating activities; jobs
Remittances	Money sent to houses from overseas
Shelter	Houses and residences
Habitability	The quality of a place being fit to live

4.2.1.3. System Boundary

The identification of key variables in the system also helped to determine the system boundary. In Figure 4-2 the key variables have been organised by pillars as described in Duvet et al.'s (2021) Framework of Habitability Pillars for Atolls. This framework highlights five pillars of habitability for atolls islands with two exogenous system drivers of climate change and globalisation. In our model, we additionally include 'Societal Conditions' as an endogenous pillar, which were acknowledged but not explicitly analysed in the original framework. When possible, factor concepts in Table 4-1 were translated into quantifiable variables in the model. For example, *water availability* was modelled as tank water, groundwater, and desalination supply under the Freshwater Supply pillar. Others, such as *transport*, *utilities*, and *social services* were consolidated generally into *public services*. In addition to the systematic literature review and local expert knowledge, the pillars within this framework provided a third triangulation point from which to build confidence that the core aspects of habitability were brought into the model.

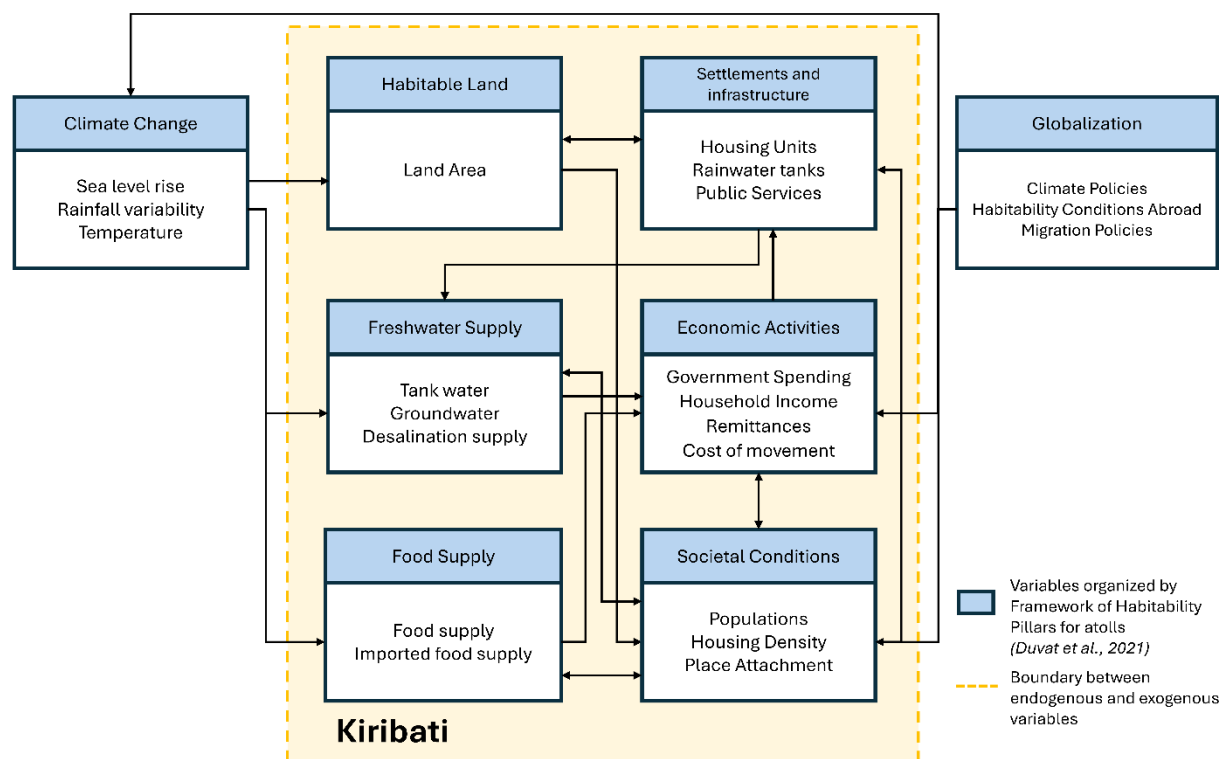


Figure 4-2 System boundary conceptualisation based on key habitability variables indicated by local stakeholders and organised into pillars from Duvat et al.'s (2021) Framework of Habitability Pillars for Atolls

4.2.1.3.1. Location Boundaries

South Tarawa is the national capital of Kiribati and home to government offices, hospital and clinics, and universities. From 1990 to 2020, South Tarawa experienced a 149% growth in population mostly stemming from high rates of internal migration. As of the 2020 Census, 52.8% of Kiribati's population resides in South Tarawa (SPC, 2022). Rapid population increase has coupled with growing climate impacts to cause poor living conditions in some parts of South Tarawa (Wyett, 2014). In highly dense urban settlements, such as Betio, a village in South Tarawa, poor water, sanitation, and hygiene (WASH) infrastructure and practices lead to high rates of infectious disease among residents (ADB, 2021). Water security issues are expected to rise due to sea level rise impacts such as overtopping and groundwater intrusion as well as increased extraction rates (Duvat et al., 2021; Post et al., 2018).

In this work, the "Outer Islands" refer to all islands in Kiribati excluding South Tarawa. With the exception of Kiritimati Island (located in the Line Islands - Figure 4-3), the outer islands are rural with characteristics of low population density and high reliance on land-based livelihoods such as agriculture, livestock rearing, fisheries, and handicrafts (SPC, 2021). The outer islands struggle with higher degrees of WASH deficiencies than South Tarawa with large amounts of the population without access to an improved water source (34.2% of rural population in Kiribati not using an improved drinking water source), 72.6% without safely managed sanitation services, and 46.8% practicing open defecation (SPC, 2022). Within the Outer Islands, Kiritimati Island is the only urban centre. While it's population size and density are still currently

low (SPC, 2022), Kiritimati Island has been identified as a development hotspot and potential resettlement path to diffuse population pressures in South Tarawa (ADB, 2010; Pacific Community, 2017).

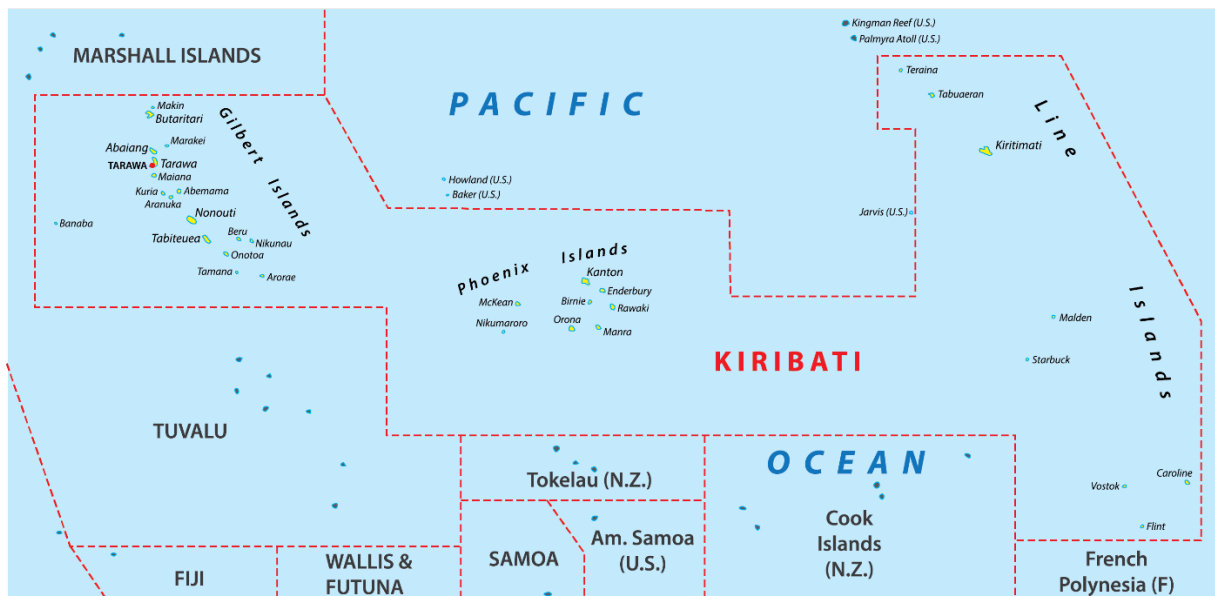


Figure 4-3 Map of Kiribati islands (Source: WorldAtlas)

Currently, outmigration remains relatively low due to limited migration pathways for I-Kiribati people (Bedford et al., 2023; Wyett, 2014). In this work, Australia was used as a representative proxy for “abroad”. Australia has been used as a destination location in previous modelling of migration from Kiribati because of established relationships between the countries (Bedford et al., 2016; Wyett, 2014).

In this research, we categorised the residential and potential destination location options as South Tarawa, the Outer Islands, and abroad. While it is recognised that there is heterogeneity amongst islands that make up the “Outer Islands”, they share a higher resemblance in their rural characteristics than to highly urbanised South Tarawa. Hennekam and Sanders (2002) similarly characterise the difference between rural and urban centres, while emphasising the need for the inclusion of interacting spatial areas. In Kiribati, and other Pacific and island states, existing histories of mobility tie together far-reaching islands and necessitate the inclusion of both areas within the system boundary (Barnett & McMichael, 2018; Farbotko et al., 2018; Kelman et al., 2019). While there are also strong mobility ties to neighbouring countries, such as Fiji, characteristics of international locations were not endogenously included in the model to instead focus more directly on the dynamics within Kiribati. The potential migration flows that are simulated in the model are shown in Figure 4-4.

4.2.1.4. Reference Modes

Following the identification of key variables, reference modes were developed independently by the research team to reflect the narratives described by participants during scoping discussions. A *reference mode* represents the observed behaviour of key variables in a system over time with bifurcation of possible pathways that are either hoped for or feared to come about (Hines & Lyneis, 2007). It captures the trends

or patterns (like growth, decline, oscillation, or stability) that a system dynamics model aims to replicate, explain, or improve upon, and serves as starting point to create a stock and flow model. In the sections below, we share reference modes arising from narratives for dynamics most frequently discussed by participants – related to issues of land, population density, and water (Figure 4-5).

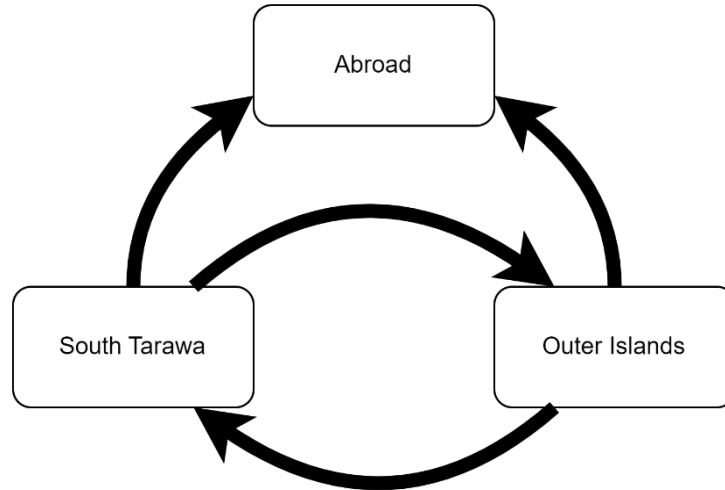


Figure 4-4 Available migration flows in the SFS Model

We also include causal loop diagrams (CLDs) of interactions driving the behaviour illustrated in each reference mode, hypothesised by the research team. These hypothesised interactions were subsequently used to conceptualise the SFS model structure, as explained in Section 2.3. Each CLD forms a sub-dynamic hypothesis that contributed to the complete dynamic hypothesis (Figure 4-7), along with causal structures identified through the participatory system mapping workshop.

4.2.1.4.1. Land Squeeze

In general, more housing units are needed to accommodate families as populations grow. The traditional housing structure of I-Kiribati homes is single story, so the footprint of land needed for each housing unit is distinct (i.e. multi-story apartment complexes are not typical). The core feedback to describe this situation is *balancing loop*, meaning that factors in the system counteract to create stable behaviour – in this case the availability of land bottlenecks the amount of people who can live in a place.

Land in Kiribati is generally titled and passed down through generations of a family. Internal migration in Kiribati is supported through strong social ties, in particular familial, throughout the country allowing people from the outer islands to move to South Tarawa and find a place with family members on ancestral land. While increasing opportunities for family members, this has also led to high population density. This is illustrated in the ‘Tight-knit families’ reinforcing feedback loop. A *reinforcing loop* is one where there are no intervening factors to limit the perpetual growth or decline of a system. In this reference mode of population, tighter living conditions bypass limits of land area, facilitating a perpetual cycle of population growth. Although crowding of residences creates a quick fix for the land squeeze restriction, a growing population strains resources on the island.

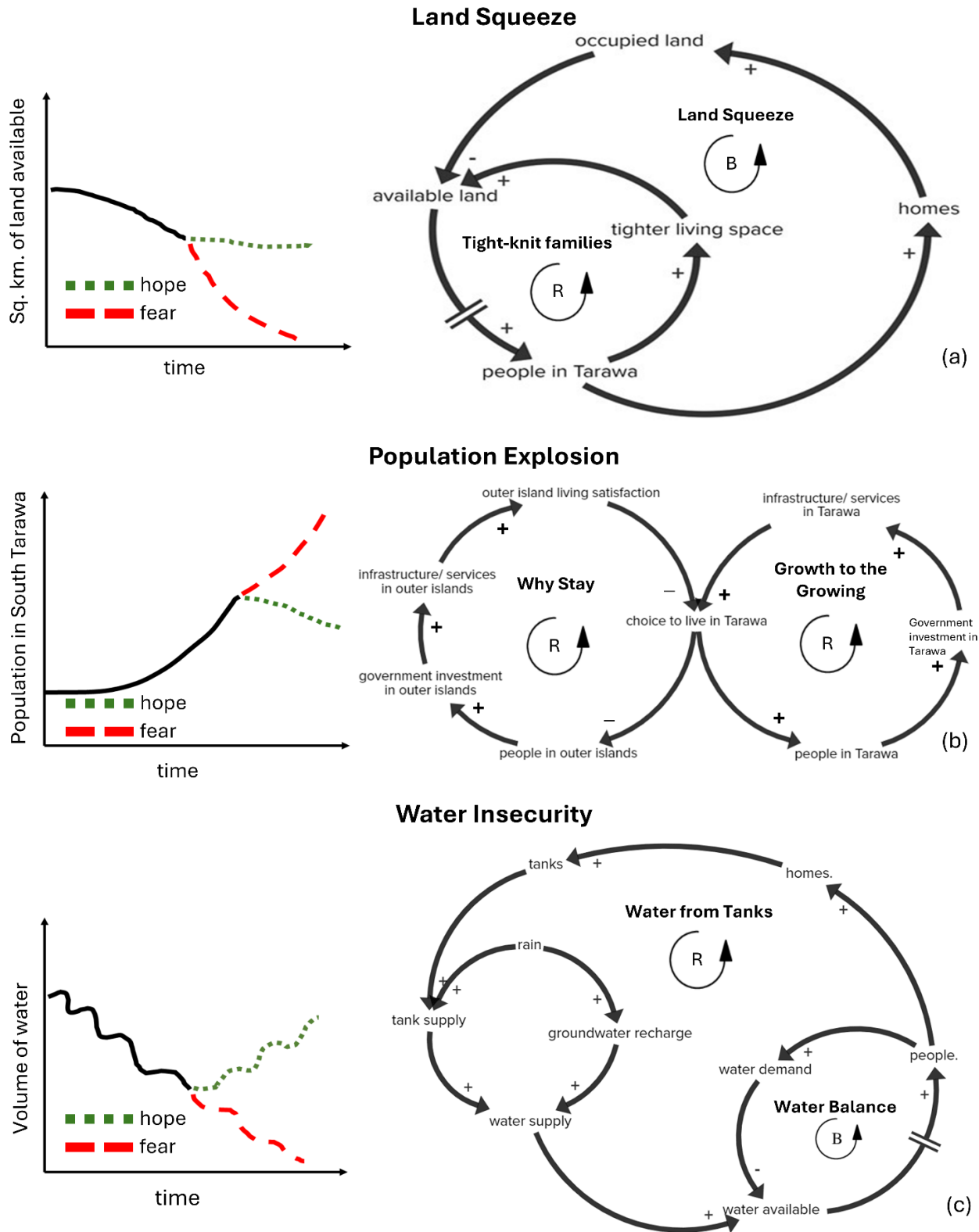


Figure 4-5 Reference modes and sub-dynamic hypothesis CLDs, a) land squeeze, b) population explosion, c) water insecurity

4.2.1.4.2. Population Explosion

The population in South Tarawa has seen massive growth in the past half century. Although climate impacts may play a factor in some emigrants' decisions to move to the capital, discussants shared that most currently come for the social services and job opportunities in South Tarawa. Health services and education opportunities are top motivating factors pulling people to the capital. Two of the country's four hospitals are located in South Tarawa and are perceived to have the highest standard of care and resources in the country. Similarly, many in Kiribati perceive the standards of education to be higher in South Tarawa. For higher education, all educational institutes and university campuses are located in Tarawa. The capital island is also home to the national government of Kiribati, the largest employer in the country.

As the population grows in South Tarawa, social services increase to meet the needs of the residents. As the social services grow, so too does the attractiveness of the island. This reinforcing loop presents a cycle similar to a "Success to the Successful" archetype where one option's success, in this case - attractiveness, leads to further investments and a continuation of success (Braun, 2002). As the government has a limited budget, the growth of the capital island is at the expense of outer island development. This lack of investment and development in other islands is hypothesised to cause the reinforcing behaviour for population.

4.2.1.4.3. Water Insecurity

The main source of water for residents in South Tarawa is from the freshwater lens (groundwater). Families are either connected to the centralised water distribution network and/or have their own wells which draw up the groundwater. Many houses also have rainwater harvesting tanks to supplement groundwater supply but comparatively do not supply much volume. The variability of seasonal rainfall was hypothesised to affect both the groundwater recharge as well as tank filling and is shown through the oscillation behaviour (Foon et al., 2006). The hypothesised downward trend of the total volume of water is caused by the insufficiency of rain to meet the water demands of a growing population. Although an increase in island population can lead to more housing and rainwater tanks, the 'Tight-knit families' feedback loop (Figure 4-5a) shows this is not always the case. As is, the water demands of a growing population are outpacing the supply available.

4.2.1.5. Time Horizon

The time horizon for the model was chosen to be 110 years, from 1990-2100. The starting year of the simulation was selected so that ~30 years of historical data could be used for calibration. While some models stop earlier (Kniveton et al., 2011; Naugle et al., 2019), the choice to extend the simulation until 2100 was made so that the potentials of in-situ adaptation strategies could be tested in an extended timeframe. The model time unit was years with a time step of half a year ($DT = 1/2$).

4.2.2. Dynamic Hypothesis

The dynamic hypothesis of Kiribati's social-ecological habitability system was developed iteratively, combining sub-dynamic hypotheses from scoping discussions with key loop structures identified in the participatory system mapping workshop. A *dynamic hypothesis* is a theorised causal explanation for why a

system behaves as it does (Hines & Lyneis, 2007). The key loop structures were identified from workshop factor characterisation results (Chapter 3).

We characterised factors in influence-dependence maps as leverage points (targets), volatile (to be protected), or outcome variables (to be monitored). In those results, *livelihoods*, *health*, and *habitability* were identified as outcome variables using influence mapping (Figure 9, Chapter 3). This means that these variables are highly dependent on the conditions of other variables in the system and highlight the key emergent outcomes of overall system behaviour. As such, the key loops of these outcome variables were selected to form the base of the casual loop structure from local experts' mental models. The key loops for each outcome variable were identified using a systematic loop identification algorithm established by Gupta and Suzumura (2021) and a loop scoring and ranking process for weighted networks developed by Gottschamer and Walters (2023). The impact matrix from the participatory system mapping workshop is included in Appendix III. With this algorithm, all possible loops which a particular variable is part of are identified, scored, and ranked based on the average product of link scores multiplied by the eigenvector centrality score for each factor in the loop. The top ranked loops for each outcome factor, along with the prime loop (i.e. the loop with the highest normalised eigenvector centrality score from combined component factors), were mapped in Figure 4-6. The approach of building key loop structures from outcome variables has been used in other loop analysis studies (Valcourt et al., 2020; Walters et al., 2024; Walters & Javernick-Will, 2015).

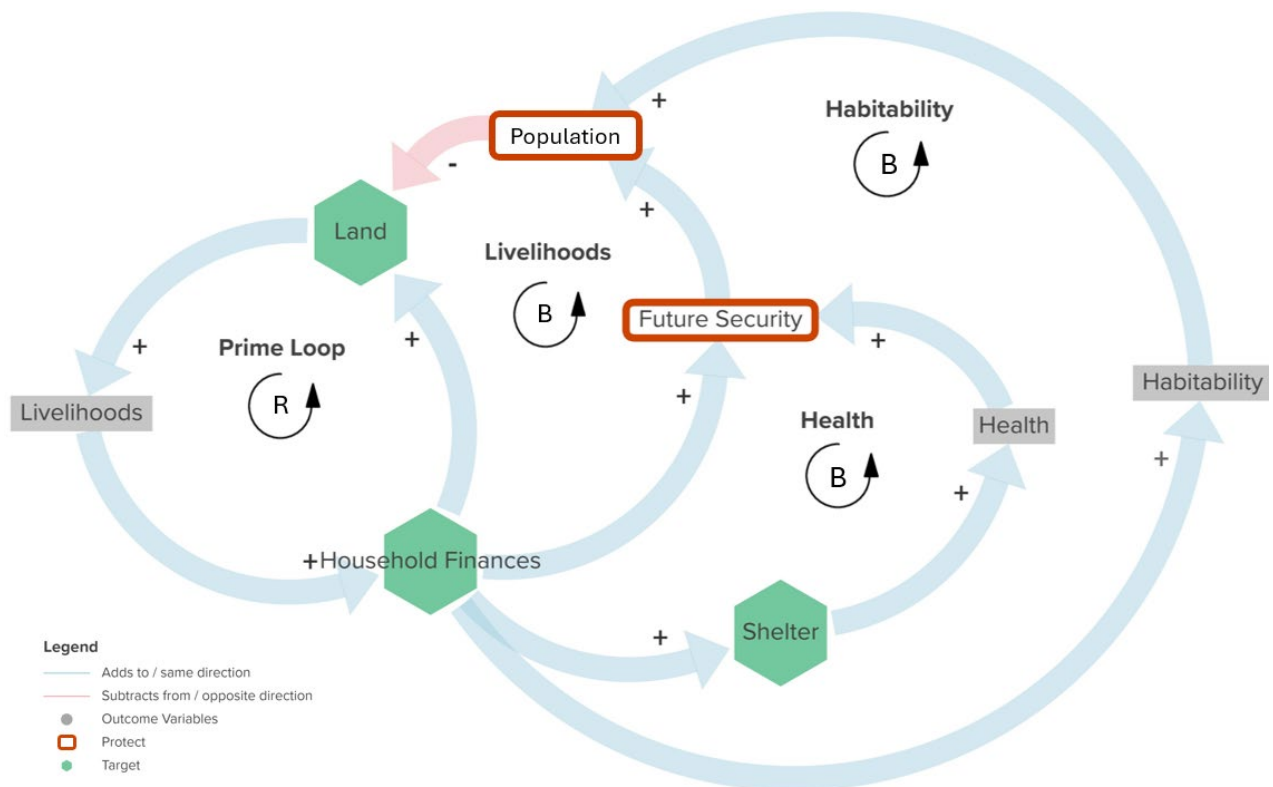


Figure 4-6 Causal loop diagram of local experts' mental models.

In Chapter 3's influence map of local experts (Figure 3-9), *household finances* had the highest levels of influence in the system. This factor can be seen as a lynchpin of the system, directly influencing the four factors of *land*, *future security*, *shelter*, and *habitability* in the CLD presented in Figure 4-6. Assuming Kiribati's demographic trend of increasing population, the availability of undeveloped *land* is expected to decrease. This will be additionally compounded by future climate impacts, such as sea level rise and heightened king tide. In this causal loop story, as the availability of *land* begins to decline, the outcome variables of *livelihoods*, *health*, and *habitability* also degrade. To combat the potential for degradation of the entire system, we look towards the leverage points, *land*, *household finances*, and *shelter*. Finding ways to bolster local economies and strengthen land area against inundation may stymie the flow-on effects of climate change and overpopulation.

The four feedback loops in Figure 4-6 in combination with the hypothesised dynamics of the three reference mode behaviours from Section 2.1.4 were used as building blocks for a complete dynamic hypothesis, structurally represented in Figure 4-7. In total, three additional feedback loops were identified after additional narrative structures were added. The reinforcing feedback loop, 'Tank Disbursement', illustrates how government investment and subsidies in water infrastructure can lead to greater water supply and affect people's choice to live in South Tarawa. The reinforcing loop, 'Land Anchor', describes how land-based financial security can root people to staying in South Tarawa while the 'Remittance Anchor' loop is balancing based on changing patterns of emigrants abroad. The feedback shown in Figure 4-7 was then used as the core structure for developing the quantitative system dynamics (SFS) model, which was used to simulate habitability dynamics in Kiribati.

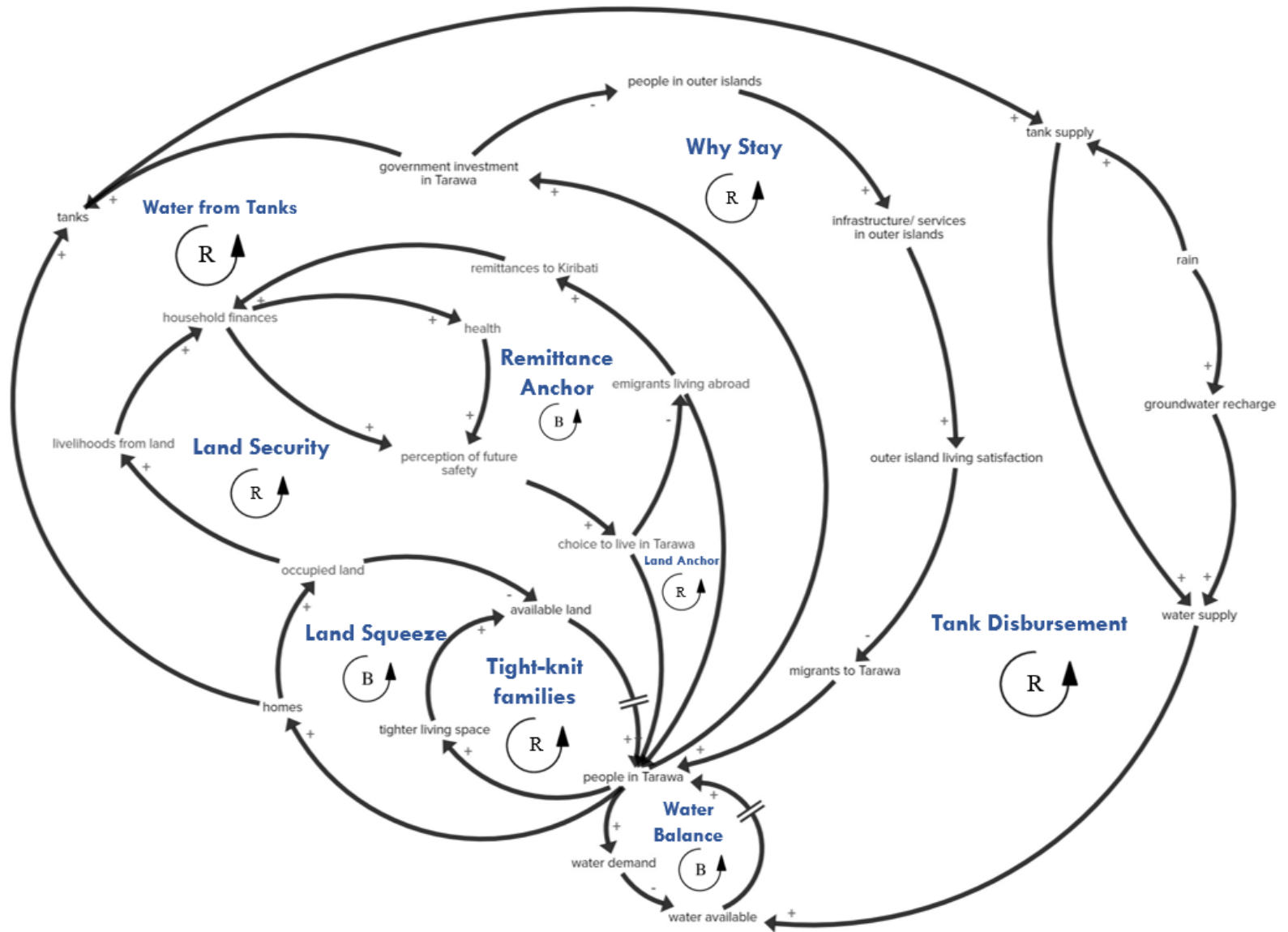


Figure 4-7 The complete dynamic hypothesis presented as a causal loop diagram.

4.2.3. Simulation Model

The stock and flow simulation (SFS) model in this chapter builds from the qualitative insights and data collected in Chapter 3 and the hypothesised causal structures from Figure 4-5 and Figure 4-6, mapped against the Framework of Habitability for Atolls by Duvat et al. (2021). In combination, these methodological steps ensured the inclusion of key concepts within the stock and flow model. The following section specifies the structure of the model by first introducing the mathematical formulas underpinning the model (i.e. utility functions) then details the habitability pillars integrated into the model. I then follow with the estimation of parameters, behavioural relationships, and initial conditions, as suggested by the standard modelling process (Hines & Lyneis, 2007; Sterman, 2000).

A summary of how each methodology steps of my thesis links and builds to the SFS Model development is shown in Figure 4-8. The SFS Model design will be detailed further in the sections following.

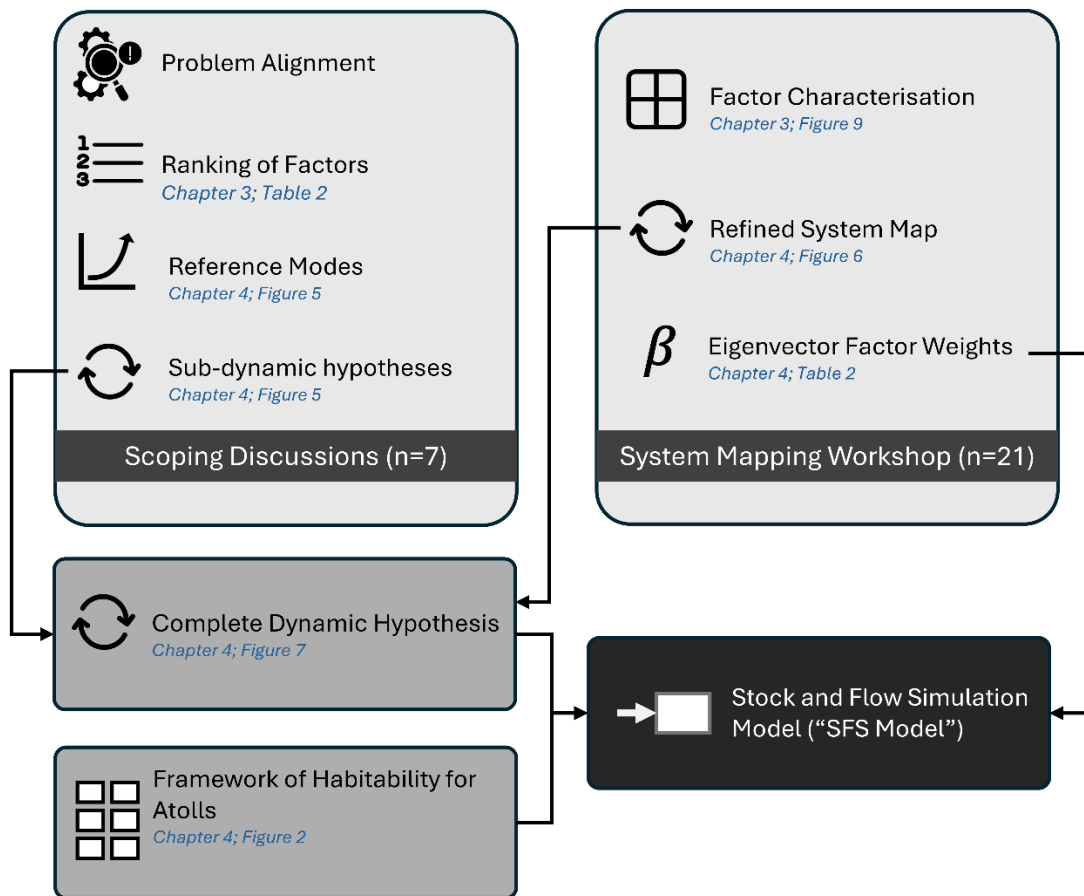


Figure 4-8 Summary of methodology links

A stock and flow model builds on a causal loop diagram (CLD) by incorporating measurable quantities (stocks) and the rates of change (flows) between them, allowing for the simulation and analysis of how a

system's behaviour unfolds and changes over time. In Figure 4-9 we provide illustrations of common iconographies used in stock and flow models. A stock, shown as a rectangle, is a variable that can accumulate (e.g. number of water tanks). The rate that a stock accumulates or diminishes are shown as input and output flows (e.g. water tanks taken out of service per year). Converters, shown as circles, have several uses including as constant values, data inputs, and functions to relate other variables in the model. Converters with dashed lines, ghost variables, were also used in the model to bring converters from other distant parts of the model closer.

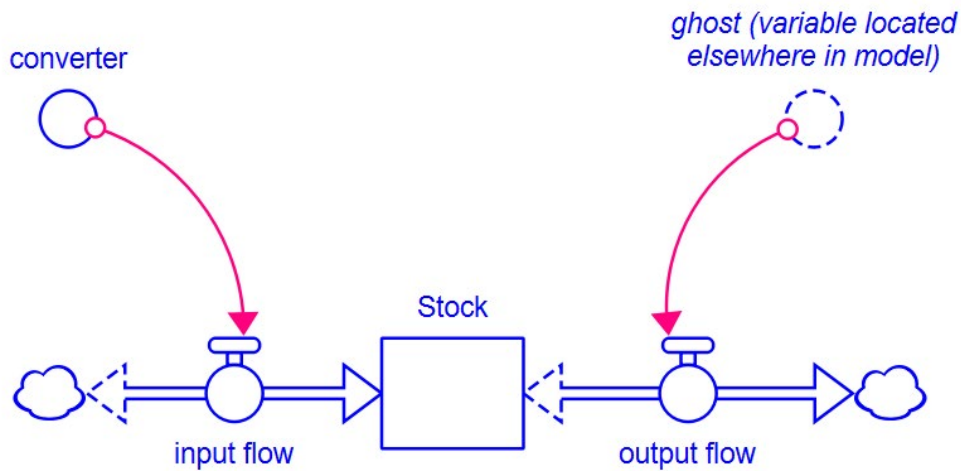


Figure 4-9 Iconography of a stock and flow model

4.2.3.1. Specification of Structure

This model aims to dynamically analyse how future climate impacts affect habitability in Kiribati. Habitability is directly assessed in the SFS model through the incorporation of utility functions, simulating a population's evaluation of their current location's attractiveness, or utility, for staying versus the utility of migrating. The utility functions are related to Duvat et al.'s (2021) Framework of Habitability Pillars for atolls where a location's utility is determined by five endogenous pillars of habitability - land, water, economics, food supply, settlements and infrastructure. Through the incorporation of climate change data and Kiribati systems knowledge from local experts, the SFS model can provide a comprehensive understanding of how these elements affect a location's long-term habitability. In the following sections, we will elaborate further on methodological choices for the incorporation of utility and push-pull theory (Lee, 1966) and the Framework of Habitability Pillars for Atolls (Duvat et al., 2021) within the SFM simulation. The full model structure is provided in Appendix IV with a [link](#) to the simulation file.

4.2.3.1.1. Place Utility and Movement

The model draws on the push-pull theory of migration (Lee, 1966). In this theory, negative and unappealing factors (e.g. crime, lack of livelihood opportunities) in a location may push residents to move somewhere else, while attractive factors in other locations (e.g. social connections, social services) may pull them towards specific destinations (de Sherbinin et al., 2022; Lee, 1966). This theory of migration is woven into

the SFS model through utility functions (Equation 1) that incorporates terms that parallel the pillars in Duvat et al.'s (2021) Framework of Habitability Pillars for atolls. The utility of a place is calculated to emulate push and pull, where positive attributes are additive and undesirable attributes are negative (Train, 1986, p. 60). While the utility function terms are all additive, negative (“push” or repel) factors arise when the ratio within the natural log is less than 1. Practically, this would happen if a person assessed a place to be less desirable than their current location. Positive terms, on the other hand, add to the utility of a region and work to “pull”, or anchor, people to desirable locations (Van Hear et al., 2018).

$$U_d = \alpha_d + \beta_1 * \ln\left(\frac{L_d}{L_i}\right) + \beta_2 * \ln\left(\frac{H_d}{H_i}\right) + \beta_3 * \ln\left(\frac{W_d}{W_i}\right) + \beta_4 * \ln\left(\frac{E_d}{E_i}\right) + \beta_5 * \ln\left(\frac{F_d}{F_i}\right) + \beta_6 * \ln\left(\frac{S_d}{S_i}\right) - C_{id} \quad (1)$$

Where:

- U = Utility of choice
- d = region evaluated
- α = baseline utility
- β_x = weighting for associated utility term
- i = initial region
- L = habitable land
- H = settlements and infrastructure
- W = freshwater supply
- E = economic activities
- F = food supply
- S = societal conditions
- C = cost of movement

The baseline utility, α , is unique to each location. This value was determined through model calibration to reference historic data for population, land area, and household density. This value captures location characteristics that were not explicitly considered in the other model variables. The term weightings, β_x , were calculated from the normalised eigenvector centrality values of each of the respective terms' link strength scores from the system map created in the local expert system mapping workshop. Eigenvector centrality was selected as the network analysis measure to evaluate factor weights due to its capacity to assess factor influence or interconnectedness from a "whole-network" perspective (Murphy & Jones, 2021). Relevant factors were consolidated into the habitability terms included in Equation 1, shown in Table 4-2 with weights.

The cost, C, represents the emotional, cultural, and monetary cost of movement between the origin location and a comparison location. As costs are often a barrier to movement (Bedford et al., 2016; Dreier & Sow, 2015; Kartiki, 2011), this term is a negative deterrence factor. The remaining terms are discussed in more detail in the following section.

The idea of utility is found in system dynamics modelling where it is conceptualised through the attractiveness principle (Forrester, 1975; Mandl, 2023). In this principle, the terms can either be multiplied

or summed depending on the inter-relatedness of the terms (Goodman, 2016). For example, if certain decision factors are considered absolute thresholds then multiplication may be a better choice. In this research, an additive function with associated term weighting was used to designate the importance of a habitability pillar to a place's overall desirability. This choice reflects our position of habitability as non-dependent on any single pillar and to allow for the weighting of pillars based on stakeholder perspectives to be better incorporated. Naugle et al. (2019) previously used this approach in a system dynamics model of climate migration in Africa. The calculated utilities for each location provided the base for the evaluating the choice between options.

Table 4-2 Habitability pillars with corresponding workshop variables ranked by eigenvector centrality

Habitability Pillars	Corresponding Workshop Variables	Pillar Weighting (normalised eigenvector centrality), β_x
Food Supply	Food Security	0.226
Economic Activities	Household Finances Livelihoods Remittances	0.266
Freshwater Supply	Water Availability	0.206
Habitable Land	Land	0.151
Settlements & Infrastructure	Shelter Utilities Transport Infrastructure	0.151

For both the South Tarawa and Outer Islands population stocks, utilities were calculated for the three options of moving abroad, moving within Kiribati, and staying in place. When the utility of staying in place was calculated (Equation 1), the comparison ratio within the natural log uses the dynamic value of the term as the numerator and the initial value (at $t=0$) as the denominator (Tidwell et al., 2015). This choice practically reflects people's likelihood to compare what they know to be the current conditions in other locations against memories of what their home locations could offer.

The utilities for each population stock were then compared using Qualitative Choice Theory (QCT) which evaluated the three options to determine the probability of undertaking each respective choice (McFadden, 1984). QCT was selected for its usefulness in comparative evaluation when options are finite, mutually exclusive, and exhaustive, as applies in this research (Train, 1986, p. 4). The probability of option selection was calculated with Equation 2 using a multinomial logit function (McFadden, 1984).

$$CP_d = \frac{EXP(U_d)}{\sum_k (EXP(U_k))} \quad (2)$$

Where:

CP = Choice Probability

U = Utility of choice

d = region in comparison

k = set of regions

The migration probability represents the fraction of each population stock that would choose that option at each quarter year timestep and was thus multiplied by the population to determine the absolute number of people moving per year. Figure 4-10 shows the system dynamics model structure where the flow (people/year) is calculated by the probabilities of moving and the population stocks.

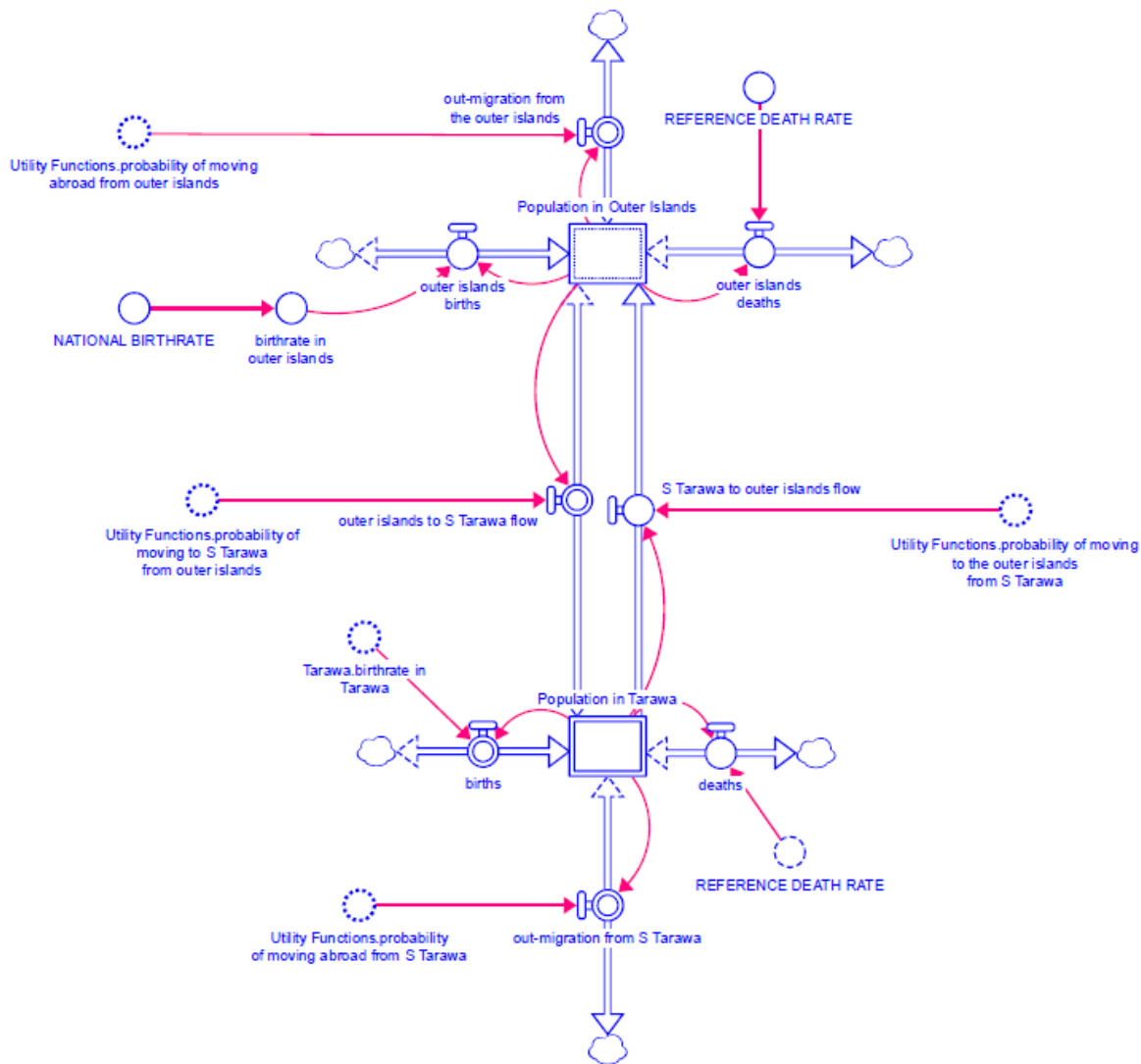


Figure 4-10 Model structure of location utilities' effect on demographics

4.2.3.1.2. Habitability Pillars

There are multiple ways of assessing habitability in a climate affected location. Historically, study of habitability and subsequent displacement centred on ideas of environmental determinism (Myers, 2002), which have since been criticised for their simplistic assumptions of hazard exposure without accounting for adaptive capacity (Milan et al., 2015). In this work, we use the definition as set by Duvat et al. (2021) who conceptualise habitability as comprised of five pillars: (1) Habitable Land, (2) Settlements and infrastructure, (3) Freshwater supply, (4) Economic activities, and (5) Food supply. Duvat’s framework also incorporates climate change and globalisation as exogenous. The following sections will provide an overview of how climate change, the pillars, and social conditions were considered and integrated into the model.

Climate Change Variables

Given the grand scope and scale of the causes of climate change, the impacts of climate change were considered as exogenous variables in the SFS model. Indeed, although human actions and mitigation decisions can influence the magnitude of climate impacts, small island nations such as Kiribati contribute little to overall climate emissions (UNDP, 2022). As such, the effects of national climate mitigation efforts were not included in this research. Similarly, policy initiatives related to climate mitigation efforts by other countries, were also chosen to be exogenous to focus more specifically on the dynamics within the country boundary of Kiribati. Climate emissions pathways were assessed however, through varying levels of climate impacts.

Differentiated impacts of climate change were integrated into the model using four shared socioeconomic pathways: SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. These pathways were selected because of their identification as top priority scenarios of analysis (O’Neill et al., 2016). Shared socioeconomic pathways (SSPs) present narratives of potential future global climate pathways based on demographic, economic trends, energy, and emissions trends, along with other development choices (Riahi et al., 2017). Narratives for each of the included SSP are shown in Table 4-3. These pathways build from previous climate projection scenarios, such as the representative concentration pathways (RCPs) to provide foresight on how current mitigation and socio-economic behaviours lead to long-term climate change trends. This allows researchers and policymakers to make informed planning choices in uncertain climate conditions.

The climate change impacts considered in this work were sea level rise, rainfall variability, and atmospheric temperature change. These impacts were selected following conversations with partners in Kiribati, as well as review of academic and grey literature, which point to these as key environmental changes in Kiribati. Projection data used for the three climate impacts were collected from NASA (Garner et al., 2021; IPCC, 2023b; Kopp et al., 2023) and World Bank’s Climate Change Knowledge Portal (IPCC, 2021), with historical sea level data from Australia’s Bureau of Meteorology (BOM, 2024). All projections used present data from Coupled Model Intercomparison Project Phase 6 (CMIP6) and are specific for Kiribati.

Table 4-3 Shared socioeconomic pathway (SSP) narratives, summarised from (O’Neill et al., 2017)

SSP 1	“Sustainability”	An optimistic pathway based on sustainable and inclusive development
SSP 2	“Middle of the Road”	A business-as-usual pathway where behaviour is similar to current and historic trends
SSP 3	“Regional Rivalry”	Nations focus on individual needs, such as energy, at the expense of others. This pathway sees little international cooperation for global climate issues
SSP 5	“Fossil-fuelled Development”	A pathway of high technological achievement driven by increased fossil fuel reliance.

Habitable Land

Land loss is a common concern of climate change impacts on small-island developing states and other coastal areas (Bellard et al., 2016; Davis et al., 2018; Finucane & Keener, 2015; Hauer, 2017; Yamamoto & Esteban, 2017). Past studies have examined how sea level rise will affect coastal processes such as erosion, flooding, and inundation and their role in the loss of habitable land and future population displacement (Jallow et al., 1996; Maldonado et al., 2013; McMichael et al., 2021; Robinson et al., 2020). Atoll islands present a unique area of study due to their highly dynamic shoreline behaviour.

Some studies and anecdotal evidence point to coastal degradation from rising sea (Barnett, 2005; Connell, 2018), while others assessing island planform have found that islands have generally experienced stability or growth in land area (Biribo & Woodroffe, 2013; Duvat, 2019; McLean & Kench, 2015; Sengupta et al., 2021; Webb & Kench, 2010). Island growth in South Tarawa, in particular, has been attributed to reclamation efforts (Duvat, 2019; Webb & Kench, 2010).

While recognising the ongoing debate of atoll growth or contraction and the need for more precise and localised data on island morphology, wind patterns, and wave condition, we use historical accretion and erosion data for Kiribati over a 30-year period as the basis for our model’s shoreline dynamics (Biribo & Woodroffe, 2013). Their study found trends of land growth in the Tarawa atoll, both with and without accounting for reclamation. However, just as we argue against environmental determinism which directly negatively affects habitability, we also note that the stability or growth of island areas alone is an unsuitable indicator of habitability (Stege, 2018). Instead, habitability stems from the complex interconnections of climate change with material (e.g. land area) and non-material (e.g. place attachment) dimensions.

This model incorporates climate-related land loss, natural accretion, and reclamation into the structure of land dynamics (Figure 4-11). Accretion and reclamation are input variables into land expansion while sea level rise related land loss is the only cause of land degradation. Land expansion used data collected from Birido & Woodroffe’s (2013) analysis of shoreline dynamics in South Tarawa and reclamation rates.

Historic reclamation rates were discontinued in the model in 2024, matching the current status of no ongoing reclamation projects.

The “Effect of sea level rise on land loss” variable is a S-shaped function which estimates the relationship between sea level rise and land loss in Kiribati. An estimation of the relationship between sea level rise and land loss was necessary due to limited topography data. The estimated relationship in this variable assumes that complete land loss will occur at three meters of sea level rise, matching with the highest elevation in South Tarawa. The rate of change in this relationship assumes that moderate sea level rise can occur with minimal impact on land, and sea level rise near three meters will have high impact until full inundation.

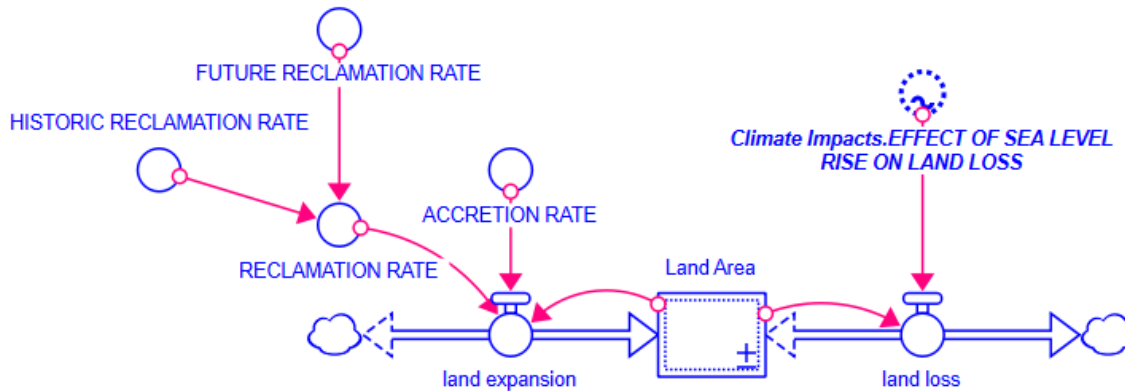


Figure 4-11 Model structure of land dynamics in South Tarawa

Settlements and Infrastructure

In coastal areas, climate impacts are expected to increasingly challenge physical infrastructure functionality and capacity (Goodess, 2013; Hanna et al., 2021). With rising sea levels, king tides - recurring flooding events, are expected to reach higher and further inland than before (McMichael et al., 2021; US EPA, 2014). As coastal flooding and erosion threatens coastal land, the residents of these areas fear for their houses and belongings (Cantieri, 2015). In some areas of South Tarawa, repeated flooding has already led to in-land movement from families living along the shores.

The impacts of climate change on settlements and infrastructure were considered in this model primarily through the impact on housing and water infrastructure. Within the model, housing lost due to coastal degradation was directly linked to the land lost from sea level rise. As land and housing stocks are lost, continued population surges and increasingly high-density villages play an increasingly important role in settlement conditions, leading to potentially unsustainable land development or overcrowding of housing (Wyett, 2014).

Water infrastructure was included in the model through rainwater harvesting tanks and desalination plants. Rainwater harvesting is a current practice in Kiribati and a proposed solution for forecasted water scarcity issues (Foon et al., 2006). The amount of rainwater collected is limited by variable rainfall amongst SSPs as well as roof catchment areas (‘Water from Tanks’ loop; Figure 7) and tank volumes. As of 2024, there

are two desalination plants in development with an estimated production volume of 6,000 cubic meters/day between the two (ADB, 2020) but were not considered in the model since they are not yet operational.

Freshwater Supply

Access to freshwater is a basic survival requirement that is increasingly threatened in Pacific atolls (Heffernan, 2012). In a global study of how environmental degradation leads to migration decisions, the unavailability of water was found to be one of the two most significant factors (Afifi & Warner, 2008). Related to sea level rise, groundwater is under threat from encroaching salt water (Finucane & Keener, 2015; Tickell, 1993), while variable rainfall patterns make water resource planning more difficult (Post et al., 2018). The narrow width and shallow aquifers of atolls make them especially susceptible to salinisation risks (ADB, 2021). In addition, highly dense urban conditions have led to over abstraction and pollution of the freshwater lens in South Tarawa (Falkland & Woodroffe, 2004). Geological conditions, coupled with increasing urban densities, have led to strained water systems in the country (Post et al., 2018).

Groundwater and rainwater are often primary sources of water supply for small islands, such as in Kiribati (Liu et al., 2006). Currently, South Tarawa's groundwater supply consists of two freshwater lens with a combined sustainable yield of 2,000 cubic meters per day (ADB, 2021). The groundwater system in the model was set up similar to Falkland & Woodroffe's (2004) "Water Balance for Tarawa" equation where change in groundwater storage is recharged through precipitation minus evapotranspiration and reduced through abstractions. Groundwater abstractions is an endogenous variable in the model, with pumping rates dictated by population demand ('Water Balance' loop; Figure 7). Recharge is directly linked to the rainfall projections from the SSPs.

The freshwater supplied through rainwater tanks is similarly influenced by the rainfall projections in each climate scenario. The amount of rainwater available from rainwater harvesting is limited by available tank and roof capacity. Consumption behaviour of rainwater also changes depending on the amount of water in the tank, mimicking a water conservation effort when supplies are low. The water is withdrawn simultaneously from the rainwater and groundwater supply. The ratio of withdrawal from these two sources is 50:50 unless constrained by limitations on either supply.

Economic Activities

Environmental degradation related to climate change has been found to have major impacts on household finances, especially in locations with heavy reliance on land-based livelihoods (Gemenne & Blocher, 2017; Groth et al., 2021). In Kiribati, more than 40% of households (31% in urban and 49% in rural) are engaged in agricultural activities and more than 80% of households participate in livestock and aquaculture activities (75% in urban and 90% in rural) (SPC, 2021). In the model, the effect of climate change on land-based livelihoods is directly incorporated through a loss of livelihood productivity per amount of land loss. This relationship recognises that most land-based livelihood activities are done in immediate housing property, and loss of this land reduces the economic productivity of these livelihoods.

Remittances were incorporated in the model as they play a significant role in household finances, with more than 30% of households nationwide reporting remittance income according to the latest household income

and expenditures report (SPC, 2021). Remittances sent home is expected to rise as more I-Kiribati decide to move abroad ('Remittance Anchor'; Figure 7) (Bernzen et al., 2019; Willett & Sears, 2020).

Food Supply

In Kiribati, poor soil quality and more accessible international trade, among other factors, has led to a heavy reliance on imported foods (Cauchi et al., 2021). In 2020, on average 70% of the diet is composed of cereals, sweets, and sugars (Troubat & Sharp, 2021). Cauchi et al. (2021) argue that though globalisation and imported foods can stem problems of hunger in the Pacific, the lack of proper nutrition in this new diet still leads to a variety of adverse health outcomes. The shift away from more traditional food production and consumption has led to increases in non-communicable diseases such as obesity, diabetes, and hypertension. While there has been a marked increase in imported food consumption, locally sourced food from home production and fishing is still an important aspect of I-Kiribati diet and culture. The latest census (SPC, 2022) noted that more than half of households in Kiribati still engage in home food production for household consumption, though only contributing to 12% of the overall diet nationally.

Food supply was split between imported food and home production in the model structure. As local food production rates were higher in rural settings than urban (16%:5% for fishing and 90%:75% for livestock and aquaculture, and 12%:4% for root crop production, respectively) (SPC, 2021) a higher local food preference was set for the outer islands than South Tarawa, at a ratio of 3:1. Future changes in home food production related to climate change are incorporated in the model through an estimated function where the difficulty of continued production increased per degree of temperature increase. This matches past research which has linked temperature rise to food productivity issues (van der Geest et al., 2020).

Societal Conditions

In the framework of atoll habitability used here, societal conditions such as beliefs, government arrangements, and place attachment are identified as foundational supports for habitability, though not explicitly assessed (Duvat et al., 2021). In our SFS model, societal conditions were included both implicitly throughout the model as well as a contributing term in the overall utility calculation of a location.

People's connection to land, place attachment, plays a significant cultural role in Kiribati and the Pacific (Constable, 2017; Oakes, 2019). Land is a bridge to ancestral and cultural heritage and past research has found that movement from traditional lands can lead to losses in identify and senses of place (Ayeb-Karlsson, 2021; McNamara et al., 2018; Schwerdtle et al., 2021). For many, leaving presents an inconsiderable option (Nunn & Campbell, 2020). To account for this high level of anchoring to their home, leaving their original location is considered as a "cost" in the model.

Emotional and financial costs were estimated then calibrated to match historical population data. To account for the higher financial burden of moving abroad, the financial costs of moving internally versus abroad were \$300 AUD and \$15,000 AUD respectively. These values were calculated from estimates of flights, shipping, visa, and other costs associated with migration. The calibration of the base emotional costs of moving resulted in similar values between movement internally versus abroad, at 49,000 and 51,000 (dimensionless) respectively.

Total emotional costs were dynamically calculated, where emotional cost was connected to land area in Kiribati with an assumption that as land is lost, emotional cost of leaving decreases. This assumption is based on the idea that as land is lost there is likewise a loss in ability to support cultural and ancestral ties, such as loss of gravesites. As these cultural connection points decline, the psychological and emotional barriers to leaving also lessen, making the evaluation of leaving less “costly”. I acknowledge this relationship is a simplification of reality, where complex emotional responses to land loss can elicit different responses to movement. However, for modelling purposes, this assumption represents a relationship between land loss and emotional costs that is useful for the context of long-term migration decision-making. This emotional cost was combined with the financial costs of movement and were barrier (or deterrence) terms in the utility equation.

4.2.3.2. Estimation of Parameters, Behavioural Relationships, and Initial Conditions

The previous section detailed the model’s overall structure, which is critical for driving the outcomes of the simulation. Estimation of parameters, behavioural relationships, and initial conditions also play a role in the model results. The decisions behind the data selection, mathematical functions, and assumptions are detailed for each variable in the model documentation (Appendix V).

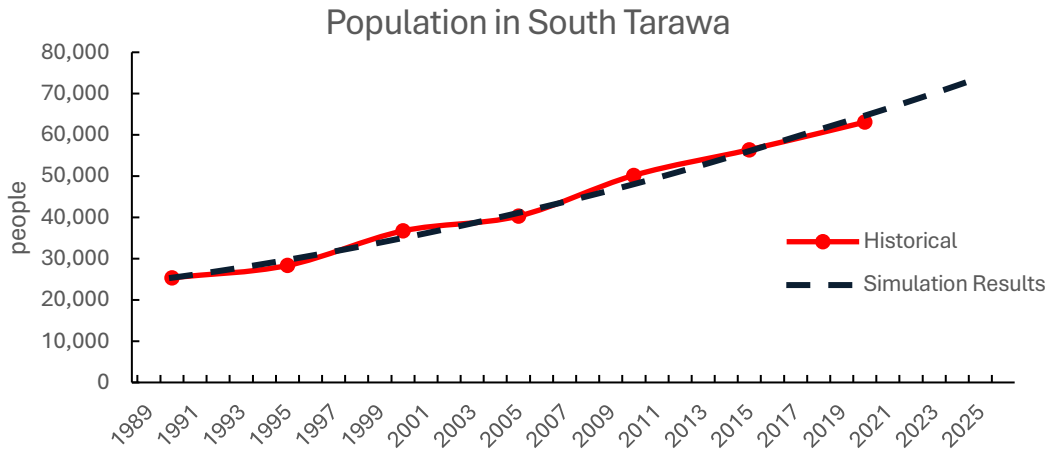
The model was calibrated using a Powell optimisation method with payoff definitions for population in South Tarawa and the Outer Islands, land area in South Tarawa, and household density in South Tarawa. Payoff specifications used squared error comparison types for selected payoff elements. Optimisation parameters included baseline utility values, financial costs to move abroad, and values for Outer Island’s health security and infrastructure and social services quality.

4.2.4. Testing

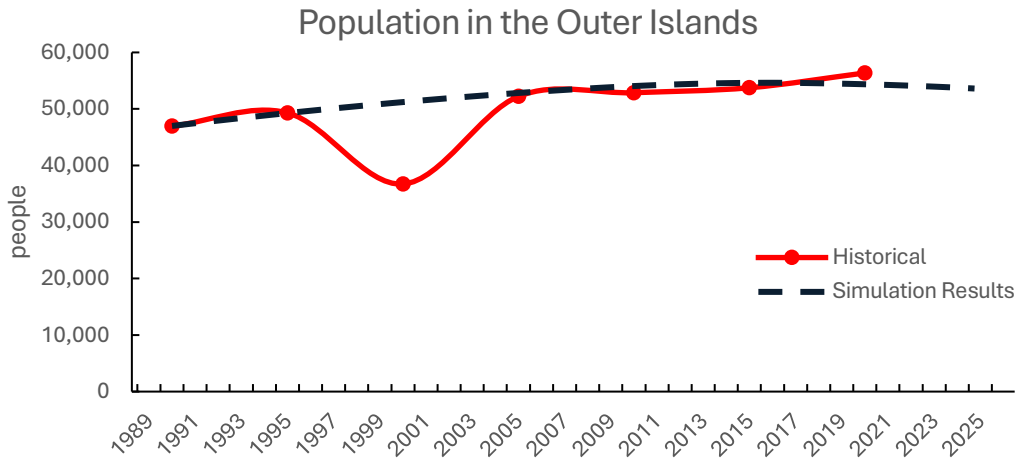
Robustness and soundness checks were performed to ensure that the model structure and behaviour matched the reference behaviours and narratives set by stakeholders and aligned with realistic conditions in Kiribati.

4.2.4.1. Behaviour Reproduction

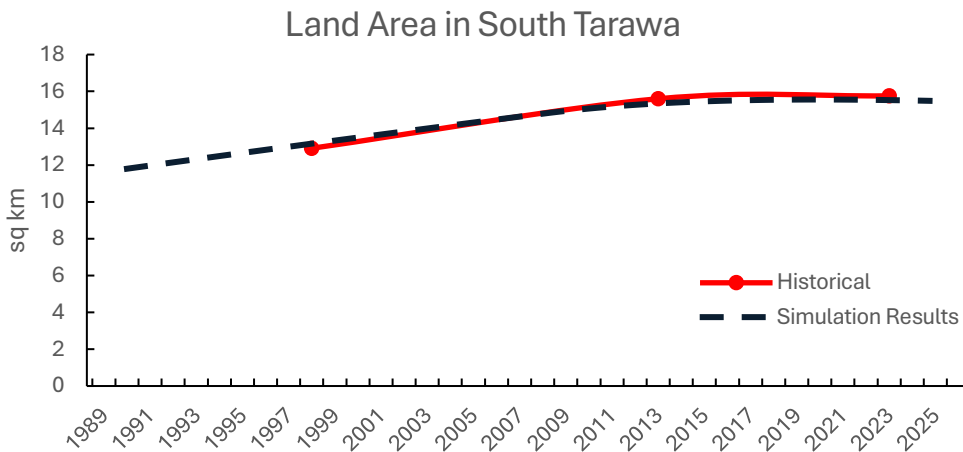
Historic data for the reference modes of population, land, and water supply were used to calibrate and evaluate the results of the model. Figure 4-12 shows the comparison of simulated population and land values to the historic data. The similarity between simulated results and historic trends was optimised through model parameters and judged visually. While the model captures general trends, such as the flattening of land area in Figure 4-12c, which aligns with the actual slowdown in reclamation projects, it does not exactly match all historical data (e.g., Figure 4-12b). Such overfitting of data would reduce the model’s overall reliability.



a.



b.



c.

Figure 4-12 Comparison of simulation to historic data; (a) population in South Tarawa (b) population in the Outer Islands (c) land area in South Tarawa

4.2.4.2. Model Confidence Building

A model can never be validated as it can never fully capture the truths of reality (Sterman, 2000). Confidence in the model can be built, however, by evaluating if it is useful in guiding conversation and not built on incorrect assumptions. The following are tests that were used to assess the model dynamics to build confidence in the model structure and results:

- **Dimensional Consistency** - Dimensional consistency ensures that all equations used in the model have appropriate and compatible units. Stella software was used to check all units and equations for unit consistency.
- **Boundary Adequacy** - To test the boundary adequacy of the model, the original dynamic hypothesis (Figure 4-7) was compared to the CLD generated from the stock and flow model. The dynamic hypothesis was built from the mental models of stakeholders in Kiribati and included key variables and feedback in the system. By revisiting the causal structure, we build confidence that the developed model addresses the identified endogenous problems and is focused on the key aspects of the system.
- **Extreme conditions testing** - Extreme conditions testing is used to verify that each input variable is realistic when taken to the extreme limits of its possible values. This test was done individually for each variable upon its addition to the model. For the overall model behaviour, extreme conditions testing was performed to make sure that key reference mode variables responded realistically when added variables were subjected to extreme conditions.

4.2.5. Analysis

Following the completion of the model's structure and testing, an analysis was performed to answer how habitability might change in Kiribati within this century. Results and discussion of this analysis are presented in Chapter 5. We began this analysis by identifying the SFS model's top feedback loops using the simulation software, Stella's, Loops that Matter (LTM) tool (Schoenberg et al., 2020).

LTM quantifies how key feedback loops contribute to system behaviour and outcomes over time by calculating the percent of dominance of each feedback loop to the overall system (refer to Schoenberg et al., (2020) for a detailed description of loop dominance calculations). Using LTM, we were able to determine which system structures were driving model behaviour at specific years and periods in order to determine how pillar influence shifts over time. The LTM analysis was set to return 100% of the loops identified in the model and combine loops that were 90% similar. The full model simulation (110 years) was divided into three periods: short-term (2025-2060), mid-term (2060-2085), and long-term (2080-2100) to better see how dynamics changed over time. The duration of each period was set retroactively to match visible shifts in behaviour of loop dominance.

In this analysis, only SSP1-2.6 and SSP5-8.5 were assessed to compare low- and high-emissions scenarios. Thirty-nine feedback loops were identified in SSP1-2.6 and thirty-six in SSP5-8.5. Top loops in each period were determined by filtering to loops that contributed 40% or more to model behaviour at any time step. This cut-off threshold was selected after inspecting the results to minimise the number of top loops identified. A list of top loops per period can be found in Appendix VI.

To analyse how habitability changed over time in the SFS model, we continued to draw upon the Framework of Habitability Pillars for Atolls (Duvat et al., 2021) above and categorised each loop to related pillar(s), as well as ‘Societal Conditions’. For example, the dominance percentage of all loops categorised as related to ‘Habitable Land’ were summed together at each time step then normalised by dividing by the total dominance contribution for each time step. Feedback loops could be categorised into multiple habitability pillars resulting in total dominance denominators above 100% before normalisation. Afterwards, at each time step of the model the total contribution of all habitability pillars’ dominance was 100% to describe completely the system’s behaviour. The habitability pillars’ dominance was plotted at each time step and compared visually to determine trends.

The behaviour outcomes of the model structure were also analysed, specifically in terms of demographic shifts (i.e. populations in South Tarawa and the outer islands). This particular outcome behaviour was selected for analysis to investigate claims of future mass displacement from atoll islands. All four SSP scenarios were run and analysed.

4.3. Limitations

Efforts were taken to ensure the model was soundly developed with tests to build confidence in the structure and results, however there are still conceptual and methodological limitations to the model presented, which we detail below.

4.3.1. Epistemic and Conceptual Limitations

The model boundary was defined to include variables most relevant to the topic of climate change and habitability in Kiribati. However, to maintain a focused model boundary, some variables were excluded, which are detailed below.

Regarding climate hazards, the model does not explicitly account for all hazards that affect the system, such as drought or ocean acidification. Kiribati has a history of being affected by periodic prolonged droughts that hamper the reliability of rainwater harvesting systems (ADB, 2021). The inclusion of precipitation projections and temperature increases illustrate the rainfall variability and additional water needs in the long-term, but do not reflect the periodic nature of drought occurrences. In future work, event modelling may be useful in predicting specific periods of water insecurity related to drought conditions. Similarly, discrete events of flooding and impacts of infrastructure and water supply were not considered in this model due to data limitations.

Also related to water, the centralised water sources included in the model were built with the assumption of no water loss through piped distribution systems. In reality, evidence has shown significant water loss through leaking pipes of up to 70% (ADB, 2020; White & Falkland, 2010). A reduction of network leakage is an aim of the ongoing South Tarawa Water Supply Project with plans to rehabilitate existing faulty distribution lines (ADB, 2020).

The system boundary also excludes Kiribati’s marine ecosystem, an expansive ocean territory. Fisheries and marine livelihoods are important in Kiribati but have been declining because of ecosystem changes, unsustainable fishing practices, and shifts in traditional food consumption (Campbell & Hanich, 2014;

Troubat & Sharp, 2021). These changes, such as shifts in fish availability near coasts, are not fully reflected in the model. Although assumptions were made about the impact of climate change on land-based livelihoods, more detailed modelling could provide greater understanding of impacts on the marine system and fisheries in Kiribati. The system boundary also exogenises dynamics of living and moving abroad that may affect migration decision-making such as strengthened social networks or more congestion in destination locations. Similarly, international migration policies which may facilitate migration were not considered.

Additionally, there are other socio-economic factors that interact with the system but were not included to keep the model manageable. Future iterations of the model could examine health, livelihoods, and food security in more detail. These aspects were simplified in the model but additional details for climate change's relationship with water-related disease, copra production, and food consumption would add extra nuance for the system. Similarly, the populations per region are assumed to behave homogeneously when in reality, demographic and personal characteristics lead to differentiated mobility decision-making (Merschroth et al., 2024). Future models may advance the model's decision-making components by disaggregating population groups (e.g. age, gender).

A final conceptual limitation of this work is the inherent challenge of capturing the system without the local knowledge and experience gained from living in Kiribati. Significant effort was taken to engage with and receive regular feedback from I-Kiribati partners but there may still be contextual factors missing.

4.3.2. Methodological Limitations

Data availability presented a significant challenge for the selected case locations in Kiribati which limited the ability to understand the historical behaviour of the system. Lack of reliable land elevation data for the country necessitated assumptions for relationship between sea level rise and land loss, which are incorporated into the model with assumed relationship functions. In future models, more accurate topographical data can be used to better estimate land loss. Similarly, there is limited information on key variables in the outer islands, including infrastructure capacity, demographics, and ecosystem conditions. As such, while the model incorporates more detailed dynamics for South Tarawa from known and collected data, data for the outer islands in this model often rely on generalised national statistics (e.g. national birthrates). Incorporating better data for these variables would enhance the model's rigor and alignment with reality.

A second methodological limitation with this research is in the use of a singular modelling approach to view this problem. While system dynamics was intentionally chosen for its ability to evaluate policy implications, other modelling techniques, such as agent-based modelling, may be better suited to predicting population movement related to climate change impacts. Past research has shown that different modelling approaches can produce varying results, pointing to the value of more multi-modelling approaches (de Bruin et al., 2024).

4.4. Conclusion

The purpose of the SFS model discussed in this chapter was to develop a tool for understanding the effects of climate change on habitability in Kiribati through the interrogation of the system's structure. This model represents an interpretation of the system that reasonably reflects reality in a way that is useful for policy planning. The model was able to closely reproduce historic behaviour for key variables of land and population, building confidence in the rigor of the model structure and assumptions.

The model developed in this chapter is analysed in Chapter 5, with a discussion of the current system structure in Kiribati highlights certain habitability pillars, how those pillars shift over time, and the ensuing outcomes in terms of demographics. The work presented here represents 'baseline' conditions for the model. Future work can be done which uses this baseline to test various policy and adaptation strategies for Kiribati.

Chapter 5

*Shifting habitability dynamics lead to high
internal migration in Pacific atolls*

5.1. Introduction

This chapter builds from the methodology described in Chapter 4 and is intended as a standalone presentation of the results and analysis from the developed system dynamics model. In the sections below, I provide a brief background of relevant theoretical frameworks used in the model, then move directly to the results, analysis, and discussion. The format and length of this chapter were written to match the guidelines of the intended journal outlet. An expanded discussion of overarching themes and implications are included in Chapter 6 (Conclusion).

As global temperatures rise, Pacific atolls face increasing expectations of climate hazards, such as sea level rise and drought. Conversations of climate change impacts often lead to questions of future uninhabitability and the inevitability of mass displacement (Storlazzi et al., 2018). To effectively assess these claims, there is a need to better understand the multi-faceted complexity underpinning habitability and possible impact on migration decisions (Horton, de Sherbinin, et al., 2021).

Habitability is defined by the Intergovernmental Panel on Climate Change as, “The ability of a place to support human life by providing protection from hazards which challenge human survival, and by assuring adequate space, food and freshwater” (IPCC, 2022a). In addition to environmental protections and necessities, habitability also includes a place’s capacity to provide residents the capability to lead healthy, meaningful, and dignified lives with productive livelihoods and sustainable intergenerational development (Horton, de Sherbinin, et al., 2021; Sterly et al., 2025). Building from these definitions, we recognise habitability as emerging from the multidimensional interactions between the physical environment and socially constructed elements (Farbotko & Campbell, 2022; Gemenne et al., 2021; Merschroth et al., 2024). Therefore, while hazard severity is projected to increase in the Pacific (IPCC, 2019), there is a gap in research which understands and evaluates habitability from a localised lens, centring the perspectives and lived experiences of atoll communities (Spencer et al., 2024).

In this work, we couple local knowledge with an established habitability framework to understand the impact of climate change on atolls in the Pacific, focusing on a case study in Kiribati. Specifically, we developed a model to simulate the dynamics of habitability drawing from Duvat et al.’s atoll habitability framework (2021), which recognises habitability as multidimensional ‘pillars’ including: habitable land, freshwater supply, food supply, settlements and infrastructure, and economic activities (Figure 5-1). We additionally expand to include societal conditions (e.g. demographic trends and place attachments), which were mentioned, though not assessed explicitly in Duvat’s framework. We delineate climate impacts and international policies as exogenous (external) and habitability pillars as endogenous (internal) variables.

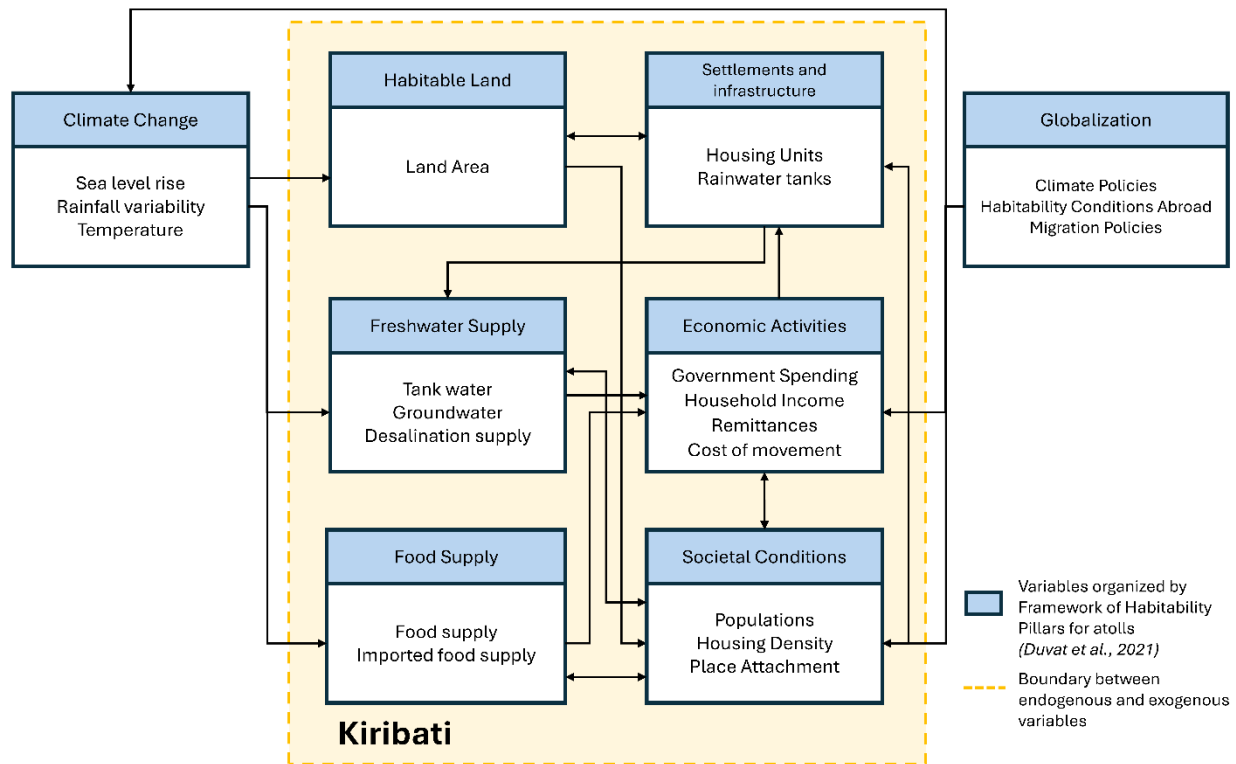


Figure 5-1 System boundary organised by the Framework of Habitability Pillars for atolls (Duvat et al., 2021)

The simulation model was developed using a system dynamics stock and flow model to analyse changes in atoll habitability driven by the direct and indirect effects of climate change. System dynamics modelling is a simulation methodology that allows for the investigation of how system structure (i.e. the web of relationships) leads to outcomes. Neither habitability, nor its components are static, so this approach allows us to analyse how evolving, non-linear relationships unfold over time (McLeman & Smit, 2006). We used participatory system mapping to ground the included variables and relationships to the lived experiences of those from Kiribati. The integration of bottom-up local expertise with a top-down habitability framework provided a valuable foundation for conceptualising and building a meaningful systems-based model of a complex phenomenon (Horton, de Sherbinin, et al., 2021).

The operationalisation of habitability in this study was derived from the concept of place utility (Wolpert, 1965), Qualitative Choice Theory (McFadden, 1984; Train, 1986), and the Push-Pull Theory of Migration (Lee, 1966), where habitability was reflected in a place's utility and influenced populations' likelihood to migrate. In the model, populations in Kiribati compare the habitability of their current location against other possible location options and evaluate the utility of internal migration, migration abroad, or remaining in place. Utility evaluations were calculated from the summation of habitability pillars, each assigned weights based on local prioritisation (O'Byrne, 2023). Please refer to Chapter 4 for more detail into the model development and calculations.

Potential climate impacts, including from sea level rise, rainfall variability, and temperature increase, were integrated into the model through four shared socioeconomic pathways (SSPs), ranging from SSP 1-2.6

(lower impact scenario) to SSP 5-8.5 (high impact scenario). Each SSP relates to associated climate projections which were used as data inputs in the model. While environmental changes are exogenous to the model, they exacerbate existing vulnerabilities and lead to amplified climate risk (Parrish et al., 2020). That is why when analysing habitability, or decisions surrounding mobility, it is necessary to consider the cascading and multi-causal pathways of climate hazards and ensuing impacts (Obokata et al., 2014). To this end, the incorporation of direct and indirect linkages to non-environmental habitability pillars are important for understanding the system holistically. To evaluate how the system dynamics shift over time, we divided the analysis timespan into three periods of near- (2025 – 2060), mid- (2060 – 2085), and long-term (2085 – 2100) dynamics.

In this research, we address the need for a more nuanced and situated understanding of the dynamics of habitability through a participatory systems approach. We ask the primary question of: How might habitability change in Kiribati within this century? This question was answered by working with community partners to map the social-ecological system structure in Kiribati and model how the influence of specific habitability pillars changes over time and between climate scenarios. In this study, we offer simulated trends of atoll dynamics over the next century and identify key areas to prioritise in adaptation planning.

5.2. Results

5.2.1. Development Inequalities Lead to Declining Habitability Trends in Outer Islands

We found that habitability, as reflected in the utility of staying in place, is likely to decline in Kiribati's outer islands. This decline is especially prominent in SSP 5-8.5, the climate scenario based on continued fossil fuel development (Figure 5-2). South Tarawa was found to have consistent levels of staying over time and between climate scenarios. In addition, in contrast to narratives of sinking islands and extreme land loss, we found that habitability is more likely to be influenced by water security challenges.

To understand these trends, we analysed habitability dynamics; specifically, how various habitability pillars shift in dominance over time. Pillar dominance indicates which dimensions of habitability are driving system outcomes. For example, in periods of low precipitation, 'Freshwater Supply' may dominate system behaviour, strongly influencing water availability and migration decisions to avoid water scarcity; whereas when precipitation is relatively stable, 'Societal Conditions' such as population density may become a key driver in influencing resource levels through consumption and migration choices for social services rather than environmental conditions.

Each pillar was calculated from the aggregation of related feedback loops (see Appendix VI for loop categorisation). In Figure 5-2, we show the pillar dominance shifts in stacked area charts, while calling out specific key feedback loops within each pillar below. Feedback loops can cause either reinforcing (R) or balancing (B) behaviour, depending on whether the loop exhibits compounding or equalising behaviour, respectively.

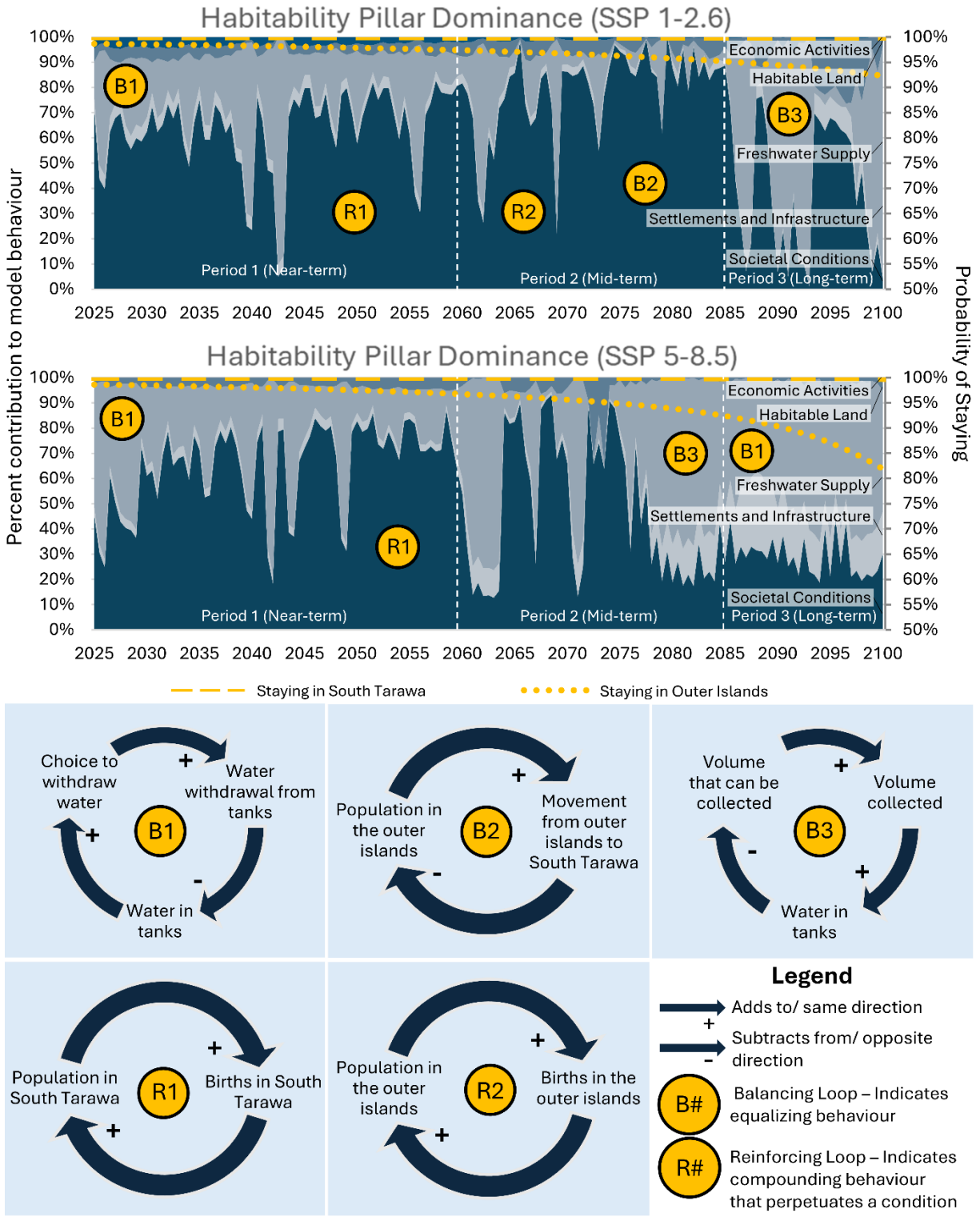


Figure 5-2 Habitability pillar dominance in Kiribati until 2100 under SSP 1-2.6 and SSP 5-8.5 with associated driving loops. Circles indicate which feedback loop is dominant in each period with Balancing Loop 1 (B1), Balancing Loop 2 (B2), Balancing Loop 3 (B3), Reinforcing Loop 1 (R1), and Reinforcing Loop 2 (R2). Placement of circles indicates which habitability pillar the loop is associated with.

In the near term (Period 1 in Figure 5-2), the two dominating pillars for both SSP1-2.6 and SSP5-5.8 are ‘Societal Conditions’ and ‘Freshwater Supply’. Balancing loop 1 (B1) related to water conservation, a key feedback loop in this period, indicates that water resources will play a significant role in shaping Kiribati’s habitability in the near-term. Water conservation in this study reflects household strategies to limit rainwater usage when tank levels are perceived to be low. While conservation efforts can be used to avoid complete water depletion, a growing population (Reinforcing loop 1; R1) further strains these efforts, exacerbating water security challenges. The oscillation of pillars in Figure 5-2 highlights the competing influence of both population growth and water demands in Kiribati.

In the mid-term (Period 2), the dominance of habitability pillars for the climate scenarios starts to deviate where ‘Freshwater Supply’ becomes dominant for SSP5-8.5, while ‘Societal Conditions’ remains influential for SSP1-2.6. Although the pillar of ‘Societal Conditions’ maintains dominance through Periods 1 and 2 in SSP1-2.6, the key feedback driving its dominance shifts from a reinforcing cycle of births and population growth in South Tarawa (R1) to focus more on population dynamics in the outer islands. In this period, dynamics related to births in the outer islands (Reinforcing Loop 2; R2) and internal migration from the outer islands to South Tarawa (Balancing loop 2; B2) take centre stage. Internal migration from the outer islands to South Tarawa stems from opportunity for higher income, social service quality, and resource availability, highlighting how the comparative assessment of connected, potential destination locations can affect people’s perceptions of their own location’s current habitability. In the outer islands, high rates of internal migration cascades into fewer births and population decline (R2).

In SSP5-8.5, ‘Freshwater Supply’ is dominant for extended lengths of time in Period 2. The core feedback loop driving behaviour in this period was related to the capacity of rainwater tanks (Balancing Loop 3; B3). In this feedback loop, the volume of water in a tank affects the amount of rainwater that can be collected. Combined with water conservation efforts, this loop indicates that the primary limitation of rainwater supply is not the amount of rainfall, but the number of rainwater tanks in South Tarawa. While present in previous periods, the jump in dominance in this period highlights the need for developing additional rainwater catchment infrastructure in the long-term and its viability as an effective adaptation solution.

In the long-term (Period 3), Balancing Loop 3, the dominant feedback in SSP5-8.5, emerges as the driving feedback loop for SSP1-2.6. This is one time period delayed from SSP5-8.5 which may reflect the delay in climate effects between the scenarios. In SSP5-8.5, ‘Freshwater Supply’ remains a dominating pillar but transitioned from B3 back to B1 as the driving feedback. The feedback dynamics in B3 highlight how tank capacity can limit water supply in South Tarawa while B1 focuses on water conservation behaviour. As tank supply is limited in Period 2 (B3), it is logical that households would begin to engage in water conservation (B1). It is notable that this period in SSP5-8.5 shows a marked uptick in internal migration from the outer islands to South Tarawa, even with anticipated water security challenges in the capital. This point highlights the complexity of migration decision-making and emphasises that decisions are not based solely on environmental factors.

For each climate scenario and period, only top feedback loops were highlighted here. Results for other top loops can be found in Appendix VI. By understanding the key driving pillars of habitability across time periods, we can adjust and strategise adaptation policies to meet evolving needs. In the example of Kiribati, the shifts in loop dominance suggest that it may be useful to focus on water conservation programs in the

near-term, development of the outer islands to influence internal migration rates in the mid-term, and water infrastructure strategies in the long-term (based on results from SSP1-2.6). These strategies are in alignment with the World Bank's (2024) latest climate and development report for Pacific atolls which calls for the protection of freshwater resources and investments in Kiritimati Island's (located in the outer islands) economic, social, and physical infrastructure. This thesis supports the benefit of these actions and offers valuable guidance on optimal implementation timing for impact.

5.2.2. On The Move - Habitability And Internal Migration

In contrast to suggestions of a national mass exodus, we find that internal migration will play a greater role than international movement in Kiribati over the next century under climate change. This aligns with past forecasts that future migration is more likely to occur internally than internationally (de Sherbinin, 2020; Siegried, 2023). Other studies have likewise identified internal migration to urban centres as an established adaptation practice for atoll nations to diversify income and reduce resource pressures (Birk & Rasmussen, 2014; Farbotko & Campbell, 2022).

In Kiribati, we show that ongoing disparities between conditions in the capital and rural outer islands could result in a growing concentration of the population in South Tarawa, as seen in Figure 5-3. Model dynamics show an exponential increase in South Tarawa's population mainly driven by a reinforcing birth cycle (R1) and in-migration (B2). While migration abroad is steady throughout the century and ramps up in the long-term, it does not dampen the upwards trend in the capital. In the outer islands, resource insecurity and fewer economic opportunities led to out-migration and a steady depopulation. While the heterogeneity of Kiribati outer islands is recognised, they are grouped in this model for simplicity. As such, care should be taken in interpreting these results as some islands, such as those receiving more rainfall, may not have the same push to leave as others.

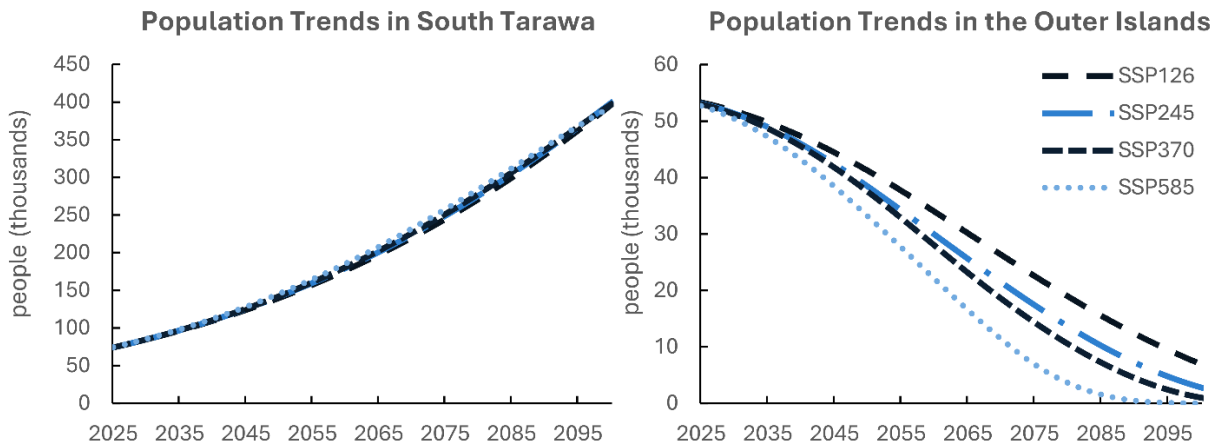


Figure 5-3 Model Behaviour for population in South Tarawa and the outer islands

While the utility of staying in place can reflect habitability, it is an important distinction to note that inversely, migration is not necessarily an indicator of uninhabitability and that decisions of movement culminate from the combination of multiple factors (Black et al., 2011; Nabong et al., 2023). In the Pacific, there is a strong history and culture of movement, including circular migration, for opportunities of

education or work (Barnett & McMichael, 2018; Kelman et al., 2019; Opeskin & MacDermott, 2009). Movement between atolls is a normal aspect of island dynamics and does not necessarily reflect uninhabitability (Barnett & McMichael, 2018).

In Kiribati, people are drawn to South Tarawa, the capital and home to the country's higher education institutions, two of the country's four hospitals, and livelihood opportunities unavailable in the outer islands; all major contributing factors to people's decisions to relocate. The pull of opportunity is related to our argument that the habitability of a place is not judged in isolation but emerges from the relative assessment of the conditions and opportunities in multiple locations. The results of this model show that the comparison of habitability conditions between South Tarawa, the outer islands, and abroad lead to high rates of movement. For example, in SSP 1-2.6 the probability of staying in the outer islands, based on relative utility and habitability, decreased by 6.4% between 2025 and 2100, compared to a 0.1% decrease in South Tarawa. The relative difference indicated between the two locations led to an 12% increase in internal migration to the capital over the same period. This point is important because it emphasises that locations do not necessarily need to be uninhabitable to elicit out-migration, there only needs to be a difference in how populations judge utilities between origin and destination. To avoid the patterns of reinforcing behaviour that lead to mass out-migration from the outer islands, policy and programs could be developed to strengthen habitability pillars to support populations' ability to stay if they want.

5.3. Conclusion

Our study shows that key dimensions of habitability will interact and shift in dominance to lead to high rates of internal migration in Kiribati, with no indications of mass national exodus. In contrast to studies that use environmental metrics as determinants and forecast pending uninhabitability, our findings reinforce that there are major reluctances to leave ancestral homes in atolls and islands with strong senses of place tied to land (Constable, 2017; Farbotko et al., 2016). This leads us to question whether a place can ever truly be uninhabitable when there is engrained value to the land. Supporting this point, faced with the knowledge of increasing climate impacts some study participants expressed their determination to stay in Kiribati whatever comes.

In this work, we focus on habitability as a dynamic and relative concept that is made up of the combined and changing interactions between multiple factors, such as safe and sufficient land, availability of food and freshwater, safe and reliable physical and social infrastructure in shelter and settlements, access to economic activities, and critical societal values and beliefs. While we indicate potential habitability trends, we do not aim to identify tipping points of habitability for Kiribati. As social-ecological systems shift and evolve, perceptions of habitability are being continually reconstructed (Merschroth et al., 2024), suggesting that such an objective, singular point may not exist (Farbotko, 2023). Current discourses furthermore debate the usefulness of such determinations (Kopp et al., 2024), with some noting that ascribing a discrete timeline to atoll uninhabitability raises ethical concerns, oversimplifying complexities and undermining the agency of island communities in how they perceive and understand their lived experiences. Moreover, narratives of uninhabitability can perpetuate harmful colonial dynamics where non-locals decide the status of Pacific islands, leading to the withholding of critical funding and the external determination of when populations should leave or remain (Bordner et al., 2020; Farbotko, 2023).

We caution against reduced investments in Pacific islands and atolls stemming from concerns that they may eventually be lost, as such assumptions overlook current solvable issues and hasten eroding conditions. With this in mind, we recommend refocusing attention on immobile populations, whether voluntarily or involuntarily. By investing in in-situ adaptation, we can support people's preferences to remain at home if they wish. Previous work has provided valuable roadmaps for utilising traditional community and nature-based knowledge to strengthen atoll resiliency (Barnett et al., 2022; Piggott-McKellar et al., 2020).

We also recognise that while there is a strong preference to staying in place, many may opt to employ migration as an adaptation strategy (Gemenne & Blocher, 2017; Webber & Barnett, 2010). In the context of climate change and extreme urbanisation, our model indicates that migration abroad may offer a coping response for those choosing to move, while also strengthening habitability pillars in Kiribati through relieved population and resource-related pressures. The Australia–Tuvalu Falepili Union Treaty provides an example of international assistance to Pacific Islands through a bilateral climate mobility agreement, offering a migration pathway in anticipation of increasing climate impacts (McAdam, 2023). In contrast to Kiribati's previous 'Migration with Dignity' scheme (McNamara, 2015), the Australia-Tuvalu agreement is solely focused on climate rather than a skills-training.

We propose that the usefulness of our model lies in its ability to identify when such adaptation strategies may be most timely implemented by determining when habitability pillars become dominant, a dynamic approach to adaptation planning which is not currently seen in scholarship or practice. Likewise, a systems analysis allows us to understand the downstream effects of proposed policy. In the Pacific, past attempts of well-intentioned adaptation, neglecting long-term and systems perspectives, have led to increased vulnerability for some climate-affected communities. For example, reclamation projects with aims of land expansions have inadvertently led to development in low-lying land areas prone to flooding and erosion (Barnett et al., 2022; Duvat et al., 2013). Likewise, attempts to use seawalls as protective measures have had unanticipated consequences in aggravating erosion and/or diverting effects to other coastal communities (Nunn et al., 2021). Evaluating potential solutions from a systems perspective provides a more comprehensive understanding of how factors interact, leading to better informed decisions and avoiding maladaptation (Meadows, 2008; Woodruff et al., 2018).

As we approached habitability as a social and culturally constructed concept, we recognise that perceptions of what makes a place habitable change between geographies, individuals, and over time. In this work, we attempted to offer nuance by breaking the system into urban (South Tarawa) and rural (outer islands), in addition to an international context. We acknowledge, however, that these categorisations generalise the populations and are a limitation of our work. Views and perceptions of habitability vary between individuals (Merschroth et al., 2024), with temporal changes adding additional complexity. Future work in this area may focus on adding important heterogenous traits between islands and demographic groups, such as gender and socio-economic status. Likewise, we acknowledge a limitation in the oversimplification or exclusion of natural processes effecting the system, such as shoreline dynamics and flooding. Though these processes undoubtedly impact the environmental system, gaps in data presented challenges for inclusion. As more data and system information becomes available, we hope that this work can serve as a foundation to build upon.

Understanding the dynamics of habitability in the face of climate change, and the implications for hazard-exposed populations, is a growing global discussion. Our contribution grounds the conceptualisation of habitability in the perceptions and lived experiences of communities in Kiribati. Our use of systems thinking and modelling highlights the dynamic nature of habitability and the need for adaptability in developing climate strategies that are responsive to changing challenges over time. Our study responds to the call for a holistic view of habitability and provides a foundation from which future adaptation solutions may be tested. Supporting climate adaptation is a global priority and this work helps to contribute long-term solutions.

Chapter 6

Conclusion

6.1. Introduction

While emissions levels will determine pathways of consequence severity, the world will face increasing climate change impacts regardless of current and future mitigation efforts (IPCC, 2023a). Climate impacts, such as rising sea levels, rainfall variability, and temperature increases, will be especially serious for Pacific atolls and forefront questions of (unin)habitability in coming decades. The work presented in this thesis advances the knowledge of habitability dynamics related to climate change for Pacific atolls, with the Pacific Island nation of Kiribati as a specific study location. The overarching aim of this thesis was to inform effective adaptation policy through the increased understanding of the holistic and interconnected impacts of climate change on habitability. The methodologies for this thesis began with a global synthesis of knowledge, which was then contextualised and applied. The flow of this work is shown in Figure 6-1.

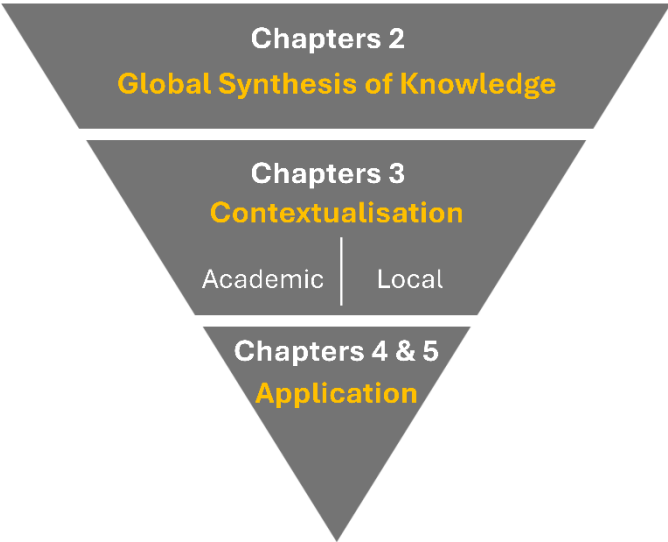


Figure 6-1 Pyramid of thesis flow

A systematic literature review was used in Chapter 2 to build a foundational knowledge of why populations move and stay in the context of climate change. This chapter addressed gaps in knowledge by synthesising how climate change may influence migration decision-making (Abel et al., 2013; Ahearn, 2012; Thiede & Gray, 2017) and the identification of indirect feedback dynamics between factors (Jokisch et al., 2019; Sakdapolrak et al., 2016). In this chapter, I conducted a systematic literature review using purposive text analysis to systematically identify causal relationships related to climate migration. By analysing the frequency of relationships noted in literature, I was able to identify 21 top climate migration factors (*Chapter 2- RQ1*) (Nabong et al., 2023). The direct and indirect relationships between these factors formed feedback loops, which were then structurally analysed to identify the effect within the climate-migration system (*Chapter 2- RQ2*). The results of this work emphasise the role of financial capital and livelihoods in people’s decisions to migrate (Nabong et al., 2023), two factors which are increasingly affected by climate change (e.g. degradation of soil quality leading to less agriculture income) (Bastakoti et al., 2017; Kulshreshtha & Kulshreshtha, 2014; Lei et al., 2017; Mendenhall et al., 2020).

In Chapter 3, I explored how the relationships among the 21 factors identified in Chapter 2 varied across different climate and geographical contexts. This work answered calls for a contextualised understanding of climate migration systems for specific climate hazards (Gray & Mueller, 2012; Kabir et al., 2018; Renaud et al., 2011) and localities (Bates-Eamer, 2019; Hanna et al., 2021). I used a two-stage contextualisation approach where I solicited perspectives from two groups: academic and local experts (*Chapter 3- RQ1*). Each expert group contextualised the relationships through their own mental models with focuses on specific hazards (academic experts) or the context of Kiribati (local experts) (*Chapter 3- RQ2*). I started with the survey of academic experts to gain a broader understanding of how factors interconnect across different climate change hazard contexts. With the survey results, combined with the insights from the systematic literature review (Chapter 2), I was better equipped to engage with local experts in Kiribati, having developed a deeper understanding of the nexus between climate, migration, and habitability. While the survey provided me with a strong foundation of knowledge, comparisons between the two expert groups highlight the additional nuance that can be gained through community engagement (*Chapter 3- RQ3*). Specifically, the results of the academic experts indicated that sea level rise is a highly complex phenomenon with no single leverage point, indicating the need for further research. Collecting localised mental models from Kiribati, a nation of primarily atoll islands experiencing the impacts of sea level rise, allowed me to further explore these relationships and better understand the impacts of sea level rise in the Pacific. From the results of local experts, I identified system leverage points, outcome variables, and core dynamic feedback in Kiribati's social-ecological system.

The key system interactions identified through local expert interviews and workshop were then used to build a dynamic hypothesis of Kiribati's climate habitability system and to develop a system dynamics stock and flow simulation (SFS) model. The resulting SFS model allowed me to understand how climate change may affect habitability by simulating the dynamics of how habitability pillars interact and shift in dominance when affected by climate change (*Chapter 5- RQ1*). The model development methodology was described in Chapter 4 with the analysis of results in Chapter 5. Through continued engagement with local experts, the dynamic hypothesis and articulation of the problem were iteratively revised and refined throughout the modelling process to match the realities of local experts in Kiribati. This chapter answered calls to better understand how the drivers of migration and habitability evolve over time (Nelson et al., 2020) through the incorporation of localised knowledge (Farbotko, 2023; Farbotko & Campbell, 2022a; Fleetwood, 2023; Horton et al., 2021). The gaps and contributions of each chapter, along with the research questions, are shown in Figure 6-2.

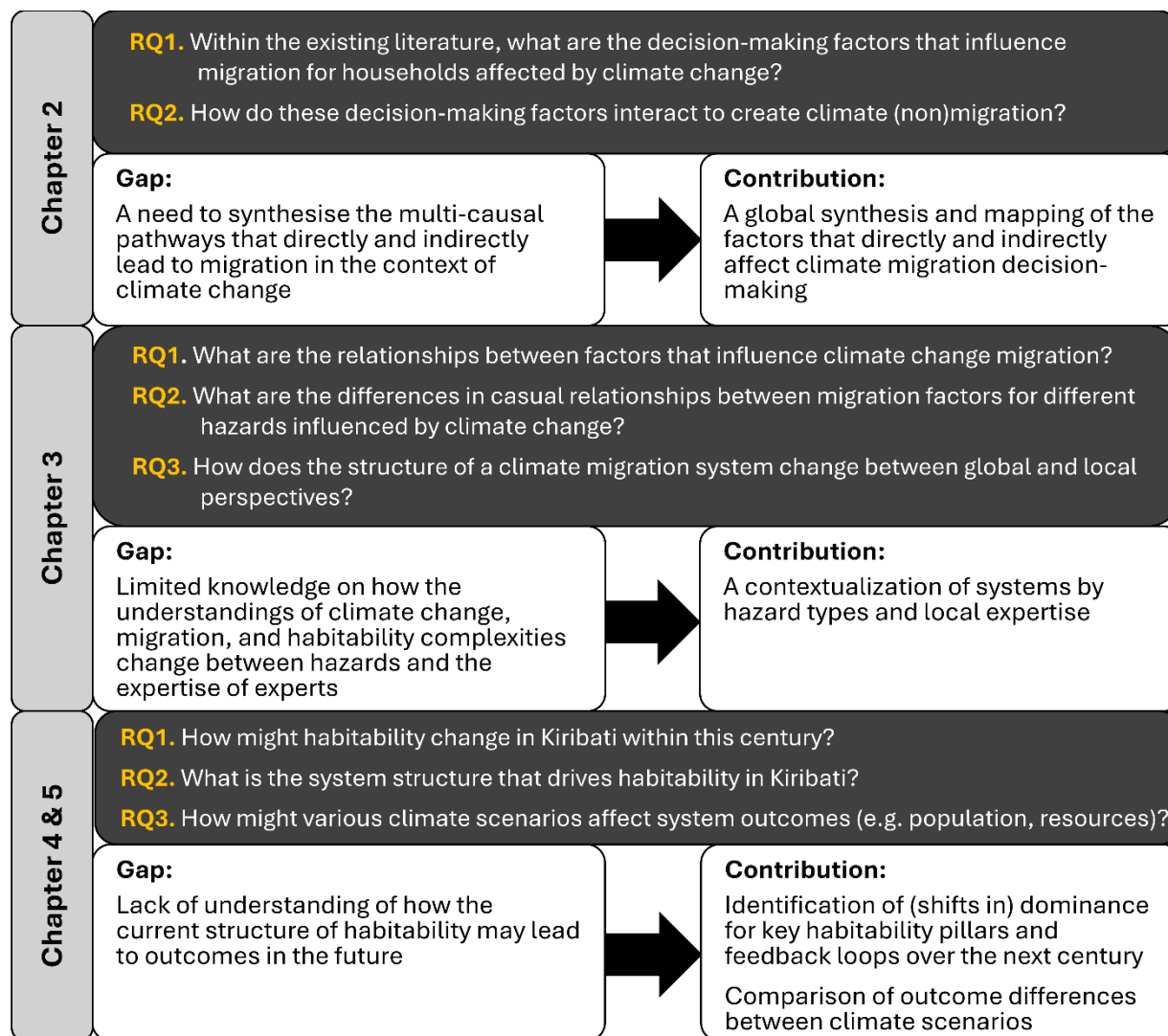


Figure 6-2 Summary of chapters' research questions, gaps, and contributions

6.2. Theoretical Contributions

The field of climate habitability is a growing, albeit nascent, field of scholarship (Sterly et al., 2025). As researchers debate the implications of climate impacts for affected populations, the work of this thesis advances theory related to (1) the causality between climate impacts, uninhabitability, and displacement, (2) reinforcing the importance of the locally derived systems knowledge by showing contrasts with global knowledge of academic experts (3) the operationalisation of theory to quantifiably simulate habitability, and (4) the analysis of key drivers of habitability to identify future trends in the Pacific.

Many studies recognise the multi-faceted nature of systems surrounding migration decisions and habitability perceptions (Black et al., 2011; Duvat et al., 2021). However, directly linking hazards to displacement is still common for models (Kam et al., 2021; Koubi et al., 2016) and media (Honarmand Ebrahimi & Ossewaarde, 2019). By systematically mapping the myriad of direct and indirect linkages that

affect climate migration decision-making, I support conceptual claims of multi-causality with comprehensive evidence from the literature. Through a systems analysis, I helped untangle the complex web of decision-making into refined relationships. My thesis advances scholarship at the nexus of climate, habitability, and migration by coupling multi-causal migration knowledge with habitability theories to more clearly and quantifiably link habitability changes to mobility outcomes.

In addition to recognition of the importance of multi-causal thinking, there have been increased calls for studies to approach topics of habitability and migration through more bottom-up, community-engaged research (Farbotko, 2023; Horton, Sherbinin, et al., 2021; Piggott-McKellar et al., 2020; Stege, 2018). Previous discussions have focused on the ethical implications of Western research generalising and delineating points of uninhabitability and deciding when communities should move (Farbotko & Campbell, 2022; Merschroth et al., 2024). In this thesis, I add to the argument of community-engaged research by comparatively showing the difference in mental models between those with academic and lived experience expertise. In these comparisons, local experts were able provide contextual nuance to factors, discussing their relevancy and relationship to other factors in Kiribati.

Moving forward, it is important to recognise that global theories provide comprehensive overviews (i.e. starting points) for conceptualising migration drivers and habitability pillars that should be whittled down or adapted through local knowledge, such as I did in the factor relevancy activity (*Chapter 3, Section 3.1.2*). The omissions and revisions of factor concepts from scoping discussants, as well as the rich narratives of each factor relationship from workshop participants provides evidence of the benefits of localised knowledge. I point to the value of these added contextual understandings, in addition to the moral and ethical rationales, to encourage increased investment in community engagement in research and project planning.

Related to the development of the SFS Model, my thesis advanced theory in both the novel application of habitability theory to simulation modelling and the theoretical insights which arose from the model. The operationalisation of habitability through a simulation model offers a new methodology for assessing habitability, which has previously only been qualitatively considered. My work is transdisciplinary, integrating knowledge from multiple disciplines and the local knowledge of non-academic partners. The model developed in this thesis bridges both top-down and bottom-up climate knowledge to understand how climate change may affect habitability in the future. My SFS Model successfully builds from both bottom-up local knowledge data to develop a community-centred conceptualisation of the habitability system and top-down climate science projections and theoretical frameworks to understand how the system may experience changes resulting from climate change. The coupling of both top-down and bottom-up approaches has previously been recommended as a path forward in research to build from global knowledge while accounting for the nuance and uniqueness of specific contexts (Horton, Sherbinin, et al., 2021).

The insights gained from my SFS Model also contribute to the conversation of future habitability by indicating that warnings of mass displacement from Pacific atolls may be overestimated. Instead, I found that internal migration, rather than international, is likely to dominate mobility trends in Kiribati. In evaluating climate migration in terms of habitability, this finding reinforces that future modelling should incorporate not just drivers of migration but also anchor points that affect mobility decisions. In Kiribati,

costs of movement abroad- both financial and emotional- affected people's decisions to move internally rather than abroad.

In analysing the dynamics of habitability in Kiribati, the SFS Model also allowed me to identify shifts in which pillars were most influential over time. As an example from scenario SSP1-2.6, I found that feedback dominance shifted from water conservation practices to internal movement to water infrastructure adequacy in the near-, mid-, and long-term respectively. This identification of dynamics driving habitability pillars helps to advance adaptation planning to meet changing needs over time. This finding reinforces that habitability should not be viewed as static or binary, but evolving, and points to the need for similarly regularly updated climate adaptation priorities to meet needs.

6.3. Practical Contributions

My thesis findings also offer useful insights for policymakers, development and humanitarian agencies, and governments. This work's main practical contribution is the use of systems thinking to support climate-affected communities adapt to climate change in the Pacific through the identification of intervention points over time. Systems thinking has previously been used to examine the far reaching effects of climate change through multiple sectors in New Zealand and has shown to be useful in bridging the transition between disaster risk response and climate change adaptation (Lawrence et al., 2020). Likewise, by mapping the interconnection between social and environmental systems in Pacific Islands affected by climate change, we can look to develop adaptation strategies that address current needs without putting future needs or other sectors at risk.

Within the specific context of Kiribati, the causal relationships were analysed through a simulation model to identify leverage (i.e. intervention) points and how they might change over time. Leverage points have the highest potential for creating cascading effects throughout systems with minimal potential of being influenced by outside, unintended factors. The results of Chapter 5 show that water security issues dominate the near term (2025-2060) and long term (2085-2111). The identification of water as habitability pillar priority and the need to invest in water infrastructure is well aligned with findings from Chapter 3 which points to *physical infrastructure* as an ideal leverage point for systems experiencing drought. In Kiribati, *physical infrastructure* for water resources could be in the form of strengthened centralised water supply systems or more rainwater harvesting tanks, which were found to link to increased *health, livelihoods, social capital*, and many more knock-on effects that would improve the quality of life in Kiribati.

In the mid-period (2060-2085) I found that internal migration dynamics may play a key role in Kiribati with high levels of movement from the outer islands to South Tarawa. These results suggest that higher levels of investment now in developing the outer islands could help to allow people to stay in their home islands and avoid over-densification of South Tarawa. While there have been efforts to develop Kiritimati Island (ADB, 2010), there has been less attention given to other outer islands in Kiribati. In Chapter 2, I found that investments particularly in *livelihoods* and subsequent gains in household *financial capital* greatly affect migration decision-making. Investments in livelihood opportunities in the outer islands could help support people to stay and generate their income locally, reducing the pull of income differential between islands. For example, recent government subsidies in copra production has been found to incentivise living

in the outer islands (The World Bank, 2024). Similar programs could continue to encourage livelihood growth outside of South Tarawa.

Lastly, the results of my model show that Habitable Land did not emerge as a top habitability pillar in the coming century. While land changes are commonly discussed as a proxy for habitability, my work emphasises the need to expand our focus to other pillars for a more comprehensive view what makes a place habitable. This is not to say that land loss will not occur or be important, only that it is less dominant in this model than other driving dynamics, such as water challenges and internal movement.

Indeed, analysis of land area in South Tarawa shows noticeable decline without the continuation of reclamation efforts. Land loss would exacerbate existing population density issues in the capital island, suggesting the need for protection measures such as erosion control or land reclamation projects. In Chapter 3, I found that *land* was a leverage point in Kiribati's social-ecological system, indicating that developing strategies to limit land loss could have a cascade of benefits. Other leverage points, such as investments in building infrastructure, could assist in stemming home loss, building damage, and other indirect impacts of sea level rise and related land loss. These interventions fit well with existing humanitarian and development initiatives that assist in housing reconstruction/ rehabilitation projects (CARE International, 2024; Habitat For Humanity, 2024). By further investing in these programs, we can create a flow of benefits, including improved health, food security, and home-based livelihood opportunities, among others to support resiliency in Kiribati.

6.4. Future Directions

While this thesis provides a strong foundation of knowledge, future studies should continue to examine adaptation planning for Kiribati and other Pacific Island nations. I intentionally chose to develop a stock and flow model for its ability to examine how the structure of a system leads to outcomes. In my thesis work, I used the model to explore how the system structure leads to changes in habitability drivers over time. However, there is further potential to use the SFS Model to perform policy scenario analysis. In Chapter 5, I identify possible policy interventions based on model results; however, future research on policy scenarios should be developed in collaboration with local partners. Future work should test how various adaptation plans can be used to help communities in Kiribati adapt to the impacts of climate change. Strategic policy planning that includes long-term dynamics is useful in designing intervention strategies that avoid unintended maladaptation.

The SFS Model also presents a useful template which I hope can be used and built upon in future research. The structure of the system identified in this model represents a snapshot of the system in Kiribati as it is currently. As the system changes, the trends and outcomes identified here will also likewise change. Future work should include maintaining and updating this structure to match system changes as policies are adopted. The template of this model may also be useful as a structure from which to adapt and build to understand how climate change may affect other similar atoll nations. As emphasised in this thesis, localised knowledge is needed to ensure an adapted model is fit-for-purpose within a new system. The conceptualisation and operationalisation of habitability, as used here, is a useful starting point though in building our understanding of climate impacts and the effects on habitability around the world.

More generally, I recommend future research to continue the use of transdisciplinary methodologies to ensure practical relevance of habitability and migration research for climate-affected communities. I recommend increased coordination between academic research teams and governments to develop research agendas that address top areas of needs regarding future habitability in the face of climate change. Further, research on such an existential topic should continue to push to prioritise the leadership of affected communities in directing projects to work towards more grounded, ethical, and just solutions.

6.5. Conclusion

The work in this thesis advances our understanding of how climate change relates to habitability and migration in the Pacific by examining the multi-causal relationships between factors and identifying points of intervention for adaptation planning. Through the examination of system dynamics, as built from the perspectives of local experts in Kiribati, I found that warnings of mass climate displacement may be overstated. Resource availability and economic opportunity differentials between islands are likely to lead to high rates of internal migration in Kiribati. However, a deep connection to land and other anchoring factors has the potential to keep people in place in the face of climate impacts.

I present the findings from this thesis as a discussion point from which to spur dialogues on how to support communities to remain in their homes if they wish. The results of this work do not downplay the severity of climate change or its role in contributing to an existential crisis for atoll islanders, indeed, increased climate change mitigation is a necessary first step to supporting communities.

The significance of this work for Kiribati, and other atoll nations, is the emphasis on engaging with climate-affected communities to understand their preferences in adaptation and supporting their agency in choice. This means finding and funding ways for communities to maintain habitability at homes, according to their own conceptualisations, while also supporting pathways of dignified migration for those who would rather adapt to climate change through migration. Ultimately, this research highlights the need to understand habitability through a localised and systems-based lens to develop holistic climate change adaptation policies effectively.

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Appendix I

Factor Definitions

<p>Aid programs Programs that offer monetary or in-kind assistance Ex. livelihoods, shelter</p>
<p>Assets Physical things that are owned and worth money Ex. vehicles, livestock, equipment</p>
<p>Community Family, friends, neighbours, and other social networks</p>
<p>Cost of living Cost of rent/housing, regular food costs, etc.</p>
<p>Security Lack of unlawful activity Ex. no theft, drugs, exploitation, murder</p>
<p>Environmental degradation Air, Soil, or water quality getting worse</p>
<p>Food security Access to and availability of food to maintain health</p>
<p>Health Physical and mental health</p>
<p>Livelihoods Income-generating activities; jobs</p>

<p>Physical infrastructure (community) Community buildings (hospitals, schools), roads, utilities</p>
<p>Physical infrastructure (homes) Family houses and residences</p>
<p>Attachment to Kiribati Emotional ties to the land, culture, or society</p>
<p>Political stability Stable political system, lack of conflict (between citizen or citizens and the government)</p>
<p>Remittances Money sent to you from overseas</p>
<p>Resource availability Availability of natural resources needed for living such as water, wood, clean air</p>
<p>Safety perception for future Idea that Kiribati will be liveable for many generations</p>
<p>Social equality Even distribution of resources in society</p>
<p>Social services Health services (healthcare and sanitation), education services, community amenities</p>

Appendix II

Interview Guide

Interview Guide

Objectives:

- (1) Understand how the problem of long-term habitability loss (related to climate change) is conceptualized by stakeholders
- (2) Identify key factors that make Kiribati habitable
- (3) Prioritize and categorize the factors of habitability in Kiribati (how does shelter rank amongst stakeholders' priorities?)

Estimated Time: 1 hour

Agenda:

Topic	Activity	Key Questions
Climate change and its effect on habitability and liveability in Kiribati (20 min)	Open ended discussion	How do you think about this problem (of climate change in Kiribati) long term? <i>Does this match how I conceptualize the problem?</i>
Identification the main factors of habitability and habitability loss (10 min)	Listing of factors <i>(open ended, no prompts)</i>	Based on the previous description of the problem, what are some of the main factors at play? <i>Include both factors that contribute to making Kiribati enjoyable to live AND those that decrease habitability</i>
Alignment of factors to literature (20 min)	Discussion of how the factors identified through a global literature review apply to Kiribati <i>(discuss each factor individually)</i>	Does each factor contribute to habitability (loss) in Kiribati? Is there a more nuanced version of how this applies in Kiribati?
Prioritization (10 min)	Token exercise	If given 5 tokens to rank, which factors have the most importance? <i>Tokens will have 1 -5 numbering</i>

Appendix III

Impact Matrix

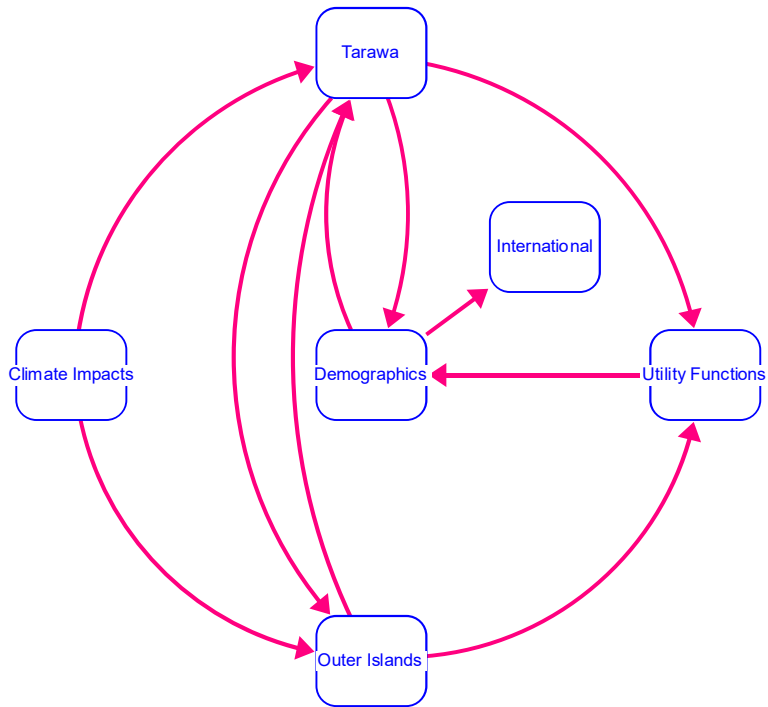
Impact Matrix from Participatory System Mapping Workshop

	Community	Household Expenses	Household Finances	Food Security	Future Safety	Health	Land	Livelihoods	Remittances	Water Availability	Shelter	Social Services	Transport Infrastructure	Utilities	Habitability
Community	0	0	0	-2	-2	-2	-3	2	2	-3	3	3	1	0	0
Household Expenses	0	0	-3	0	0	0	0	3	0	0	0	0	0	0	0
Household Finances	0	0	0	3	3	3	3	-2	0	3	3	3	0	3	3
Food Security	3	3	0	0	3	3	3	0	-3	0	0	0	0	0	3
Future Safety	3	0	-1	-2	0	2	0	3	0	0	0	2	2	2	3
Health	1	3	0	0	3	0	0	3	0	0	0	-2	0	0	2
Land	2	0	0	3	3	0	0	3	0	3	3	3	2	1	3
Livelihoods	0	0	3	3	3	0	0	0	0	0	0	0	0	1	2
Remittances	0	0	3	0	0	2	0	1	0	0	0	0	0	0	0
Water Availability	2	-2	0	1	2	3	0	2	0	0	0	0	0	1	3
Shelter	2	2	0	0	3	3	-2	2	0	0	0	0	0	2	3
Social Services	2	2	0	0	3	3	0	0	2	2	1	0	1	1	2
Transport Infrastructure	1	0	0	1	3	1	1	2	0	2	1	3	0	1	0
Utilities	2	2	2	0	0	2	0	0	1	1	0	2	1	0	2
Habitability	3	0	0	0	3	1	0	0	-2	0	0	0	2	2	0

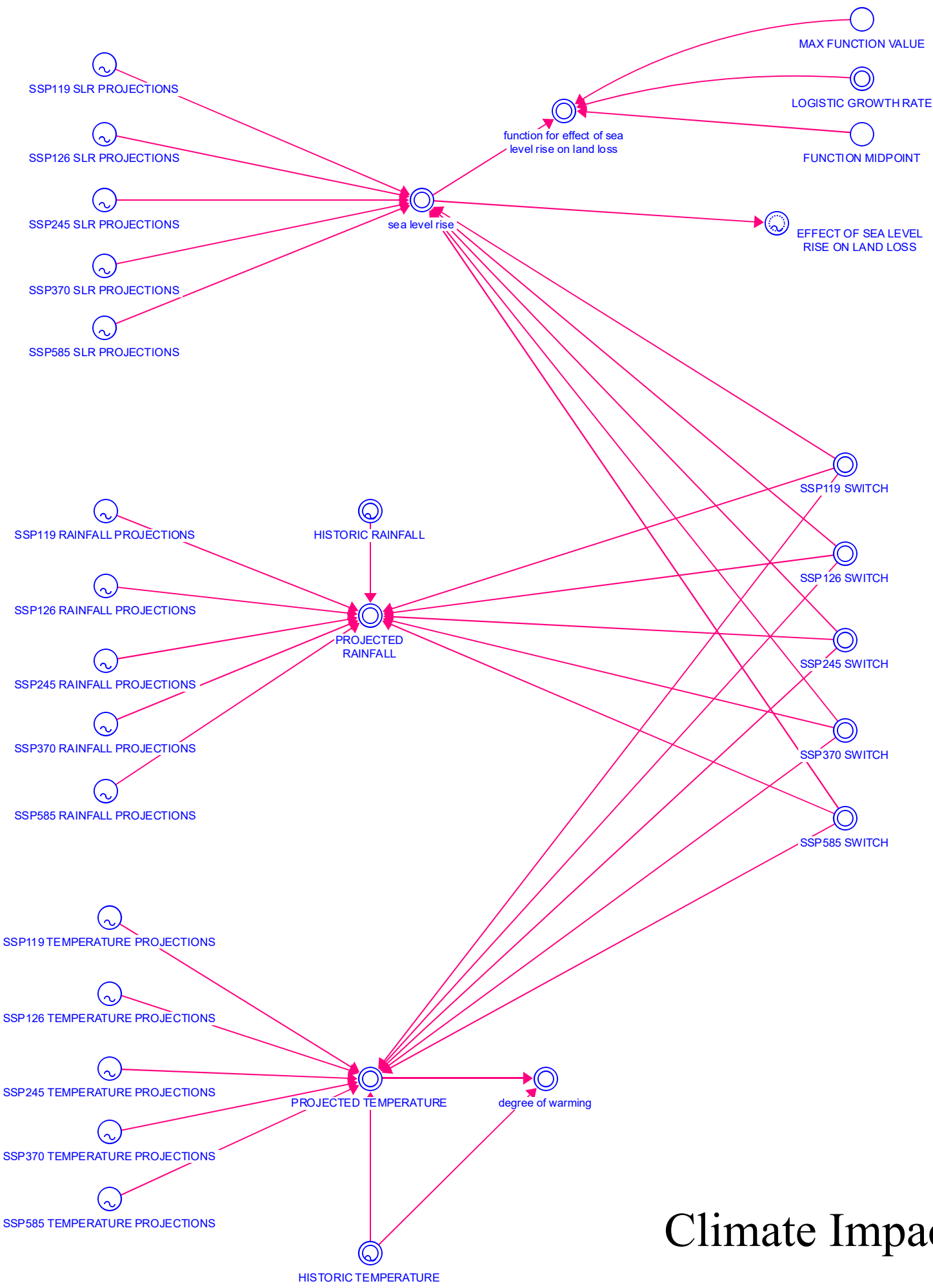
Appendix IV

Model Structure

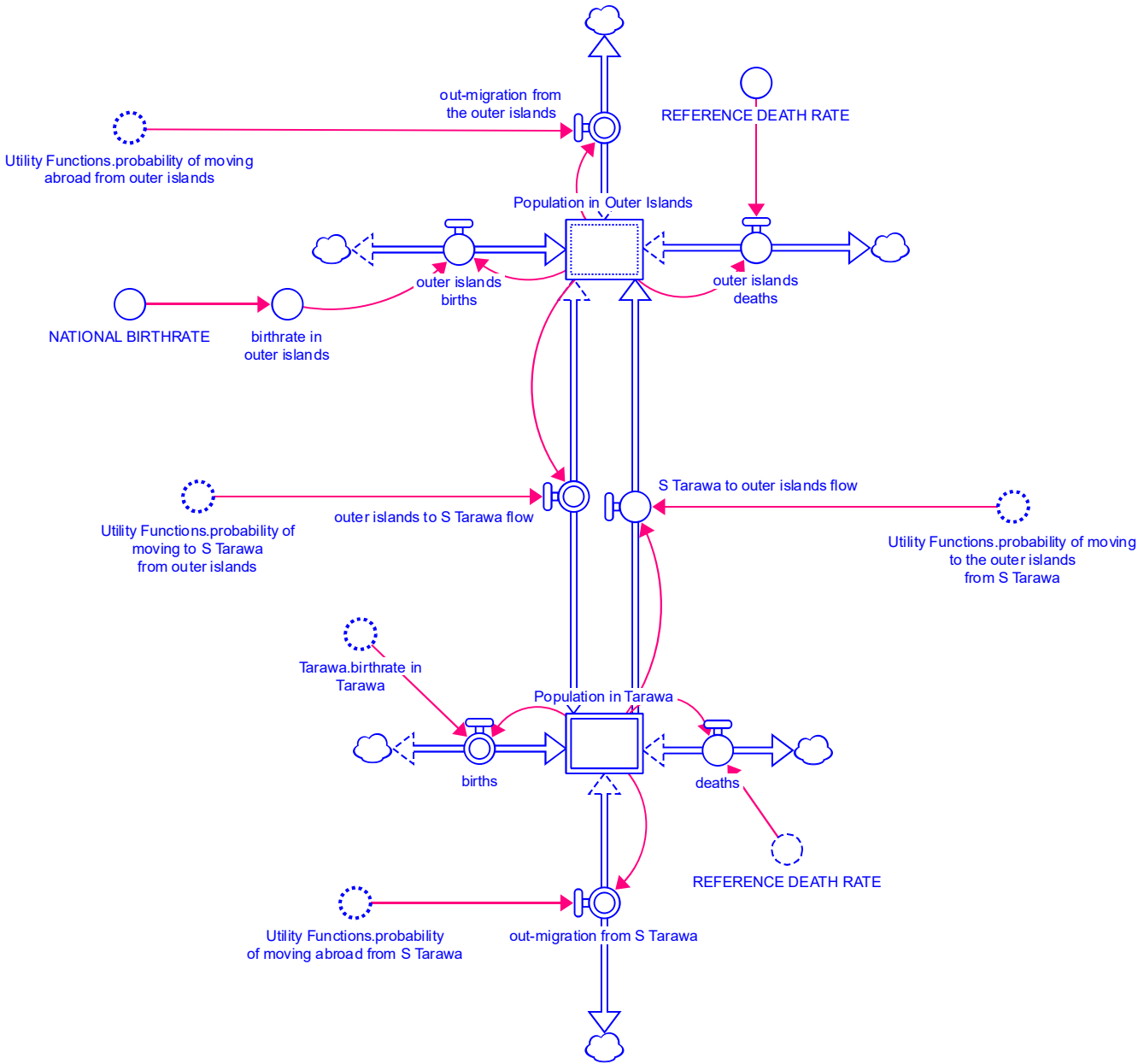
The simulation model is available in both .stmx and.xmile through the GitHub repository linked [here](#).



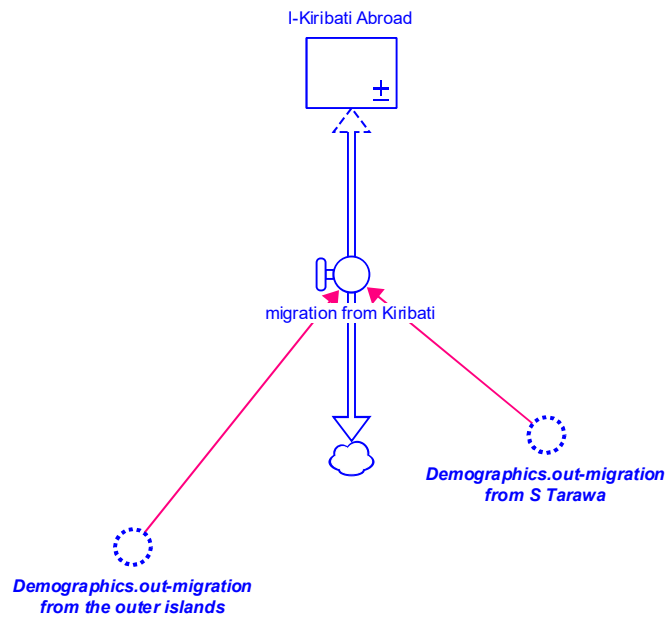
Top View



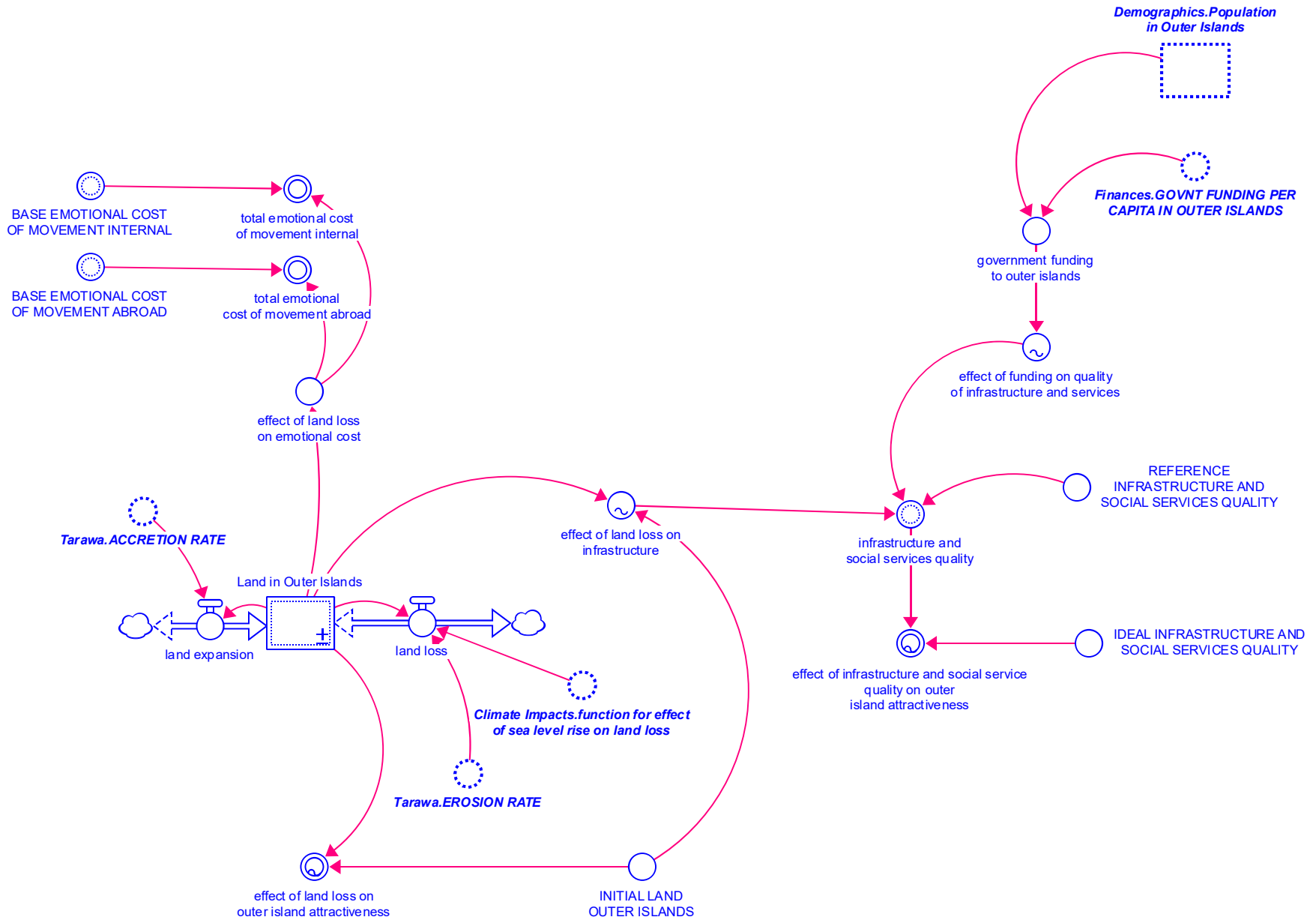
Climate Impacts



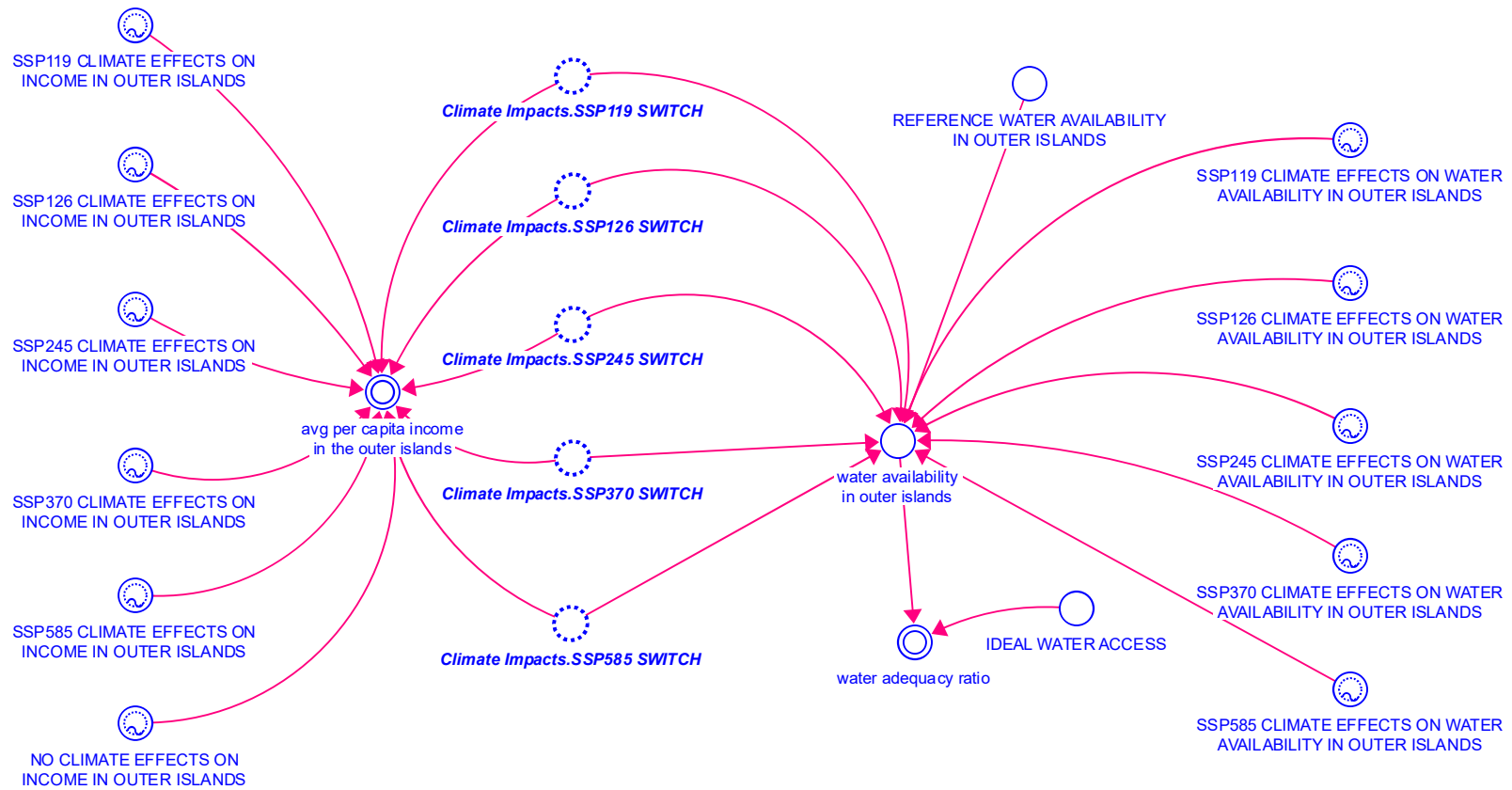
Demographics



International

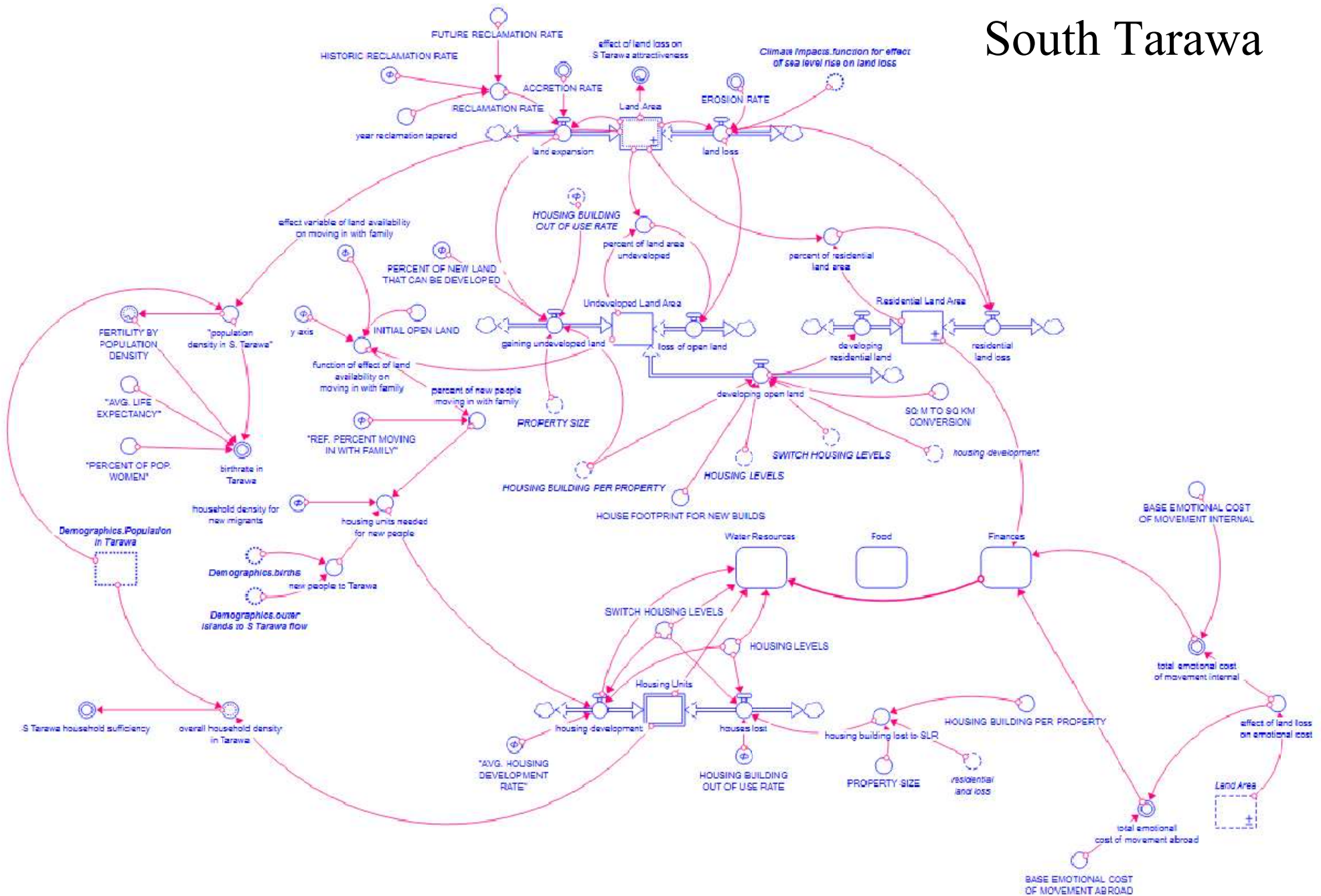


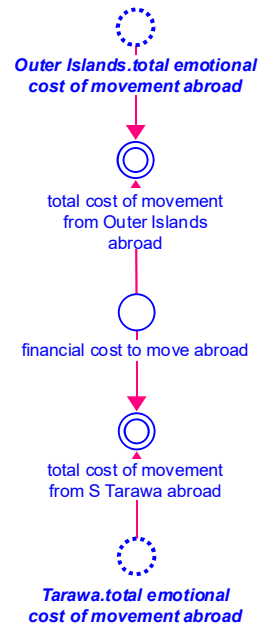
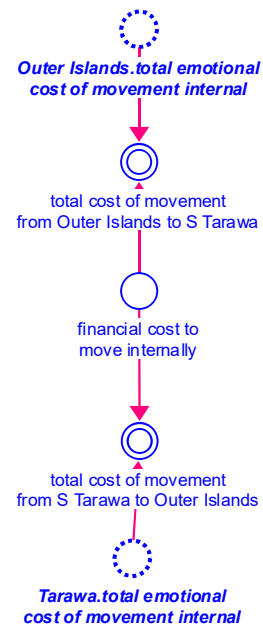
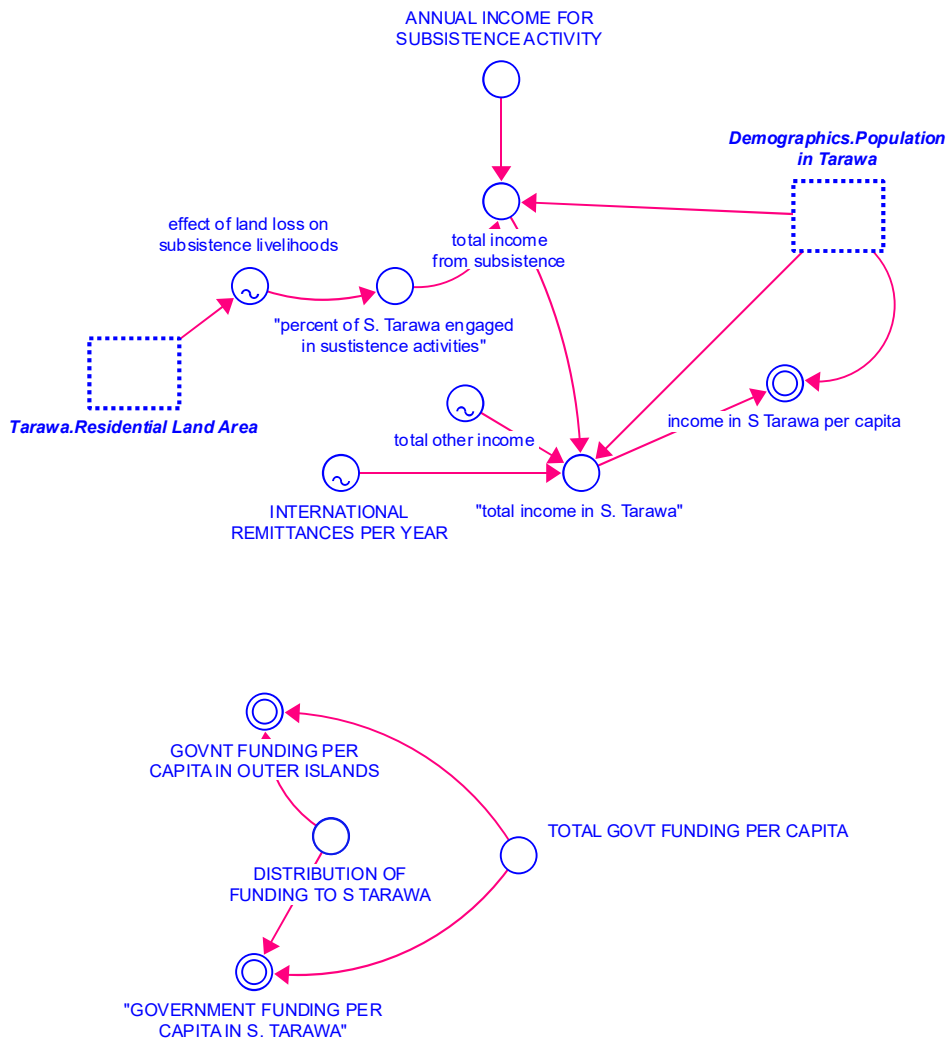
Outer Islands



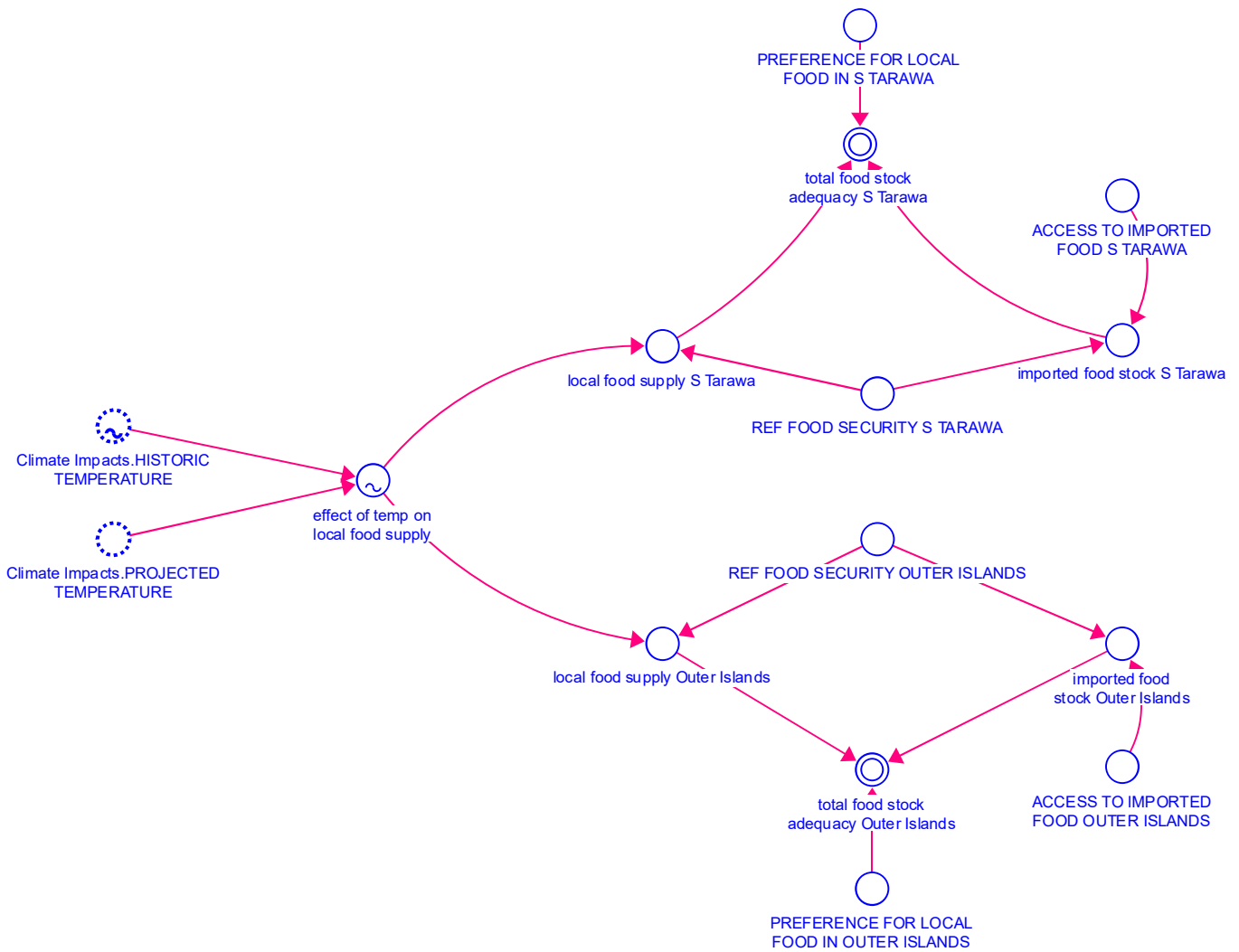
Outer Islands

South Tarawa

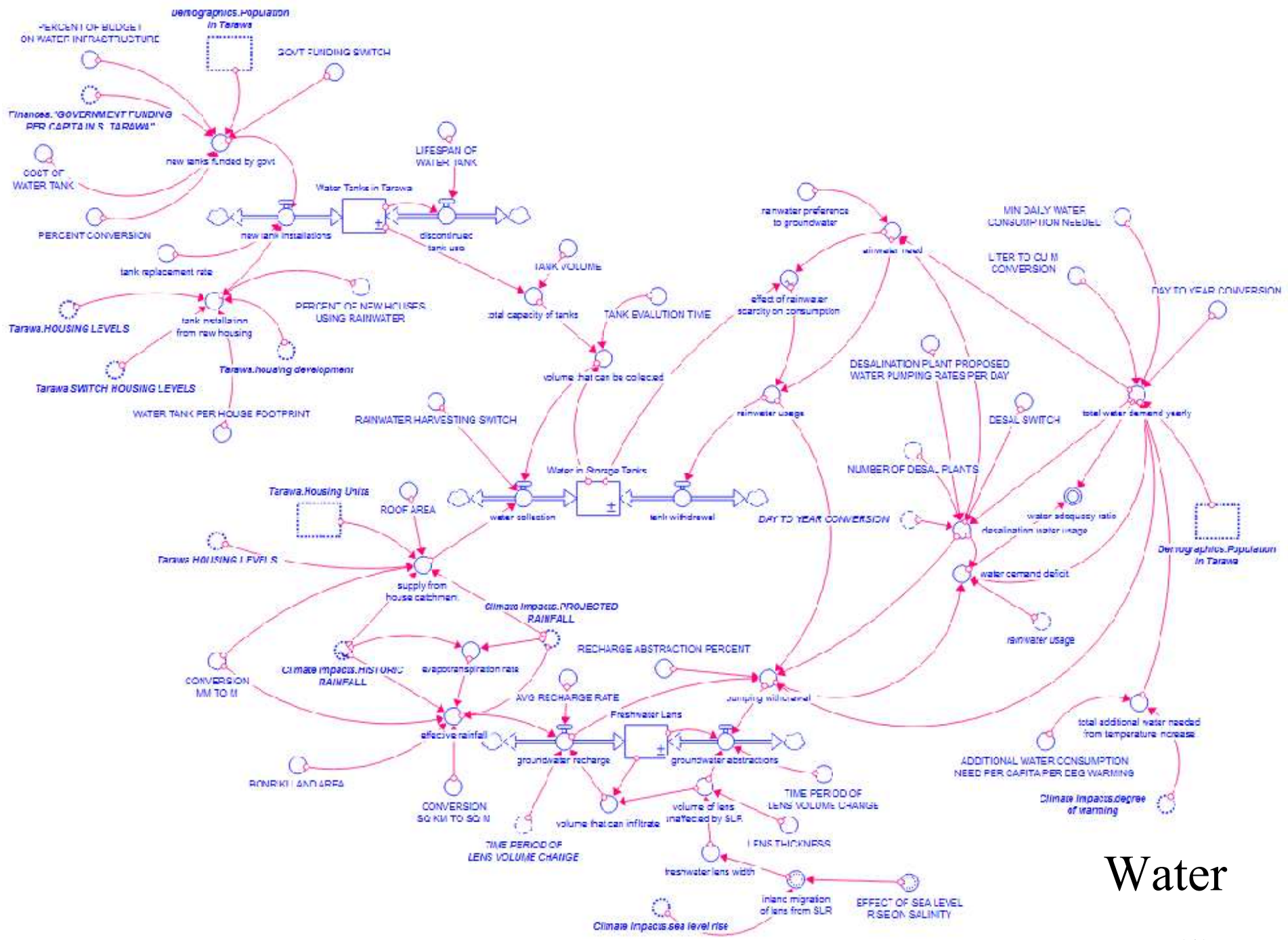




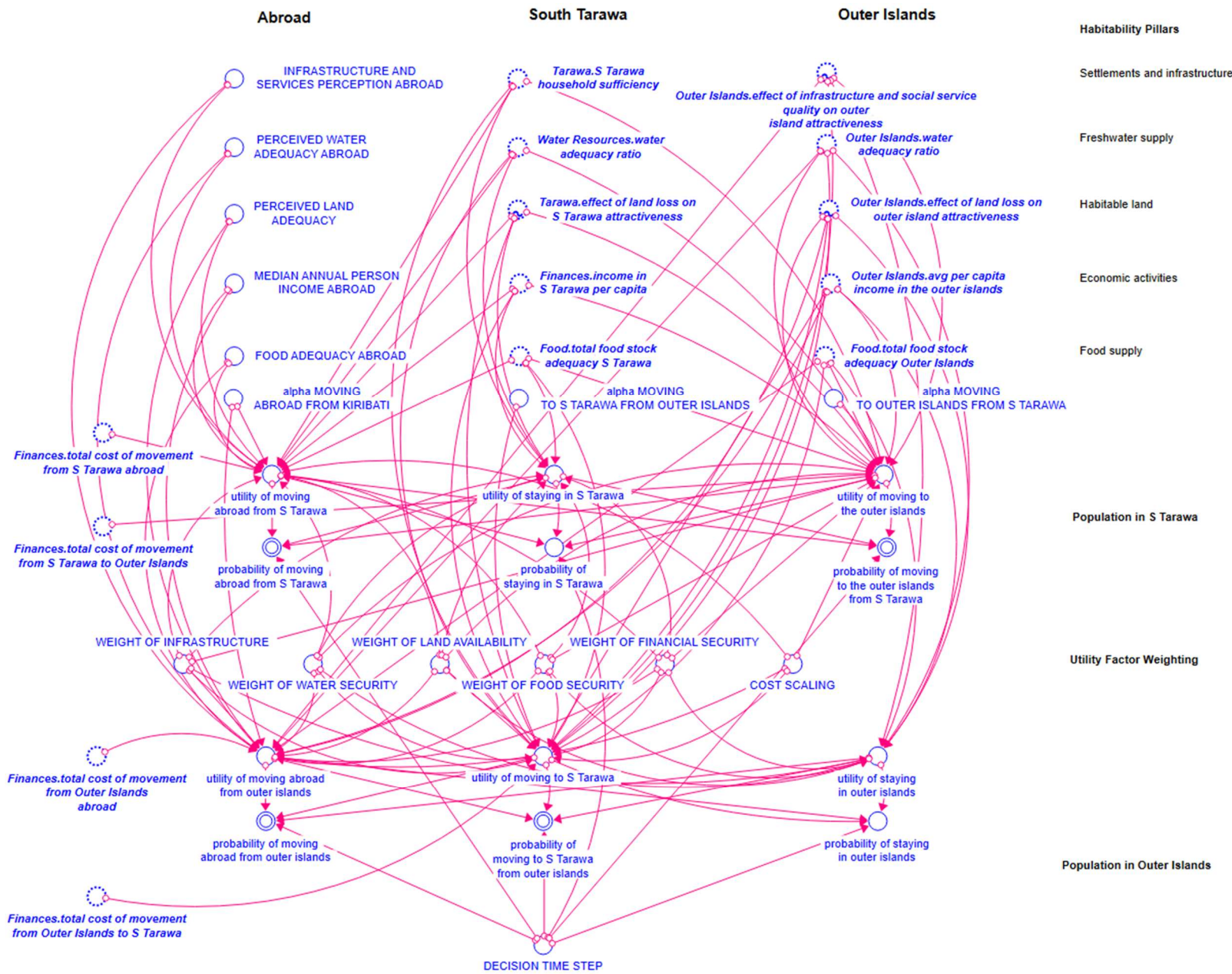
Finances



Food



Water



Utility Functions

Appendix V

Model Documentation

Model Documentation

Total	Count	Including Array Elements
Variables	302	302
Modules	9	
Stocks	11	11
Flows	26	26
Converters	265	265
Constants	93	93
Equations	198	198
Graphicals	45	45
Macro Variables	5	

	Equation	Properties	Units	Documentation	Annotation
Top-Level Model:					
Climate_Impacts:					
degree_of_warming	PROJECTED_TEMPERATURE- 27.77		Degrees C	The degree of warming is the projected temperature minus the average historical temperature between 1990-2022 (27.77deg c).	
EFFECT_OF_SEA_LEVEL_RISE_ON_LAND_LOSS	GRAPH(sea_level_rise) Points: (0.000, 0.000), (0.0612244897959, 0.0005165), (0.122448979592, 0.001171), (0.183673469388, 0.002004), (0.244897959184, 0.00307), (0.30612244898, 0.004438), (0.367346938776, 0.006198), (0.428571428571, 0.008466), (0.489795918367, 0.01139), (0.551020408163, 0.01516), (0.612244897959, 0.02001), (0.673469387755, 0.02625), (0.734693877551, 0.03425), (0.795918367347, 0.04447), (0.857142857143, 0.05746), (0.918367346939, 0.07386), (0.979591836735, 0.09439), (1.04081632653, 0.1198), (1.10204081633, 0.1509), (1.16326530612, 0.1883), (1.22448979592, 0.2323), (1.28571428571, 0.283), (1.34693877551, 0.3399), (1.40816326531, 0.4017), (1.4693877551, 0.4669), (1.5306122449, 0.5331), (1.59183673469, 0.5983), (1.65306122449, 0.6601), (1.71428571429, 0.717), (1.77551020408, 0.7677), (1.83673469388, 0.8117), (1.89795918367, 0.8491), (1.95918367347, 0.8802), (2.02040816327, 0.9056), (2.08163265306, 0.9261), (2.14285714286, 0.9425), (2.20408163265, 0.9555), (2.26530612245, 0.9658), (2.32653061224, 0.9738), (2.38775510204, 0.980), (2.44897959184, 0.9848), (2.51020408163, 0.9886), (2.57142857143, 0.9915), (2.63265306122, 0.9938), (2.69387755102, 0.9956), (2.75510204082, 0.9969), (2.81632653061, 0.998), (2.87755102041, 0.9988), (2.9387755102, 0.9995), (3.000, 1.000)		1/year	Relationship is estimated from researcher judgement. Highest elevation in Tarawa is 3m.	
function_for_effect_of_sea_level_rise_on_land_loss	MAX_FUNCTION_VALUE/(1+ EXP(-LOGISTIC_GROWTH_RATE*(sea_level_rise-FUNCTION_MIDPOINT)))		1/year	This logistic equation represents an S-shaped curve where parameters can be calibrated. $f(x) = L / (1 + e^{-k(x - x_0)})$ where: L = curve's max value k = logistic growth rate x = sea level rise x_0 = sigmoid midpoint	
FUNCTION_MIDPOINT	1.5		meters	As the primary land analysis is based in South Tarawa, the highest elevation (3m) was used as the maximum x value. The midpoint value was thus 1.5m.	

HISTORIC_RAINFALL	GRAPH(TIME) Points: (1990.00, 1861.59), (1991.00, 1876.01), (1992.00, 1746.04), (1993.00, 1851.57), (1994.00, 1458.13), (1995.00, 1047.48), (1996.00, 840.4), (1997.00, 1536.56), (1998.00, 1276.17), (1999.00, 1303.29), (2000.00, 1237.89), (2001.00, 1436.13), (2002.00, 1425.16), (2003.00, 1424.61), (2004.00, 1424.26), (2005.00, 1423.99), (2006.00, 1423.91), (2007.00, 1423.07), (2008.00, 1421.25), (2009.00, 1424.72), (2010.00, 1423.85), (2011.00, 1424.26), (2012.00, 1424.26), (2013.00, 1424.26), (2014.00, 1424.26), (2015.00, 1424.26), (2016.00, 1424.26), (2017.00, 1424.26), (2018.00, 1424.26), (2019.00, 1421.96), (2020.00, 1388.57), (2021.00, 1393.91), (2022.00, 1238.1)		mm / year	Historical rainfall data from World Bank Climate Knowledge Portal. Data downloaded from graphic, 'Observed Annual Precipitation of Kiribati for 1901-2022'. The annual mean rainfall per year was used. Note: The same value was reported from 2011-2018. This data was used in the absence of other data to validate. Source: https://climateknowledgeportal.worldbank.org/country/kiribati/climate-data-historical
HISTORIC_TEMPERATURE	GRAPH(TIME) Points: (1990.00, 27.750), (1991.00, 27.720), (1992.00, 27.710), (1993.00, 27.670), (1994.00, 27.740), (1995.00, 27.790), (1996.00, 27.750), (1997.00, 27.750), (1998.00, 27.790), (1999.00, 27.650), (2000.00, 27.720), (2001.00, 27.770), (2002.00, 27.790), (2003.00, 27.790), (2004.00, 27.800), (2005.00, 27.800), (2006.00, 27.780), (2007.00, 27.760), (2008.00, 27.730), (2009.00, 27.750), (2010.00, 27.690), (2011.00, 27.710), (2012.00, 27.790), (2013.00, 27.780), (2014.00, 27.780), (2015.00, 27.800), (2016.00, 27.810), (2017.00, 27.800), (2018.00, 27.780), (2019.00, 27.870), (2020.00, 27.920), (2021.00, 27.890), (2022.00, 27.770)		Degrees C	Data for historic temperature is from the World Bank Climate Knowledge Portal (Table: 'Observed Annual Average Mean Surface Air Temperature of Kiribati for 1901-2022'). Source: https://climateknowledgeportal.worldbank.org/country/kiribati/climate-data-historical
LOGISTIC_GROWTH_RATE	5		1/meters	Value was determined through calibration to historic land area data.
MAX_FUNCTION_VALUE	1		1 / year	A maximum function value of 1 indicates 100% inundation.
PROJECTED_RAINFALL	IF TIME < 2023 THEN HISTORIC_RAINFALL ELSE (IF SSP119_SWITCH = 1 THEN SSP119_RAINFALL_PROJECTIONS ELSE (IF SSP126_SWITCH = 1 THEN SSP126_RAINFALL_PROJECTIONS ELSE (IF SSP245_SWITCH = 1 THEN SSP245_RAINFALL_PROJECTIONS ELSE (IF SSP370_SWITCH = 1 THEN SSP370_RAINFALL_PROJECTIONS ELSE (IF SSP585_SWITCH = 1 THEN SSP585_RAINFALL_PROJECTIONS ELSE HISTORIC_RAINFALL))))))		mm / year	Historic data was available and used up to 2023, after which projected rainfall data was used for each respective SSP.
PROJECTED_TEMPERATURE	IF TIME < 2022 THEN HISTORIC_TEMPERATURE ELSE (IF SSP119_SWITCH = 1 THEN SSP119_TEMPERATURE_PROJECTIONS ELSE (IF SSP126_SWITCH = 1 THEN SSP126_TEMPERATURE_PROJECTIONS ELSE (IF SSP245_SWITCH = 1 THEN SSP245_TEMPERATURE_PROJECTIONS ELSE (IF SSP370_SWITCH = 1 THEN SSP370_TEMPERATURE_PROJECTIONS ELSE (IF SSP585_SWITCH = 1 THEN SSP585_TEMPERATURE_PROJECTIONS ELSE HISTORIC_TEMPERATURE))))))		Degrees C	Historic data was available and used up to 2022, after which projected rainfall data was used for each respective SSP. Note: there is a discrepancy between historic data in 2022 (27.77deg C) and the projected degrees of warming in 2022 for the SSPs where the projected temperature is lower than observed. As such, there is a dip in the trend at this point.
sea_level_rise	IF TIME < 2020 THEN RAMP(0.0017, 1990, 2020) ELSE (IF SSP119_SWITCH = 1 THEN SSP119_SLR_PROJECTIONS ELSE (IF SSP126_SWITCH = 1 THEN SSP126_SLR_PROJECTIONS ELSE (IF SSP245_SWITCH = 1 THEN SSP245_SLR_PROJECTIONS ELSE (IF SSP370_SWITCH = 1 THEN SSP370_SLR_PROJECTIONS ELSE (IF SSP585_SWITCH = 1 THEN SSP585_SLR_PROJECTIONS ELSE 0.05))))))		meters	The average sea level from 1995-2014 (1.6535m) in Kiribati was used as the baseline. The ramp from 1990-2020 was calculated as the slope from baseline historic level to the beginning of the projections in 2020 (~1.70m). After 2020, IPCC data was used for each respective SSP.

SSP119_RAINFALL_PROJECTIONS	GRAPH(TIME) Points: (2023.00, 1167.33), (2024.00, 1220.17), (2025.00, 1233.9), (2026.00, 1245), (2027.00, 1280.07), (2028.00, 1301.72), (2029.00, 1215.78), (2030.00, 1166.27), (2031.00, 1372.81), (2032.00, 1211.7), (2033.00, 1182.72), (2034.00, 1246.4), (2035.00, 1281.81), (2036.00, 1247.51), (2037.00, 1373.13), (2038.00, 1301.07), (2039.00, 1256.84), (2040.00, 1327.65), (2041.00, 1284.92), (2042.00, 1299.49), (2043.00, 1307.63), (2044.00, 1276.37), (2045.00, 1259.89), (2046.00, 1412.38), (2047.00, 1268.71), (2048.00, 1351.38), (2049.00, 1422.8), (2050.00, 1329.69), (2051.00, 1311.53), (2052.00, 1294.12), (2053.00, 1314.64), (2054.00, 1308.11), (2055.00, 1361.28), (2056.00, 1385.51), (2057.00, 1367.48), (2058.00, 1331.65), (2059.00, 1343.04), (2060.00, 1392.39), (2061.00, 1387), (2062.00, 1395.24), (2063.00, 1377.5), (2064.00, 1341.15), (2065.00, 1318.92), (2066.00, 1466.13), (2067.00, 1341.92), (2068.00, 1350.75), (2069.00, 1361.45), (2070.00, 1329.98), (2071.00, 1320.11), (2072.00, 1346.68), (2073.00, 1439.24), (2074.00, 1355.44), (2075.00, 1343.56), (2076.00, 1394.49), (2077.00, 1333.43), (2078.00, 1411.36), (2079.00, 1356.94), (2080.00, 1310.75), (2081.00, 1354.38), (2082.00, 1358.96), (2083.00, 1358.63), (2084.00, 1350.53), (2085.00, 1383.17), (2086.00, 1383.76), (2087.00, 1356.83), (2088.00, 1375.95), (2089.00, 1372.54), (2090.00, 1332.2), (2091.00, 1361.32), (2092.00, 1354.06), (2093.00, 1356.43), (2094.00, 1380.08), (2095.00, 1364.32), (2096.00, 1356.94), (2097.00, 1366.57), (2098.00, 1434.37), (2099.00, 1383.03), (2100.00, 1423.84)		mm / year	Data from Climate Change Knowledge Portal, 'Projected Precipitation'. https://climateknowledgeportal.worldbank.org/country/kiribati/cmip5
SSP119_SLR_PROJECTIONS	GRAPH(TIME) Points: (2020.00, 0.054), (2030.00, 0.100), (2040.00, 0.138), (2050.00, 0.193), (2060.00, 0.230), (2070.00, 0.293), (2080.00, 0.342), (2090.00, 0.404), (2100.00, 0.455)		meters	Projections are based on 'IPCC AR6 Sea-Level Rise Projections' specifically for Betio, South Tarawa, Kiribati (psmsl_id 1804). Median values for each SSP projection was used. Projection values are relative to a 1995-2014 baseline. This baseline was calculated to be 1.6535m from the Australian Government Bureau of Meteorology's historical sea level data.
SSP119_SWITCH	0		Dimensionless	Switch turns on scenario for SSP 1-1.9.

<p>SSP119_TEMPERATURE_PROJECTIONS</p>	<p>GRAPH(TIME) Points: (2014.00, 26.890), (2015.00, 27.010), (2016.00, 27.060), (2017.00, 27.120), (2018.00, 27.140), (2019.00, 27.110), (2020.00, 27.110), (2021.00, 27.180), (2022.00, 27.170), (2023.00, 27.220), (2024.00, 27.220), (2025.00, 27.230), (2026.00, 27.260), (2027.00, 27.330), (2028.00, 27.370), (2029.00, 27.240), (2030.00, 27.350), (2031.00, 27.470), (2032.00, 27.320), (2033.00, 27.310), (2034.00, 27.340), (2035.00, 27.380), (2036.00, 27.420), (2037.00, 27.490), (2038.00, 27.510), (2039.00, 27.440), (2040.00, 27.450), (2041.00, 27.480), (2042.00, 27.480), (2043.00, 27.490), (2044.00, 27.460), (2045.00, 27.520), (2046.00, 27.580), (2047.00, 27.500), (2048.00, 27.590), (2049.00, 27.570), (2050.00, 27.520), (2051.00, 27.490), (2052.00, 27.470), (2053.00, 27.500), (2054.00, 27.470), (2055.00, 27.510), (2056.00, 27.540), (2057.00, 27.550), (2058.00, 27.540), (2059.00, 27.520), (2060.00, 27.530), (2061.00, 27.510), (2062.00, 27.510), (2063.00, 27.470), (2064.00, 27.470), (2065.00, 27.470), (2066.00, 27.500), (2067.00, 27.450), (2068.00, 27.470), (2069.00, 27.480), (2070.00, 27.430), (2071.00, 27.450), (2072.00, 27.450), (2073.00, 27.440), (2074.00, 27.440), (2075.00, 27.400), (2076.00, 27.400), (2077.00, 27.390), (2078.00, 27.380), (2079.00, 27.370), (2080.00, 27.360), (2081.00, 27.390), (2082.00, 27.400), (2083.00, 27.380), (2084.00, 27.350), (2085.00, 27.380), (2086.00, 27.360), (2087.00, 27.350), (2088.00, 27.350), (2089.00, 27.340), (2090.00, 27.340), (2091.00, 27.350), (2092.00, 27.350), (2093.00, 27.340), (2094.00, 27.410), (2095.00, 27.340), (2096.00, 27.380), (2097.00, 27.380), (2098.00, 27.430), (2099.00, 27.450), (2100.00, 27.440)</p>		<p>Degrees C</p>	<p>Data for projected temperature is from the World Bank Climate Knowledge Portal (Table: 'Projected Average Mean Surface Air Temperature Kiribati; (Ref. Period:1995-2014), Multi-Model Ensemble').</p> <p>Source: https://climateknowledgeportal.worldbank.org/country/kiribati/climate-data-projections</p>	
<p>SSP126_RAINFALL_PROJECTIONS</p>	<p>GRAPH(TIME) Points: (2023.00, 1260.31), (2024.00, 1399.4), (2025.00, 1196.26), (2026.00, 1154.97), (2027.00, 1187.94), (2028.00, 1405.49), (2029.00, 1304.56), (2030.00, 1264.23), (2031.00, 1427.6), (2032.00, 1155.48), (2033.00, 1319.07), (2034.00, 1418.04), (2035.00, 1196.03), (2036.00, 1182.95), (2037.00, 1336.78), (2038.00, 1263.27), (2039.00, 1243.77), (2040.00, 1226.55), (2041.00, 1335.3), (2042.00, 1340.87), (2043.00, 1363.93), (2044.00, 1272.48), (2045.00, 1269.65), (2046.00, 1600.82), (2047.00, 1313.62), (2048.00, 1182.41), (2049.00, 1373.21), (2050.00, 1589.61), (2051.00, 1402.61), (2052.00, 1101.57), (2053.00, 1265.18), (2054.00, 1325), (2055.00, 1487.43), (2056.00, 1557.23), (2057.00, 1463.88), (2058.00, 1256.94), (2059.00, 1270.18), (2060.00, 1302.74), (2061.00, 1367.56), (2062.00, 1393.32), (2063.00, 1449.48), (2064.00, 1394.45), (2065.00, 1112.87), (2066.00, 1784.74), (2067.00, 1507.69), (2068.00, 1347.37), (2069.00, 1271.56), (2070.00, 1302.84), (2071.00, 1223.27), (2072.00, 1409.27), (2073.00, 1601.04), (2074.00, 1304.19), (2075.00, 1337.9), (2076.00, 1438.73), (2077.00, 1364.49), (2078.00, 1833.67), (2079.00, 1392.75), (2080.00, 1168.29), (2081.00, 1416.76), (2082.00, 1558.89), (2083.00, 1294.41), (2084.00, 1311), (2085.00, 1466.28), (2086.00, 1591.07), (2087.00, 1430.22), (2088.00, 1302.08), (2089.00, 1378.55), (2090.00, 1303.01), (2091.00, 1511.85), (2092.00, 1353.85), (2093.00, 1312.62), (2094.00, 1151.67), (2095.00, 1308.08), (2096.00, 1230.38), (2097.00, 1254.07), (2098.00, 1504.77), (2099.00, 1457.32), (2100.00, 1464.1)</p>		<p>mm / year</p>	<p>Data from Climate Change Knowledge Portal, 'Projected Precipitation'.</p> <p>https://climateknowledgeportal.worldbank.org/country/kiribati/cmip5</p>	

SSP126_SLR_PROJECTIONS	GRAPH(TIME) Points: (2020.00, 0.056), (2030.00, 0.099), (2040.00, 0.147), (2050.00, 0.210), (2060.00, 0.259), (2070.00, 0.330), (2080.00, 0.391), (2090.00, 0.449), (2100.00, 0.510)		meters	Projections are based on 'IPCC AR6 Sea-Level Rise Projections' specifically for Betio, South Tarawa, Kiribati (psmsl_id 1804). Median values for each SSP projection was used. Projection values are relative to a 1995-2014 baseline. This baseline was calculated to be 1.6535m from the Australian Government Bureau of Meteorology's historical sea level data.
SSP126_SWITCH	0		Dimensionless	Switch turns on scenario for SSP 1-2.6.
SSP126_TEMPERATURE_PROJECTIONS	GRAPH(TIME) Points: (2014.00, 26.890), (2015.00, 27.080), (2016.00, 27.110), (2017.00, 27.090), (2018.00, 27.060), (2019.00, 27.350), (2020.00, 27.310), (2021.00, 27.180), (2022.00, 27.070), (2023.00, 27.400), (2024.00, 27.370), (2025.00, 27.190), (2026.00, 27.200), (2027.00, 27.300), (2028.00, 27.410), (2029.00, 27.350), (2030.00, 27.510), (2031.00, 27.580), (2032.00, 27.340), (2033.00, 27.530), (2034.00, 27.450), (2035.00, 27.440), (2036.00, 27.590), (2037.00, 27.560), (2038.00, 27.550), (2039.00, 27.510), (2040.00, 27.380), (2041.00, 27.670), (2042.00, 27.720), (2043.00, 27.610), (2044.00, 27.530), (2045.00, 27.570), (2046.00, 27.870), (2047.00, 27.660), (2048.00, 27.700), (2049.00, 27.820), (2050.00, 27.830), (2051.00, 27.610), (2052.00, 27.520), (2053.00, 27.790), (2054.00, 27.660), (2055.00, 27.760), (2056.00, 27.840), (2057.00, 27.770), (2058.00, 27.740), (2059.00, 27.720), (2060.00, 27.700), (2061.00, 27.760), (2062.00, 27.920), (2063.00, 27.830), (2064.00, 27.730), (2065.00, 27.770), (2066.00, 28.000), (2067.00, 27.770), (2068.00, 27.800), (2069.00, 27.980), (2070.00, 27.730), (2071.00, 27.750), (2072.00, 27.760), (2073.00, 27.900), (2074.00, 27.890), (2075.00, 27.890), (2076.00, 27.830), (2077.00, 27.850), (2078.00, 27.840), (2079.00, 27.790), (2080.00, 27.760), (2081.00, 27.970), (2082.00, 27.940), (2083.00, 27.800), (2084.00, 27.810), (2085.00, 27.790), (2086.00, 27.830), (2087.00, 27.710), (2088.00, 27.690), (2089.00, 27.710), (2090.00, 27.720), (2091.00, 27.850), (2092.00, 27.730), (2093.00, 27.670), (2094.00, 27.860), (2095.00, 27.650), (2096.00, 27.660), (2097.00, 27.630), (2098.00, 27.810), (2099.00, 27.830), (2100.00, 27.710)		Degrees C	Data for projected temperature is from the World Bank Climate Knowledge Portal (Table: 'Projected Average Mean Surface Air Temperature Kiribati; (Ref. Period:1995-2014), Multi-Model Ensemble'). Source: https://climateknowledgeportal.worldbank.org/country/kiribati/climate-data-projections

SSP245_RAINFALL_PROJECTI ONS	GRAPH(TIME) Points: (2023.00, 1092.68), (2024.00, 1272.56), (2025.00, 1257.53), (2026.00, 1300.68), (2027.00, 1101.41), (2028.00, 1178.82), (2029.00, 1403.35), (2030.00, 1026.44), (2031.00, 1387.39), (2032.00, 1332.67), (2033.00, 1035.28), (2034.00, 1307.76), (2035.00, 1282.08), (2036.00, 1084.69), (2037.00, 1550.15), (2038.00, 1327.61), (2039.00, 1112.76), (2040.00, 1419.58), (2041.00, 1409.22), (2042.00, 1262.12), (2043.00, 1174.72), (2044.00, 1148.96), (2045.00, 1183.4), (2046.00, 1462.39), (2047.00, 1155.72), (2048.00, 1525.48), (2049.00, 1418.44), (2050.00, 1240.55), (2051.00, 1294.82), (2052.00, 1342.03), (2053.00, 1262.26), (2054.00, 1328.9), (2055.00, 1472.07), (2056.00, 1223.78), (2057.00, 1288.79), (2058.00, 1389.2), (2059.00, 1615.82), (2060.00, 1560.91), (2061.00, 1364.62), (2062.00, 1541.98), (2063.00, 1470.3), (2064.00, 1311.35), (2065.00, 1538.01), (2066.00, 1649.34), (2067.00, 1146.92), (2068.00, 1611.08), (2069.00, 1341.78), (2070.00, 1242.15), (2071.00, 1411.49), (2072.00, 1552.06), (2073.00, 1689.13), (2074.00, 1291.28), (2075.00, 1317.84), (2076.00, 1776.5), (2077.00, 1574.7), (2078.00, 1375.73), (2079.00, 1270.85), (2080.00, 1375.76), (2081.00, 1557.94), (2082.00, 1405.64), (2083.00, 1620.45), (2084.00, 1689.21), (2085.00, 1682.4), (2086.00, 1553.91), (2087.00, 1480.84), (2088.00, 1701.92), (2089.00, 1437.21), (2090.00, 1452.37), (2091.00, 1439.49), (2092.00, 1619.99), (2093.00, 1444.08), (2094.00, 1579.43), (2095.00, 1677.48), (2096.00, 1406.68), (2097.00, 1394.27), (2098.00, 1719.36), (2099.00, 1345.17), (2100.00, 1672.54)		mm / year	Data from Climate Change Knowledge Portal, 'Projected Precipitation'. https://climateknowledgeportal.worldbank.org/country/kiribati/cmip5
SSP245_SLR_PROJECTIONS	GRAPH(TIME) Points: (2020.00, 0.052), (2030.00, 0.099), (2040.00, 0.152), (2050.00, 0.226), (2060.00, 0.290), (2070.00, 0.367), (2080.00, 0.452), (2090.00, 0.537), (2100.00, 0.628)		meters	Projections are based on 'IPCC AR6 Sea-Level Rise Projections' specifically for Betio, South Tarawa, Kiribati (psmsl_id 1804). Median values for each SSP projection was used. Projection values are relative to a 1995-2014 baseline. This baseline was calculated to be 1.6535m from the Australian Government Bureau of Meteorology's historical sea level data.
SSP245_SWITCH	0		Dimensionless	Switch turns on scenario for SSP 2-4.5.
SSP245_TEMPERATURE_PROJECTIONS	GRAPH(TIME) Points: (2014.00, 26.890), (2015.00, 26.920), (2016.00, 26.960), (2017.00, 27.050), (2018.00, 27.010), (2019.00, 26.900), (2020.00, 27.020), (2021.00, 27.270), (2022.00, 27.210), (2023.00, 27.180), (2024.00, 27.300), (2025.00, 27.230), (2026.00, 27.260), (2027.00, 27.270), (2028.00, 27.420), (2029.00, 27.340), (2030.00, 27.480), (2031.00, 27.660), (2032.00, 27.450), (2033.00, 27.300), (2034.00, 27.410), (2035.00, 27.470), (2036.00, 27.470), (2037.00, 27.730), (2038.00, 27.740), (2039.00, 27.520), (2040.00, 27.680), (2041.00, 27.690), (2042.00, 27.550), (2043.00, 27.650), (2044.00, 27.580), (2045.00, 27.790), (2046.00, 27.900), (2047.00, 27.740), (2048.00, 27.950), (2049.00, 27.940), (2050.00, 27.870), (2051.00, 27.900), (2052.00, 27.930), (2053.00, 27.820), (2054.00, 27.910), (2055.00, 27.900), (2056.00, 28.040), (2057.00, 28.070), (2058.00, 28.090), (2059.00, 28.210), (2060.00, 28.250), (2061.00, 27.990), (2062.00, 28.020), (2063.00, 28.070), (2064.00, 28.070), (2065.00, 28.200), (2066.00, 28.050), (2067.00, 27.990), (2068.00, 28.270), (2069.00, 28.160), (2070.00, 28.200), (2071.00, 28.330), (2072.00, 28.400), (2073.00, 28.320), (2074.00, 28.200), (2075.00, 28.290), (2076.00, 28.430), (2077.00, 28.350), (2078.00, 28.300), (2079.00, 28.450), (2080.00, 28.300), (2081.00, 28.390), (2082.00, 28.420), (2083.00, 28.500), (2084.00, 28.570), (2085.00, 28.650), (2086.00, 28.470), (2087.00, 28.560), (2088.00, 28.500), (2089.00, 28.470), (2090.00, 28.580), (2091.00, 28.630), (2092.00, 28.640), (2093.00, 28.420), (2094.00, 28.610), (2095.00, 28.560), (2096.00, 28.500), (2097.00, 28.550), (2098.00, 28.550), (2099.00, 28.610), (2100.00, 28.690)		Degrees C	Data for projected temperature is from the World Bank Climate Knowledge Portal (Table: 'Projected Average Mean Surface Air Temperature Kiribati; (Ref. Period:1995-2014), Multi-Model Ensemble'). Source: https://climateknowledgeportal.worldbank.org/country/kiribati/climate-data-projections

SSP370_RAINFALL_PROJECTIONS	GRAPH(TIME) Points: (2023.00, 1192.09), (2024.00, 1024.71), (2025.00, 1275.12), (2026.00, 1316.71), (2027.00, 1595.64), (2028.00, 1419.85), (2029.00, 945.93), (2030.00, 1039.44), (2031.00, 1281.69), (2032.00, 1219.7), (2033.00, 1167.95), (2034.00, 1160.24), (2035.00, 1247.65), (2036.00, 1307.53), (2037.00, 1567.28), (2038.00, 1357.43), (2039.00, 1197.8), (2040.00, 1240.62), (2041.00, 1178.76), (2042.00, 1494.31), (2043.00, 1336.53), (2044.00, 1248.26), (2045.00, 1201.06), (2046.00, 1464.66), (2047.00, 1253.74), (2048.00, 1358.8), (2049.00, 1636.48), (2050.00, 1319.7), (2051.00, 1304.95), (2052.00, 1255.27), (2053.00, 1443.44), (2054.00, 1309.65), (2055.00, 1286.09), (2056.00, 1554.15), (2057.00, 1531.21), (2058.00, 1476.12), (2059.00, 1160.58), (2060.00, 1624.21), (2061.00, 1695.21), (2062.00, 1573.9), (2063.00, 1433.26), (2064.00, 1540.66), (2065.00, 1553.46), (2066.00, 1408.92), (2067.00, 1477.64), (2068.00, 1601.26), (2069.00, 1689.66), (2070.00, 1411.99), (2071.00, 1488.44), (2072.00, 1542.34), (2073.00, 1628.16), (2074.00, 1817.87), (2075.00, 1705.97), (2076.00, 1606.47), (2077.00, 1430.03), (2078.00, 1769.11), (2079.00, 1811.83), (2080.00, 1637.3), (2081.00, 1435.05), (2082.00, 1461.1), (2083.00, 1875.98), (2084.00, 1700.22), (2085.00, 1457.08), (2086.00, 1617.37), (2087.00, 1556.22), (2088.00, 1973.38), (2089.00, 2250.34), (2090.00, 1474.76), (2091.00, 1315.89), (2092.00, 1787.84), (2093.00, 2041.03), (2094.00, 2124.54), (2095.00, 1721.06), (2096.00, 1928.98), (2097.00, 2155.15), (2098.00, 2068.71), (2099.00, 2048.87), (2100.00, 2085.43)		mm / year	Data from Climate Change Knowledge Portal, 'Projected Precipitation'. https://climateknowledgeportal.worldbank.org/country/kiribati/cmip5
SSP370_SLR_PROJECTIONS	GRAPH(TIME) Points: (2020.00, 0.050), (2030.00, 0.099), (2040.00, 0.159), (2050.00, 0.235), (2060.00, 0.308), (2070.00, 0.398), (2080.00, 0.501), (2090.00, 0.616), (2100.00, 0.740)		meters	Projections are based on 'IPCC AR6 Sea-Level Rise Projections' specifically for Betio, South Tarawa, Kiribati (psmsl_id 1804). Median values for each SSP projection was used. Projection values are relative to a 1995-2014 baseline. This baseline was calculated to be 1.6535m from the Australian Government Bureau of Meteorology's historical sea level data.
SSP370_SWITCH	0		Dimensionless	Switch turns on scenario for SSP 3-7.0.
SSP370_TEMPERATURE_PROJECTIONS	GRAPH(TIME) Points: (2014.00, 26.890), (2015.00, 26.970), (2016.00, 27.040), (2017.00, 27.150), (2018.00, 27.320), (2019.00, 27.290), (2020.00, 27.000), (2021.00, 27.120), (2022.00, 27.330), (2023.00, 27.190), (2024.00, 27.090), (2025.00, 27.400), (2026.00, 27.320), (2027.00, 27.550), (2028.00, 27.430), (2029.00, 27.160), (2030.00, 27.300), (2031.00, 27.500), (2032.00, 27.490), (2033.00, 27.440), (2034.00, 27.460), (2035.00, 27.430), (2036.00, 27.540), (2037.00, 27.780), (2038.00, 27.730), (2039.00, 27.510), (2040.00, 27.560), (2041.00, 27.650), (2042.00, 27.760), (2043.00, 27.670), (2044.00, 27.680), (2045.00, 27.840), (2046.00, 28.010), (2047.00, 27.880), (2048.00, 28.030), (2049.00, 27.990), (2050.00, 27.950), (2051.00, 27.880), (2052.00, 27.990), (2053.00, 27.970), (2054.00, 28.000), (2055.00, 28.210), (2056.00, 28.250), (2057.00, 28.320), (2058.00, 28.350), (2059.00, 28.100), (2060.00, 28.480), (2061.00, 28.470), (2062.00, 28.330), (2063.00, 28.230), (2064.00, 28.440), (2065.00, 28.340), (2066.00, 28.540), (2067.00, 28.620), (2068.00, 28.760), (2069.00, 28.660), (2070.00, 28.580), (2071.00, 28.760), (2072.00, 28.860), (2073.00, 28.730), (2074.00, 28.910), (2075.00, 28.680), (2076.00, 28.610), (2077.00, 28.860), (2078.00, 28.810), (2079.00, 28.870), (2080.00, 28.990), (2081.00, 28.960), (2082.00, 29.190), (2083.00, 29.340), (2084.00, 28.980), (2085.00, 29.270), (2086.00, 29.260), (2087.00, 29.350), (2088.00, 29.590), (2089.00, 29.440), (2090.00, 29.140), (2091.00, 29.010), (2092.00, 29.340), (2093.00, 29.520), (2094.00, 29.730), (2095.00, 29.320), (2096.00, 29.630), (2097.00, 29.580), (2098.00, 29.900), (2099.00, 29.910), (2100.00, 29.680)		Degrees C	Data for projected temperature is from the World Bank Climate Knowledge Portal (Table: 'Projected Average Mean Surface Air Temperature Kiribati; (Ref. Period:1995-2014), Multi-Model Ensemble'). Source: https://climateknowledgeportal.worldbank.org/country/kiribati/climate-data-projections

SSP585_RAINFALL_PROJECTIONS	GRAPH(TIME) Points: (2023.00, 1090.7), (2024.00, 1187.51), (2025.00, 1187.44), (2026.00, 1187.89), (2027.00, 1216.32), (2028.00, 1208.29), (2029.00, 1195.79), (2030.00, 1296.46), (2031.00, 1476.86), (2032.00, 1090.37), (2033.00, 1142.79), (2034.00, 1062.64), (2035.00, 1438.13), (2036.00, 1422.71), (2037.00, 1106.15), (2038.00, 1293.65), (2039.00, 1500.08), (2040.00, 1534.34), (2041.00, 1228.68), (2042.00, 1115.68), (2043.00, 1430.46), (2044.00, 1488.82), (2045.00, 1400.02), (2046.00, 1329.48), (2047.00, 1371.76), (2048.00, 1562.75), (2049.00, 1627.84), (2050.00, 1241.75), (2051.00, 1333.22), (2052.00, 1655.35), (2053.00, 1457.23), (2054.00, 1393.86), (2055.00, 1437.13), (2056.00, 1557.13), (2057.00, 1511.23), (2058.00, 1478.82), (2059.00, 1655.88), (2060.00, 1618.68), (2061.00, 1666.77), (2062.00, 1637.72), (2063.00, 1646.51), (2064.00, 1469.51), (2065.00, 1443.24), (2066.00, 1889.01), (2067.00, 1633.96), (2068.00, 1255.64), (2069.00, 1892.83), (2070.00, 1931.08), (2071.00, 1640.38), (2072.00, 1328.43), (2073.00, 1975.1), (2074.00, 1860.67), (2075.00, 1721.82), (2076.00, 1708.73), (2077.00, 1458.36), (2078.00, 1509.08), (2079.00, 1908.96), (2080.00, 1750.88), (2081.00, 1837.98), (2082.00, 1776.76), (2083.00, 1682.2), (2084.00, 1594.2), (2085.00, 2161.66), (2086.00, 1836.84), (2087.00, 2001.99), (2088.00, 1919.98), (2089.00, 1753.03), (2090.00, 2064.48), (2091.00, 2269.25), (2092.00, 1682.81), (2093.00, 1878.97), (2094.00, 2585.36), (2095.00, 2020.26), (2096.00, 2321.99), (2097.00, 2158.2), (2098.00, 2295.86), (2099.00, 2001.93), (2100.00, 2143.09)		mm / year	Data from Climate Change Knowledge Portal, 'Projected Precipitation'. https://climateknowledgeportal.worldbank.org/country/kiribati/cmip5
SSP585_SLR_PROJECTIONS	GRAPH(TIME) Points: (2020.00, 0.060), (2030.00, 0.111), (2040.00, 0.169), (2050.00, 0.250), (2060.00, 0.334), (2070.00, 0.439), (2080.00, 0.554), (2090.00, 0.692), (2100.00, 0.826)		meters	Projections are based on 'IPCC AR6 Sea-Level Rise Projections' specifically for Betio, South Tarawa, Kiribati (psmsl_id 1804). Median values for each SSP projection was used. Projection values are relative to a 1995-2014 baseline. This baseline was calculated to be 1.6535m from the Australian Government Bureau of Meteorology's historical sea level data.
SSP585_SWITCH	1		Dimensionless	Switch turns on scenario for SSP 5-8.5.
SSP585_TEMPERATURE_PROJECTIONS	GRAPH(TIME) Points: (2014.00, 26.890), (2015.00, 27.110), (2016.00, 27.200), (2017.00, 27.260), (2018.00, 27.230), (2019.00, 26.980), (2020.00, 27.210), (2021.00, 27.270), (2022.00, 27.190), (2023.00, 27.280), (2024.00, 27.280), (2025.00, 27.290), (2026.00, 27.450), (2027.00, 27.430), (2028.00, 27.520), (2029.00, 27.410), (2030.00, 27.470), (2031.00, 27.580), (2032.00, 27.400), (2033.00, 27.340), (2034.00, 27.520), (2035.00, 27.730), (2036.00, 27.680), (2037.00, 27.570), (2038.00, 27.820), (2039.00, 28.000), (2040.00, 28.040), (2041.00, 27.810), (2042.00, 27.840), (2043.00, 28.110), (2044.00, 28.220), (2045.00, 28.190), (2046.00, 27.900), (2047.00, 28.060), (2048.00, 28.320), (2049.00, 28.210), (2050.00, 28.060), (2051.00, 28.270), (2052.00, 28.190), (2053.00, 28.310), (2054.00, 28.260), (2055.00, 28.350), (2056.00, 28.380), (2057.00, 28.620), (2058.00, 28.680), (2059.00, 28.790), (2060.00, 28.590), (2061.00, 28.830), (2062.00, 28.810), (2063.00, 28.750), (2064.00, 28.870), (2065.00, 28.900), (2066.00, 29.020), (2067.00, 29.020), (2068.00, 28.890), (2069.00, 29.140), (2070.00, 29.250), (2071.00, 29.300), (2072.00, 29.240), (2073.00, 29.300), (2074.00, 29.560), (2075.00, 29.310), (2076.00, 29.570), (2077.00, 29.320), (2078.00, 29.500), (2079.00, 29.520), (2080.00, 29.680), (2081.00, 29.750), (2082.00, 29.870), (2083.00, 29.810), (2084.00, 29.700), (2085.00, 30.050), (2086.00, 29.940), (2087.00, 30.080), (2088.00, 29.970), (2089.00, 29.950), (2090.00, 30.290), (2091.00, 30.260), (2092.00, 30.090), (2093.00, 30.240), (2094.00, 30.420), (2095.00, 30.250), (2096.00, 30.540), (2097.00, 30.470), (2098.00, 30.460), (2099.00, 30.470), (2100.00, 30.490)		Degrees C	Data for projected temperature is from the World Bank Climate Knowledge Portal (Table: 'Projected Average Mean Surface Air Temperature Kiribati; (Ref. Period:1995-2014), Multi-Model Ensemble'). Source: https://climateknowledgeportal.worldbank.org/country/kiribati/climate-data-projections

Demographics:

Population_in_Outer_Islands(t)	$Population_in_Outer_Islands(t - dt) + (outer_islands_births + S_Tarawa_to_outer_islands_flow - outer_islands_to_S_Tarawa_flow - outer_islands_deaths - "out-migration_from_the_outer_islands") * dt$	INIT Population_in_Outer_Islands = 46995	people	Initial population for outer islands was calculated from the 'Total' population (72,335) minus the population of South Tarawa (25,380) for the year 1990 = 46,955 people. Source: Kiribati Census Atlas 2022	NON-NEGATIVE
Population_in_Tarawa(t)	$Population_in_Tarawa(t - dt) + (births + outer_islands_to_S_Tarawa_flow - deaths - "out-migration_from_S_Tarawa" - S_Tarawa_to_outer_islands_flow) * dt$	INIT Population_in_Tarawa = 25380	people	The census count for South Tarawa in 1990 was 25380 people. Source: Kiribati Census Atlas 2022	NON-NEGATIVE
births	$Population_in_Tarawa * Tarawa.birthrate_in_Tarawa$		people/Years	This flow represents the birth rate for South Tarawa.	
deaths	$Population_in_Tarawa * REFERENCE_DEATH_RATE$	OUTFLOW PRIORITY: 1	people/Years	This flow represents the death rate for South Tarawa.	
"out-migration_from_S_Tarawa"	$Population_in_Tarawa * Utility_Functions.probability_of_moving_abroad_from_S_Tarawa$	OUTFLOW PRIORITY: 2	people/Years	This flow represents the rate of people moving abroad from South Tarawa.	
"out-migration_from_the_outer_islands"	$(Population_in_Outer_Islands * Utility_Functions.probability_of_moving_abroad_from_outer_islands)$	OUTFLOW PRIORITY: 3	people/Years	This flow represents the rate of people moving abroad from the outer islands.	
outer_islands_births	$Population_in_Outer_Islands * birthrate_in_outer_islands$		people/Years	This flow represents the birth rate for the outer islands.	
outer_islands_deaths	$Population_in_Outer_Islands * REFERENCE_DEATH_RATE$	OUTFLOW PRIORITY: 2	people/Years	This flow represents the death rate for the outer islands.	
outer_islands_to_S_Tarawa_flow	$(Population_in_Outer_Islands * Utility_Functions.probability_of_moving_to_S_Tarawa_from_outer_islands)$	OUTFLOW PRIORITY: 1	people/Years	The flow represents the rate of people from the outer islands moving to South Tarawa.	
S_Tarawa_to_outer_islands_flow	$(Population_in_Tarawa * Utility_Functions.probability_of_moving_to_the_outer_islands_from_S_Tarawa)$	OUTFLOW PRIORITY: 3	people/Years	The flow represents the rate of people from South Tarawa moving to the outer islands.	UNIFLOW
birthrate_in_outer_islands	$NATIONAL_BIRTHRATE / 1000$		people/(people * year)	Birthrate is divided by 1000 to account for the historical crude birthrate of 1 birth per 1000 people.	
NATIONAL_BIRTHRATE	$30000000 * EXP(-0.007 * TIME)$		people/(people * year)	Data is available for crude birthrates at a national level for Kiribati. A logarithmic trend line was used to fit Kiribati birthrate data from 1960-2022. Source: https://data.worldbank.org/indicator/SP.DYN.CBRT.IN?locations=KI	
REFERENCE_DEATH_RATE	0.007		people/(people * year)	Average deathrate calculated from 1990-2021 is 7 deaths/ 1000 people. Deathrate is divided by 1000 to account for the historical crude deathrate of 1 death per 1000 people. Source: https://data.worldbank.org/indicator/SP.DYN.CDRT.IN?locations=KI	
International:					
"I-Kiribati_Abroad"(t)	$"I-Kiribati_Abroad"(t - dt) + (- migration_from_Kiribati) * dt$	INIT "I-Kiribati_Abroad" = 5000	people	This stock represents the number of I-Kiribati who have moved abroad. This is outside the model boundary.	
migration_from_Kiribati	Demographics."out-migration_from_S_Tarawa"+Demographics."out-migration_from_the_outer_islands"		people/Years	This flow represents the rate of people moving abroad from Kiribati (both from South Tarawa and the outer islands). This flow is only included for comparison to historic data.	
Outer_Islands:					
Land_in_Outer_Islands(t)	$Land_in_Outer_Islands(t - dt) + (land_expansion - land_loss) * dt$	INIT Land_in_Outer_Islands = 326	sq km	Calculated from total land area minus land areas of South Tarawa and Kiritmati (Table 5 of Kiribati Census Atlas 2022).	
land_expansion	$Land_in_Outer_Islands * Tarawa.ACCRETION_RATE$		sq km/year	Land expansion in the outer islands only includes natural accretion. No reclamation is considered.	
land_loss	$Land_in_Outer_Islands * (Climate_Impacts.function_for_effect_of_sea_level_rise_on_land_loss + Tarawa.EROSION_RATE)$		sq km / year	Land loss is calculated from erosion rates as well as anticipated exacerbation of land loss from sea level rise.	
avg_per_capita_income_in_the_outer_islands	IF Climate_Impacts.SSP119_SWITCH = 1 THEN SSP119_CLIMATE_EFFECTS_ON_INCOME_IN_OUTER_ISLANDS ELSE (IF Climate_Impacts.SSP126_SWITCH = 1 THEN SSP126_CLIMATE_EFFECTS_ON_INCOME_IN_OUTER_ISLANDS ELSE (IF Climate_Impacts.SSP245_SWITCH = 1 THEN SSP245_CLIMATE_EFFECTS_ON_INCOME_IN_OUTER_ISLANDS ELSE (IF Climate_Impacts.SSP370_SWITCH = 1 THEN SSP370_CLIMATE_EFFECTS_ON_INCOME_IN_OUTER_ISLANDS ELSE (IF Climate_Impacts.SSP585_SWITCH = 1 THEN SSP585_CLIMATE_EFFECTS_ON_INCOME_IN_OUTER_ISLANDS ELSE NO_CLIMATE_EFFECTS_ON_INCOME_IN_OUTER_ISLANDS))))))		Dimensionless	Average per capita household income based on estimated relationships for each SSP.	

BASE_EMOTIONAL_COST_OF_MOVEMENT_ABROAD	50940.34349		Dimensionless	Base emotional cost of moving abroad is calculated through a calibration optimization of population movement. This value represents the emotional cost of leaving home (ancestral lands), especially relevant in the Pacific where place attachment is high.
BASE_EMOTIONAL_COST_OF_MOVEMENT_INTERNAL	49194.57802		Dimensionless	Base emotional cost of internal movement is calculated through a calibration optimization of population movement. This value represents the emotional cost of leaving home (ancestral lands), especially relevant in the Pacific where place attachment is high.
effect_of_funding_on_quality_of_infrastructure_and_services	GRAPH(government_funding_to_outer_islands//INIT(government_funding_to_outer_islands)) Points: (0.000, 0.000), (0.200, 0.5073), (0.400, 0.8946), (0.600, 1.190), (0.800, 1.416), (1.000, 1.588), (1.200, 1.720), (1.400, 1.820), (1.600, 1.897), (1.800, 1.955), (2.000, 2.000)		Dimensionless	The relationship of infrastructure and services quality to funding was based on the researcher's judgement.
effect_of_infrastructure_and_social_service_quality_on_outer_island_and_attractiveness	GRAPH(infrastructure_and_social_services_quality // IDEAL_INFRASTRUCTURE_AND_SOCIAL_SERVICES_QUALITY) Points: (0.000, 0.000), (0.100, 0.2277), (0.200, 0.4089), (0.300, 0.5529), (0.400, 0.6675), (0.500, 0.7586), (0.600, 0.8311), (0.700, 0.8887), (0.800, 0.9345), (0.900, 0.971), (1.000, 1.000)		Dimensionless	This relationship represents how the attractiveness of being (staying) in the outer islands is affected by the infrastructure and social services quality. The relationship assumes that there is not a 1:1 ratio of service quality to attractiveness.
effect_of_land_loss_on_emotional_cost	(1-((INIT(Land_in_Outer_Islands)-Land_in_Outer_Islands)/INIT(Land_in_Outer_Islands)))		Dimensionless	The effect of land loss on emotional cost relationship assumed that the emotional cost of movement will decrease as land is lost.
effect_of_land_loss_on_infrastructure	GRAPH(Land_in_Outer_Islands//INITIAL_LAND_OUTER_ISLANDS) Points: (0.000, 0.000), (0.100, 0.3352), (0.200, 0.5601), (0.300, 0.7111), (0.400, 0.8123), (0.500, 0.8803), (0.600, 0.9259), (0.700, 0.9565), (0.800, 0.977), (0.900, 0.9908), (1.000, 1.000)		Dimensionless	This relationship assumes that not all land lost will have been occupied by infrastructure in the outer islands. Effect of land loss is on the total loss of the infrastructure.
effect_of_land_loss_on_outer_island_and_attractiveness	GRAPH(Land_in_Outer_Islands//INITIAL_LAND_OUTER_ISLANDS) Points: (0.000, 0.000), (0.100, 0.124), (0.200, 0.2419), (0.300, 0.354), (0.400, 0.4607), (0.500, 0.5622), (0.600, 0.6587), (0.700, 0.7505), (0.800, 0.832), (0.900, 0.921), (1.000, 1.000)		Dimensionless	This estimated relationship represents how the attractiveness of staying (being) in the outer islands declines as land is lost.
government_funding_to_outer_islands	Demographics.Population_in_Outer_Islands*Finances.GOVNT_FUNDING_PER_CAPITA_IN_OUTER_ISLANDS		Australian Dollars/Year	Total funding to the outer islands is the per capita funding times the dynamic population.
IDEAL_INFRASTRUCTURE_AND_SOCIAL_SERVICES_QUALITY	1		Dimensionless	Assumed ideal infrastructure and social service quality of 1.
IDEAL_WATER_ACCESS	1		Dimensionless	Ideal water access would be 100% (value of 1).
infrastructure_and_social_services_quality	((0.7)*effect_of_funding_on_quality_of_infrastructure_and_services+(0.3)*effect_of_land_loss_on_infrastructure)*REFERENCE_INFRASTRUCTURE_AND_SOCIAL_SERVICES_QUALITY		Dimensionless	The reference infrastructure and social services quality in the outer islands is dynamically affected by government funding to the outer islands and effects of climate change on service quality. These contributions were weighted through researcher judgment to reflect a higher influence of funding on service and infrastructure quality.
INITIAL_LAND_OUTER_ISLANDS	326		sq km	Calculated from total land area minus land areas of South Tarawa and Kiritmati (Table 5 of Kiribati Census Atlas 2022).
NO_CLIMATE_EFFECTS_ON_INCOME_IN_OUTER_ISLANDS	GRAPH(TIME) Points: (1990.0, 500), (2000.0, 1000), (2006.0, 1324), (2019.0, 2593), (2030.0, 3250), (2040.0, 3920), (2050.0, 4350), (2060.0, 4760), (2070.0, 5140), (2080.0, 5510), (2090.0, 5800), (2100.0, 6000)		Dimensionless	Relationship estimated from discussions of climate change's anticipated effect on income in the outer islands. Historic income in the outer islands was used for 2006 (\$1,324AUD) and 2019 (\$2,593AUD). Source: 2006 (Table 3.3) and 2019 (Table 139) Kiribati Household Income and Expenditures Survey
REFERENCE_INFRASTRUCTURE_AND_SOCIAL_SERVICES_QUALITY	0.2		Dimensionless	A value of 0.20 was estimated from discussions with local partners. A low reference value reflects lack of development in the outer islands.
REFERENCE_WATER_AVAILABILITY_IN_OUTER_ISLANDS	0.7		Dimensionless	This reference value was estimated from discussions with local partners.
SSP119_CLIMATE_EFFECTS_ON_INCOME_IN_OUTER_ISLANDS	GRAPH(TIME) Points: (1990.0, 500), (2000.0, 1000), (2006.0, 1324), (2019.0, 2593), (2030.0, 3730), (2040.0, 4210), (2050.0, 4540), (2060.0, 4740), (2070.0, 4890), (2080.0, 5000), (2090.0, 5000), (2100.0, 5000)		Dimensionless	Relationship estimated from discussions of climate change's anticipated effect on income in the outer islands. Historic income in the outer islands was used for 2006 (\$1,324AUD) and 2019 (\$2,593AUD).

	(2100.0, 5000)			Source: 2006 (Table 3.3) and 2019 (Table 139) Kiribati Household Income and Expenditures Survey
SSP119_CLIMATE_EFFECTS_ON _WATER_AVAILABILITY_IN_OUT ER_ISLANDS	GRAPH(TIME) Points: (1990.0, 1.000), (2002.22222222, 0.9444), (2014.44444444, 0.8889), (2026.66666667, 0.8333), (2038.88888889, 0.7778), (2051.11111111, 0.7222), (2063.33333333, 0.6667), (2075.55555556, 0.6111), (2087.77777778, 0.5556), (2100.0, 0.500)		Dimensio nless	The relationship shown matches trends anticipated from discussants with local partners. These trends do not match the IPCC projections for future rainfall for the country. For this relationship, local knowledge and expertise was used. However, these downward trends do not necessarily apply to all outer islands. Some outer islands receive sufficient rainfall to meet needs. This trend shows the most extreme water cases in the outer islands to show the highest range potential for movement.
SSP126_CLIMATE_EFFECTS_ON _INCOME_IN_OUTER_ISLANDS	GRAPH(TIME) Points: (1990.0, 500), (2000.0, 1000), (2006.0, 1324), (2019.0, 2593), (2030.0, 3100), (2040.0, 3530), (2050.0, 3850), (2060.0, 4170), (2070.0, 4420), (2080.0, 4500), (2090.0, 4610), (2100.0, 4610)		Dimensio nless	Relationship estimated from discussions of climate change's anticipated effect on income in the outer islands. Historic income in the outer islands was used for 2006 (\$1,324AUD) and 2019 (\$2,593AUD). Source: 2006 (Table 3.3) and 2019 (Table 139) Kiribati Household Income and Expenditures Survey
SSP126_CLIMATE_EFFECTS_ON _WATER_AVAILABILITY_IN_OUT ER_ISLANDS	GRAPH(TIME) Points: (1990.0, 1.000), (2002.22222222, 0.9389), (2014.44444444, 0.8778), (2026.66666667, 0.8167), (2038.88888889, 0.7556), (2051.11111111, 0.6944), (2063.33333333, 0.6333), (2075.55555556, 0.5722), (2087.77777778, 0.5111), (2100.0, 0.450)		Dimensio nless	The relationship shown matches trends anticipated from discussants with local partners. These trends do not match the IPCC projections for future rainfall for the country. For this relationship, local knowledge and expertise was used. However, these downward trends do not necessarily apply to all outer islands. Some outer islands receive sufficient rainfall to meet needs. This trend shows the most extreme water cases in the outer islands to show the highest range potential for movement.
SSP245_CLIMATE_EFFECTS_ON _INCOME_IN_OUTER_ISLANDS	GRAPH(TIME) Points: (1990.0, 500), (2000.0, 1000), (2006.0, 1324), (2019.0, 2593), (2030.0, 3230), (2040.0, 3400), (2050.0, 3530), (2060.0, 3640), (2070.0, 3730), (2080.0, 3820), (2090.0, 3920), (2100.0, 3950)		Dimensio nless	Relationship estimated from discussions of climate change's anticipated effect on income in the outer islands. Historic income in the outer islands was used for 2006 (\$1,324AUD) and 2019 (\$2,593AUD). Source: 2006 (Table 3.3) and 2019 (Table 139) Kiribati Household Income and Expenditures Survey

SSP245_CLIMATE_EFFECTS_ON _WATER_AVAILABILITY_IN_OUT ER_ISLANDS	GRAPH(TIME) Points: (1990.0, 1.000), (2002.22222222, 0.9333), (2014.44444444, 0.8667), (2026.66666667, 0.800), (2038.88888889, 0.7333), (2051.11111111, 0.6667), (2063.33333333, 0.600), (2075.55555556, 0.5333), (2087.77777778, 0.4667), (2100.0, 0.400)		Dimensio nless	The relationship shown matches trends anticipated from discussants with local partners. These trends do not match the IPCC projections for future rainfall for the country. For this relationship, local knowledge and expertise was used. However, these downward trends do not necessarily apply to all outer islands. Some outer islands receive sufficient rainfall to meet needs. This trend shows the most extreme water cases in the outer islands to show the highest range potential for movement.
SSP370_CLIMATE_EFFECTS_ON _INCOME_IN_OUTER_ISLANDS	GRAPH(TIME) Points: (1990.0, 500), (2000.0, 1000), (2006.0, 1324), (2019.0, 2593), (2030.0, 3020), (2040.0, 3260), (2050.0, 3400), (2060.0, 3510), (2070.0, 3560), (2080.0, 3570), (2090.0, 3570), (2100.0, 3590)		Dimensio nless	Relationship estimated from discussions of climate change's anticipated effect on income in the outer islands. Historic income in the outer islands was used for 2006 (\$1,324AUD) and 2019 (\$2,593AUD). Source: 2006 (Table 3.3) and 2019 (Table 139) Kiribati Household Income and Expenditures Survey

SSP370_CLIMATE_EFFECTS_ON_WATER_AVAILABILITY_IN_OUTER_ISLANDS	GRAPH(TIME) Points: (1990.0, 1.000), (2002.22222222, 0.9278), (2014.44444444, 0.8556), (2026.66666667, 0.7833), (2038.88888889, 0.7111), (2051.11111111, 0.6389), (2063.33333333, 0.5667), (2075.55555556, 0.4944), (2087.77777778, 0.4222), (2100.0, 0.350)		Dimensionless	The relationship shown matches trends anticipated from discussions with local partners. These trends do not match the IPCC projections for future rainfall for the country. For this relationship, local knowledge and expertise was used. However, these downward trends do not necessarily apply to all outer islands. Some outer islands receive sufficient rainfall to meet needs. This trend shows the most extreme water cases in the outer islands to show the highest range potential for movement.	
SSP585_CLIMATE_EFFECTS_ON_INCOME_IN_OUTER_ISLANDS	GRAPH(TIME) Points: (1990.0, 500), (2000.0, 1000), (2006.0, 1324), (2019.0, 2593), (2030.0, 2960), (2040.0, 3100), (2050.0, 3270), (2060.0, 3350), (2070.0, 3350), (2080.0, 3370), (2090.0, 3370), (2100.0, 3350)		Dimensionless	Relationship estimated from discussions of climate change's anticipated effect on income in the outer islands. Historic income in the outer islands was used for 2006 (\$1,324AUD) and 2019 (\$2,593AUD). Source: 2006 (Table 3.3) and 2019 (Table 139) Kiribati Household Income and Expenditures Survey	
SSP585_CLIMATE_EFFECTS_ON_WATER_AVAILABILITY_IN_OUTER_ISLANDS	GRAPH(TIME) Points: (1990.0, 1.000), (2002.22222222, 0.9222), (2014.44444444, 0.8444), (2026.66666667, 0.7667), (2038.88888889, 0.6889), (2051.11111111, 0.6111), (2063.33333333, 0.5333), (2075.55555556, 0.4556), (2087.77777778, 0.3778), (2100.0, 0.300)		Dimensionless	The relationship shown matches trends anticipated from discussions with local partners. These trends do not match the IPCC projections for future rainfall for the country. For this relationship, local knowledge and expertise was used. However, these downward trends do not necessarily apply to all outer islands. Some outer islands receive sufficient rainfall to meet needs. This trend shows the most extreme water cases in the outer islands to show the highest range potential for movement.	
total_emotional_cost_of_movement_abroad	BASE_EMOTIONAL_COST_OF_MOVEMENT_ABROAD*effect_of_land_loss_on_emotional_cost		Dimensionless	The total emotional cost of movement abroad accounts for the base emotional cost and the effect that land loss may have had on it.	
total_emotional_cost_of_movement_internal	BASE_EMOTIONAL_COST_OF_MOVEMENT_INTERNAL*effect_of_land_loss_on_emotional_cost		Dimensionless	The total emotional cost of internal movement accounts for the base emotional cost and the effect that land loss may have had on it.	
water_adequacy_ratio	water_availability_in_outer_islands/IDEAL_WATER_ACCESS		Dimensionless	Water adequacy is the amount that is available divided by the ideal amount.	
water_availability_in_outer_islands	REFERENCE_WATER_AVAILABILITY_IN_OUTER_ISLANDS* IF Climate_Impacts.SSP119_SWITCH = 1 THEN SSP119_CLIMATE_EFFECTS_ON_WATER_AVAILABILITY_IN_OUTER_ISLANDS ELSE (IF Climate_Impacts.SSP126_SWITCH = 1 THEN SSP126_CLIMATE_EFFECTS_ON_WATER_AVAILABILITY_IN_OUTER_ISLANDS ELSE (IF Climate_Impacts.SSP245_SWITCH = 1 THEN SSP245_CLIMATE_EFFECTS_ON_WATER_AVAILABILITY_IN_OUTER_ISLANDS ELSE (IF Climate_Impacts.SSP370_SWITCH = 1 THEN SSP370_CLIMATE_EFFECTS_ON_WATER_AVAILABILITY_IN_OUTER_ISLANDS ELSE (IF Climate_Impacts.SSP585_SWITCH = 1 THEN SSP585_CLIMATE_EFFECTS_ON_WATER_AVAILABILITY_IN_OUTER_ISLANDS ELSE 1))))))		Dimensionless	Water availability in the outer islands based on estimated relationships for each SSP.	
Tarawa:					
Housing_Units(t)	Housing_Units(t - dt) + (housing_development - houses_lost) * dt	INIT Housing_Units = 2786	housing unit	Based on a linear trendline from household counts in 2005, 2010, 2015, and 2022 there was an estimated 1692 households in 1990. Source: Kiribati 2006 Household Income and Expenditures Report	NON-NEGATIVE
Land_Area(t)	Land_Area(t - dt) + (land_expansion - land_loss) * dt	INIT Land_Area = 11.8	sq km	South Tarawa land area values for 1968 and 1998 were interpolated to find the estimated land area in 1990. Source: Table 3 Summary of area changes for the two areas, and the entire atoll, over the 30-year period (1968–1998) Biribo & Woodroffe (2013)	
Residential_Land_Area(t)	Residential_Land_Area(t - dt) + (developing_residential_land - residential_land_loss) * dt	INIT Residential_Land_Area = 5.17	sq km	Map areas for residential land were calculated from pdf measurement tool using the 2017 National Government Land Use Plan.	

Undeveloped_Land_Area(t)	$Undeveloped_Land_Area(t - dt) + (gaining_undeveloped_land - loss_of_open_land - developing_open_land) * dt$	INIT Undeveloped_Land_Area = 0.2	sq km	Map areas for undeveloped land were calculated from pdf measurement tool using the 2017 National Government Land Use Plan.	NON-NEGATIVE
developing_open_land	$housing_development / (HOUSING_BUILDING_PER_PROPERTY / HOUSING_FOOTPRINT_FOR_NEW_BUILDS * SQ_M_TO_SQ_KM_CONVERSION * IF_SWITCH_HOUSING_LEVELS = 1 THEN HOUSING_LEVELS ELSE 1)$	OUTFLOW PRIORITY: 2	sq km / year	Development of open land is based on housing development.	
developing_residential_land	developing_open_land		sq km/year	As open land development is currently only based on housing development, this value is also used as the amount of land added for residential land area.	
gaining_undeveloped_land	$land_expansion * PERCENT_OF_NEW_LAND_THAT_CAN_BE_DEVELOPED + (HOUSING_BUILDING_OUT_OF_USE_RATE / (HOUSING_BUILDING_PER_PROPERTY * PROPERTY_SIZE))$		sq km/year	New undeveloped land comes from land expansion and land where buildings are destroyed.	
houses_lost	$(HOUSING_BUILDING_OUT_OF_USE_RATE + housing_building_lost_to_SLR) * IF_SWITCH_HOUSING_LEVELS = 1 THEN HOUSING_LEVELS ELSE 1$		housing unit / years	Five houses are estimated to be lost per year from damage. Additional house loss from from loss of land.	
housing_development	$("AVG_HOUSING_DEVELOPMENT_RATE" * IF_SWITCH_HOUSING_LEVELS = 1 THEN HOUSING_LEVELS ELSE 1) + housing_units_needed_for_new_people$		housing unit / years	The housing development rate is calculated from the average housing development rate plus the units needed to accommodate new people in South Tarawa. New housing development can be built upward in multistory housing if policy option is turned on.	
land_expansion	$SMTH1((ACCRETION_RATE * Land_Area) + RECLAMATION_RATE, 10)$		sq km/Years	Total new land from both reclaimed land and natural accretion.	
land_loss	$Land_Area * (Climate_Impacts.function_for_effect_of_sea_level_rise_on_land_loss + EROSION_RATE)$		sq km/Years	Land loss is calculated from erosion rates as well as anticipated exacerbation of land loss from sea level rise.	
loss_of_open_land	$land_loss * percent_of_land_area_undeveloped$	OUTFLOW PRIORITY: 1	sq km / year	Land loss to undeveloped area from erosion and sea level rise is assumed to be proportional to percent of undeveloped land to total land area.	
residential_land_loss	$land_loss * percent_of_residential_land_area$		sq km/year	Land loss to residential land area from erosion and sea level rise is assumed to be proportional to percent of residential land to total land area.	
"AVG_HOUSING_DEVELOPMENT_RATE"	39.89720007		housing building / year	This rate was calculated through a calibration optimization of household density.	
"AVG_LIFE_EXPECTANCY"	65		years	Average life expectancy was calculated as the mean life expectancy between 1990-2021. Source: https://data.worldbank.org/indicator/SP.DYN.LE00.IN?end=2021&locations=KI&start=1990	
"PERCENT_OF_POP_WOMEN"	0.52		women / people	Source: Kiribati Census Atlas 2022	
"population_density_in_S_Tarawa"	$Demographics.Population_in_Tarawa / Land_Area$		People/Kilometers ²	Population density is calculated from the population in South Tarawa divided by the total land area.	
"REF_PERCENT_MOVING_IN_WITH_FAMILY"	0.210064222		Dimensionless	This value was calculated through a calibration optimization of household density.	
ACCRETION_RATE	0.001		1 / years	Table 9 of Biribo & Woodroffe et al. (2013) provides the percent accretion for 8 measurement locations in South Tarawa, for both their lagoon and ocean sides. The average of both lagoon and ocean sides were taken for each location, then all 8 locations were averaged. Table 6 of the same study indicates that only 11% of accretion is natural (as opposed to reclamation). As reclamation is separated in this model, only 11% of the accretion rate from Table 9 was used. Overall, there was calculated to be a 3% accretion of land area over the period of 1968-1998. This value was divided by 30 to calculate accretion per year (0.105%/year). Source: Biribo & Woodroffe (2013)	
BASE_EMOTIONAL_COST_OF_MOVEMENT_ABROAD	50951.82163		Dimensionless	Base emotional cost of moving abroad is calculated through a calibration optimization of population movement. This value represents the emotional cost of leaving home (ancestral lands), especially relevant in the Pacific where place attachment is high.	

BASE_EMOTIONAL_COST_OF_MOVEMENT_INTERNAL	49196.2986		Dimensionless	Base emotional cost of internal movement is calculated through a calibration optimization of population movement. This value represents the emotional cost of leaving home (ancestral lands), especially relevant in the Pacific where place attachment is high.
birthrate_in_Tarawa	(LOOKUP(FERTILITY_BY_POPULATION_DENSITY, ("population_density_in_S_Tarawa")))*"PERCENT_OF_POP_WOMEN"/"AVG_LIFE_EXPECTANCY"		people / (people* year)	The fertility rate is based on the relationship with the population density. As fertility rate is expressed as births/woman, it is multiplied by the sex ratio in South Tarawa and divided by the life expectancy.
effect_of_land_loss_on_emotional_cost	1-((INIT(Land_Area)-Land_Area)/INIT(Land_Area))		Dimensionless	The effect of land loss on emotional cost relationship assumed that the emotional cost of movement will decrease as land is lost.
effect_of_land_loss_on_S_Tarawa_attractiveness	GRAPH(Land_Area//INIT(Land_Area)) Points: (0.000, 0.000), (0.100, 0.124), (0.200, 0.2419), (0.300, 0.354), (0.400, 0.4607), (0.500, 0.5622), (0.600, 0.6587), (0.700, 0.7505), (0.800, 0.832), (0.900, 0.921), (1.000, 1.000)		Dimensionless	This estimated relationship represents how the attractiveness of staying (being) in South Tarawa declines as land is lost.
effect_variable_of_land_availability_on_moving_in_with_family	-0.014507824		Dimensionless	This value was calculated through a calibration optimization of household density.
EROSION_RATE	0.00457		1/ year	Table 9 of Biribo & Woodroffe et al. (2013) provides the percent erosion for 8 measurement locations in South Tarawa, for both their lagoon and ocean sides. The average of both lagoon and ocean sides were taken for each location, then all 8 locations were averaged. Overall, there was calculated to be a 14% erosion of land area over the period of 1968-1998. This value was divided by 30 to calculate the erosion per year (0.457%/year).
FERTILITY_BY_POPULATION_DENSITY	GRAPH("population_density_in_S_Tarawa"/INIT("population_density_in_S_Tarawa")) Points: (380, 6.781), (709.272727273, 6.040), (1038.54545455, 4.997), (1367.81818182, 5.100), (1697.09090909, 4.920), (2026.36363636, 4.701), (2355.63636364, 4.411), (2684.90909091, 4.103), (3014.18181818, 3.928), (3343.45454545, 3.843), (3672.72727273, 3.706), (4002, 3.300)		people/ (women)	Rotella et al. (2021) provides data on the relationship between national population density and national fertility rates. National fertility rates provided here were assumed to apply similarly to South Tarawa, though population density was much higher in the same time period. This graphical converter shows the national fertility rates per population density in South Tarawa. Population density in South Tarawa was calculated from national census data. The time period for this data is 1963-2020. Sources: Fertility data: Rotella A, Varnum MEW, Sng O, Grossmann I. Increasing population densities predict decreasing fertility rates over time: A 174-nation investigation. Am Psychol. 2021 Sep;76(6):933-946. doi: 10.1037/amp0000862. PMID: 34914431. Population density data: Historical Census Data.
function_of_effect_of_land_availability_on_moving_in_with_family	(Undeveloped_Land_Area//INITIAL_OPEN_LAND)*effect_variable_of_land_availability_on_moving_in_with_family+y_axis		Dimensionless	Function represents linear relationship between open land area and the percent of people moving in with family where x is the change in land availability and the slope and y intercept were calibrated to historic household data.
FUTURE_RECLAMATION_RATE	0		sq km/ years	This variable is included for future policy analysis. It is currently set at 0 to show the effects of no future reclamation.
HISTORIC_RECLAMATION_RATE	0.222366614		sq km/ year	Rate calibrated to match current land area (15.76 sqkm).
HOUSE_FOOTPRINT_FOR_NEW_BUILDS	70		sq m / property	Gives footprint of concrete (80 sq m) and timber (60 sq m) in Fiji. Average of 70 sq m is used. Fiji can be used as a proximate for Kiribati housing structure. This assumes that new builds have no space in their property outside of the dimensions of their house. Source: 'UNDP Pacific Housing Guide 2023'.
household_density_for_new_migrants	4.394004541		people/ housing unit	This density was calculated through a calibration optimization of household density.

housing_building_lost_to_SLR	residential_land_loss*PROPERTY_SIZE*HOUSING_BUILDING_PER_PROPERTY		housing building/Year	Calculation of how many housing buildings would be lost to sea level rise based on residential land loss.
HOUSING_BUILDING_OUT_OF_USE_RATE	26.19129499		housing building / year	This out of use rate was calculated through a calibration optimization of household density.
HOUSING_BUILDING_PER_PROPERTY	1		housing building/property	There value indicated there is 1 housing building per property.
HOUSING_LEVELS	3		housing unit / housing building	Housing levels represent the number of stories a housing building could have. This value is used to indicate the number of units in a building, assuming one unit per level.
housing_units_needed_for_new_people	new_people_to_Tarawa/household_density_for_new_migrants*(1-percent_of_new_people_moving_in_with_family)		housing unit / year	Housing units needed calculated from the new people in South Tarawa divided by the household density for new people times the percentage that are likely to move into their own housing (100% minus the percent moving in with family).
INITIAL_OPEN_LAND	0.222636758		sq km	Map areas were calculated from pdf measurement tool using the 2017 National Government Land Use Plan. Same value as initial for 'Undeveloped Land Area'.
new_people_to_Tarawa	Demographics.births+Demographics.outer_islands_to_S_Tarawa_flow		people/years	New people to Tarawa are calculated from births and in-migration.
overall_household_density_in_Tarawa	Demographics.Population_in_Tarawa/Housing_Units		people/housing unit	Household density calculated as population in South Tarawa divided by the housing units.
percent_of_land_area_undeveloped	Undeveloped_Land_Area/Land_Area		Dimensionless	Calculated from the amount of undeveloped land area and the total land area.
PERCENT_OF_NEW_LAND_THAT_CAN_BE_DEVELOPED	0.237370083		Dimensionless	This value was calculated through a calibration optimization of household density. It is assumed that not all new land added can be developed on. For example, shoreline accretion may only add minimal amounts to existing property.
percent_of_new_people_moving_in_with_family	("REF_PERCENT_MOVING_IN_WITH_FAMILY"*function_of_effect_of_land_availability_on_moving_in_with_family)		Dimensionless	This function represents the amount of people that will choose to move in with family based on the available land.
percent_of_residential_land_area	Residential_Land_Area//Land_Area		Dimensionless	Calculated from the amount of residential land area and the total land area.
PROPERTY_SIZE	540		property /sq km	The initial values for housing units (2786 houses) and residential land (5.17 sq km) at time 0 were used to find the average square area per household land (0.001856 sq km / house). Using this value, it is estimated that 540 houses would be lost per 1 sq km of residential land lost.
RECLAMATION_RATE	(IF TIME < year_reclamation_tapered THEN HISTORIC_RECLAMATION_RATE ELSE FUTURE_RECLAMATION_RATE)		sq km/years	Total net area by reclamation (363sq km from 1968-1998) was divided by 30 to find reclamation rate per year. Reclamation rate per year= 0.12 sqkm/year. Source: Biribo & Woodroffe (2013)
S_Tarawa_household_sufficiency	MIN(1, 1/(overall_household_density_in_Tarawa/INIT(overall_household_density_in_Tarawa)))		Dimensionless	Household sufficiency function represents relationship where the sufficiency decreases as the household density rises above the initial value. The sufficiency is capped at 1.
SQ_M_TO_SQ_KM_CONVERSION	1000000		sq m / sq km	Conversion of sq m to sq km.
SWITCH_HOUSING_LEVELS	0		Dimensionless	Switch turns on policy scenario of multi-story housing. This is turned off as most housing is currently one level.
total_emotional_cost_of_movement_abroad	BASE_EMOTIONAL_COST_OF_MOVEMENT_ABROAD*effect_of_land_loss_on_emotional_cost		Dimensionless	The total emotional cost of movement abroad accounts for the base emotional cost and the effect that land loss may have had on it.
total_emotional_cost_of_movement_internal	BASE_EMOTIONAL_COST_OF_MOVEMENT_INTERNAL*effect_of_land_loss_on_emotional_cost		Dimensionless	The total emotional cost of internal movement accounts for the base emotional cost and the effect that land loss may have had on it.
y_axis	2.209161737		Dimensionless	This value was calculated through a calibration optimization of household density.
year_reclamation_tapered	2008		year	This year was chosen as it is the last year of shoreline analysis in the latest study (Duvat, 2013).
Utility_Functions:				

alpha_MOVING_ABROAD_FROM_KIRIBATI	0		Dimensionless	Alpha value was calculated through calibration optimisation to historic population values.
alpha_MOVING_TO_OUTER_ISLANDS_FROM_S_TARAWA	9.349392108		Dimensionless	Alpha value was calculated through calibration optimisation to historic population values.
alpha_MOVING_TO_S_TARAWA_FROM_OUTER_ISLANDS	0.043625133		Dimensionless	Alpha value was calculated through calibration optimisation to historic population values.
COST_SCALING	10000		Dimensionless	
DECISION_TIME_STEP	1		year	Decision time step of 1 year set to match the evaluation time step of the model.
FOOD_ADEQUACY_ABROAD	1		Dimensionless	The adequacy of resources and services abroad was set to 1 to represent a high comparison point.
INFRASTRUCTURE_AND_SERVICES_PERCEPTION_ABROAD	1		Dimensionless	The adequacy of resources and services abroad was set to 1 to represent a high comparison point.
MEDIAN_ANNUAL_PERSON_INCOME_ABROAD	45351		AUD/(people*year)	Australia data was used as a proxy for "international". The median annual personal income for migrants was \$45,351 in 2019-2020. Source: https://www.abs.gov.au/media-centre/media-releases/new-migrant-jobs-and-income-data-release
PERCEIVED_LAND_ADEQUACY	1		Dimensionless	The adequacy of resources and services abroad was set to 1 to represent a high comparison point.
PERCEIVED_WATER_ADEQUACY_ABROAD	1		Dimensionless	The adequacy of resources and services abroad was set to 1 to represent a high comparison point.
probability_of_moving_abroad_from_outer_islands	$(\text{EXP}(\text{utility_of_moving_abroad_from_outer_islands}) / (\text{EXP}(\text{utility_of_moving_abroad_from_outer_islands}) + \text{EXP}(\text{utility_of_moving_to_S_Tarawa}) + \text{EXP}(\text{utility_of_staying_in_outer_islands}))) / \text{DECISION_TIME_STEP}$		1/ year	The probability of option selection was calculated using a multinomial logit function.
probability_of_moving_abroad_from_S_Tarawa	$((\text{EXP}(\text{utility_of_moving_abroad_from_S_Tarawa}) / (\text{EXP}(\text{utility_of_moving_abroad_from_S_Tarawa}) + \text{EXP}(\text{utility_of_staying_in_S_Tarawa}) + \text{EXP}(\text{utility_of_moving_to_the_outer_islands}))) / \text{DECISION_TIME_STEP}$		1 / year	The probability of option selection was calculated using a multinomial logit function.
probability_of_moving_to_S_Tarawa_from_outer_islands	$((\text{EXP}(\text{utility_of_moving_to_S_Tarawa}) / (\text{EXP}(\text{utility_of_moving_abroad_from_outer_islands}) + \text{EXP}(\text{utility_of_moving_to_S_Tarawa}) + \text{EXP}(\text{utility_of_staying_in_outer_islands}))) / \text{DECISION_TIME_STEP}$		1 / year	The probability of option selection was calculated using a multinomial logit function.
probability_of_moving_to_the_outer_islands_from_S_Tarawa	$(\text{EXP}(\text{utility_of_moving_to_the_outer_islands}) / (\text{EXP}(\text{utility_of_moving_abroad_from_S_Tarawa}) + \text{EXP}(\text{utility_of_staying_in_S_Tarawa}) + \text{EXP}(\text{utility_of_moving_to_the_outer_islands}))) / \text{DECISION_TIME_STEP}$		1/year	The probability of option selection was calculated using a multinomial logit function.
probability_of_staying_in_outer_islands	$(\text{EXP}(\text{utility_of_staying_in_outer_islands}) / (\text{EXP}(\text{utility_of_moving_abroad_from_outer_islands}) + \text{EXP}(\text{utility_of_moving_to_S_Tarawa}) + \text{EXP}(\text{utility_of_staying_in_outer_islands}))) / \text{DECISION_TIME_STEP}$		1/ year	The probability of option selection was calculated using a multinomial logit function.
probability_of_staying_in_S_Tarawa	$(\text{EXP}(\text{utility_of_staying_in_S_Tarawa}) / (\text{EXP}(\text{utility_of_moving_abroad_from_S_Tarawa}) + \text{EXP}(\text{utility_of_staying_in_S_Tarawa}) + \text{EXP}(\text{utility_of_moving_to_the_outer_islands}))) / \text{DECISION_TIME_STEP}$		1/ year	The probability of option selection was calculated using a multinomial logit function.
utility_of_moving_abroad_from_outer_islands	$\text{WEIGHT_OF_INFRASTRUCTURE} * \text{LN}(\text{INFRASTRUCTURE_AND_SERVICES_PERCEPTION_ABROAD} / \text{Outer_Islands.effect_of_infrastructure_and_social_service_quality_on_outer_island_attractiveness}) +$ $\text{WEIGHT_OF_WATER_SECURITY} * \text{LN}(\text{PERCEIVED_WATER_ADEQUACY_ABROAD} / \text{Outer_Islands.water_adequacy_ratio}) +$ $\text{WEIGHT_OF_LAND_AVAILABILITY} * \text{LN}(\text{PERCEIVED_LAND_ADEQUACY} / \text{Outer_Islands.effect_of_land_loss_on_outer_island_attractiveness}) +$ $\text{WEIGHT_OF_FOOD_SECURITY} * \text{LN}(\text{FOOD_ADEQUACY_ABROAD} / \text{Food.total_food_stock_adequacy_Outer_Islands}) +$ $\text{WEIGHT_OF_FINANCIAL_SECURITY} * \text{LN}(\text{MEDIAN_ANNUAL_PERSON_INCOME_ABROAD} / \text{Outer_Islands.avg_per_capita_income_in_the_outer_islands}) -$ $\text{Finances.total_cost_of_movement_from_Outer_Islands_abroad} / \text{COST_SCALING} - \text{alpha_MOVING_ABROAD_FROM_KIRIBATI}$		Dimensionless	Calculated through additive utility function with terms related to the Habitability Pillars for atolls framework where each pillar is weighted according to local prioritisation.

<p>utility_of_moving_abroad_from_S_Tarawa</p>	<p>WEIGHT_OF_INFRASTRUCTURE*LN(INFRASTRUCTURE_AND_SERVICES_PERCEPTION_ABROAD/Tarawa.S_Tarawa_household_sufficiency)+ WEIGHT_OF_WATER_SECURITY*LN(PERCEIVED_WATER_ADEQUACY_ABROAD/Water_Resources.water_adequacy_ratio)+ WEIGHT_OF_LAND_AVAILABILITY*LN(PERCEIVED_LAND_ADEQUACY/Tarawa.effect_of_land_loss_on_S_Tarawa_attractiveness)+ WEIGHT_OF_FOOD_SECURITY*LN(FOOD_ADEQUACY_ABROAD/Food.total_food_stock_adequacy_S_Tarawa)+ WEIGHT_OF_FINANCIAL_SECURITY*LN(MEDIAN_ANNUAL_PERSON_INCOME_ABROAD/Finances.income_in_S_Tarawa_per_capita)- Finances.total_cost_of_movement_from_S_Tarawa_abroad/COST_SCALING -alpha_MOVING_ABROAD_FROM_KIRIBATI</p>		<p>Dimensionless</p>	<p>Calculated through additive utility function with terms related to the Habitability Pillars for atolls framework where each pillar is weighted according to local prioritisation.</p>	
<p>utility_of_moving_to_S_Tarawa</p>	<p>WEIGHT_OF_INFRASTRUCTURE*LN(Tarawa.S_Tarawa_household_sufficiency/Outer_Islands.effect_of_infrastructure_and_social_service_quality_on_outer_island_attractiveness)+ WEIGHT_OF_WATER_SECURITY*LN(Water_Resources.water_adequacy_ratio/Outer_Islands.water_adequacy_ratio)+ WEIGHT_OF_LAND_AVAILABILITY*LN(Tarawa.effect_of_land_loss_on_S_Tarawa_attractiveness/Outer_Islands.effect_of_land_loss_on_outer_island_attractiveness)+ WEIGHT_OF_FOOD_SECURITY*LN(Food.total_food_stock_adequacy_S_Tarawa/Food.total_food_stock_adequacy_Outer_Islands)+ WEIGHT_OF_FINANCIAL_SECURITY*LN(Finances.income_in_S_Tarawa_per_capita/Outer_Islands.avg_per_capita_income_in_the_outer_islands) - Finances.total_cost_of_movement_from_Outer_Islands_to_S_Tarawa/COST_SCALING - alpha_MOVING_TO_S_TARAWA_FROM_OUTER_ISLANDS</p>		<p>Dimensionless</p>	<p>Calculated through additive utility function with terms related to the Habitability Pillars for atolls framework where each pillar is weighted according to local prioritisation.</p>	
<p>utility_of_moving_to_the_outer_islands</p>	<p>WEIGHT_OF_INFRASTRUCTURE*LN(Outer_Islands.effect_of_infrastructure_and_social_service_quality_on_outer_island_attractiveness/Tarawa.S_Tarawa_household_sufficiency)+ WEIGHT_OF_WATER_SECURITY*LN(Outer_Islands.water_adequacy_ratio/Water_Resources.water_adequacy_ratio)+ WEIGHT_OF_LAND_AVAILABILITY*LN(Outer_Islands.effect_of_land_loss_on_outer_island_attractiveness/Tarawa.effect_of_land_loss_on_S_Tarawa_attractiveness)+ WEIGHT_OF_FOOD_SECURITY*LN(Food.total_food_stock_adequacy_Outer_Islands/Food.total_food_stock_adequacy_S_Tarawa)+ WEIGHT_OF_FINANCIAL_SECURITY*LN(Outer_Islands.avg_per_capita_income_in_the_outer_islands/Finances.income_in_S_Tarawa_per_capita)- Finances.total_cost_of_movement_from_S_Tarawa_to_Outer_Islands/COST_SCALING - alpha_MOVING_TO_OUTER_ISLANDS_FROM_S_TARAWA</p>		<p>Dimensionless</p>	<p>Calculated through additive utility function with terms related to the Habitability Pillars for atolls framework where each pillar is weighted according to local prioritisation.</p>	
<p>utility_of_staying_in_outer_islands</p>	<p>WEIGHT_OF_FINANCIAL_SECURITY*LN(Outer_Islands.avg_per_capita_income_in_the_outer_islands//INIT(Outer_Islands.avg_per_capita_income_in_the_outer_islands))+ WEIGHT_OF_FOOD_SECURITY*LN(Food.total_food_stock_adequacy_Outer_Islands//INIT(Food.total_food_stock_adequacy_Outer_Islands))+ WEIGHT_OF_LAND_AVAILABILITY*LN(Outer_Islands.effect_of_land_loss_on_outer_island_attractiveness//INIT(Outer_Islands.effect_of_land_loss_on_outer_island_attractiveness))+ WEIGHT_OF_WATER_SECURITY*LN(Outer_Islands.water_adequacy_ratio//INIT(Outer_Islands.water_adequacy_ratio))+ WEIGHT_OF_INFRASTRUCTURE*LN(Outer_Islands.effect_of_infrastructure_and_social_service_quality_on_outer_island_attractiveness//INIT(Outer_Islands.effect_of_infrastructure_and_social_service_quality_on_outer_island_attractiveness))</p>		<p>Dimensionless</p>	<p>Calculated through additive utility function with terms related to the Habitability Pillars for atolls framework where each pillar is weighted according to local prioritisation.</p>	

utility_of_staying_in_S_Tarawa	$WEIGHT_OF_INFRASTRUCTURE * LN(Tarawa.S_Tarawa_household_sufficiency // INIT(Tarawa.S_Tarawa_household_sufficiency)) +$ $WEIGHT_OF_WATER_SECURITY * LN(Water_Resources.water_adequacy_ratio // INIT(Water_Resources.water_adequacy_ratio)) +$ $WEIGHT_OF_LAND_AVAILABILITY * LN(Tarawa.effect_of_land_loss_on_S_Tarawa_attractiveness // INIT(Tarawa.effect_of_land_loss_on_S_Tarawa_attractiveness)) +$ $WEIGHT_OF_FOOD_SECURITY * LN(Food.total_food_stock_adequacy_S_Tarawa // INIT(Food.total_food_stock_adequacy_S_Tarawa)) +$ $WEIGHT_OF_FINANCIAL_SECURITY * LN(Finances.income_in_S_Tarawa_per_capita // INIT(Finances.income_in_S_Tarawa_per_capita))$		Dimensionless	Calculated through additive utility function with terms related to the Habitability Pillars for atolls framework where each pillar is weighted according to local prioritisation.
WEIGHT_OF_FINANCIAL_SECURITY	0.266		Dimensionless	Polarity and strength of utility factor connections, relative to other utility factors, were found through focus group data (conducted November 2024 in South Tarawa, Kiribati). Eigenvector centrality scores were calculated for each utility factor then normalized.
WEIGHT_OF_FOOD_SECURITY	0.226		Dimensionless	Polarity and strength of utility factor connections, relative to other utility factors, were found through focus group data (conducted November 2024 in South Tarawa, Kiribati). Eigenvector centrality scores were calculated for each utility factor then normalized.
WEIGHT_OF_INFRASTRUCTURE	0.151		Dimensionless	Polarity and strength of utility factor connections, relative to other utility factors, were found through focus group data (conducted November 2024 in South Tarawa, Kiribati). Eigenvector centrality scores were calculated for each utility factor then normalized.
WEIGHT_OF_LAND_AVAILABILITY	0.151		Dimensionless	Polarity and strength of utility factor connections, relative to other utility factors, were found through focus group data (conducted November 2024 in South Tarawa, Kiribati). Eigenvector centrality scores were calculated for each utility factor then normalized.
WEIGHT_OF_WATER_SECURITY	0.206		Dimensionless	Polarity and strength of utility factor connections, relative to other utility factors, were found through focus group data (conducted November 2024 in South Tarawa, Kiribati). Eigenvector centrality scores were calculated for each utility factor then normalized.
Finances:				
"GOVERNMENT_FUNDING_PER_CAPITA_IN_S_TARAWA"	TOTAL_GOV_T_FUNDING_PER_CAPITA * DISTRIBUTION_OF_FUNDING_TO_S_TARAWA		AUD / (people * year)	
"percent_of_S_Tarawa_engaged_in_sustistence_activities"	0.041 * effect_of_land_loss_on_sustistence_livelihoods		house/household	The amount of people engaged in subsistence activities will remain the same or decrease based on land loss. Sourced from "Percentage of Persons Aged 15+ by Type of Economic Activity and Island Group" (Table 2.4, pg 12). 4.1% of such people in S. Tarawa are reported to engage in subsistence economic activities.
"total_income_in_S_Tarawa"	(INTERNATIONAL_REMITTANCES_PER_YEAR + (total_other_income * Demographics.Population_in_Tarawa) + (total_income_from_subistence))		Australian Dollars / (Years)	Total income in South Tarawa is the combination of remittances, subsistence activity, and other income.
ANNUAL_INCOME_FOR_SUBSISTENCE_ACTIVITY	6226		AUD / (people * year)	Sourced from "Per capita income by source and Urban/Rural" (Table 3.3, pg. 16) in the Analytical Report on the 2006 Kiribati Household Income and Expenditure Survey The total annual income for "Home Produce Sales" (\$1,242,000AUD) and "Subsistence activity" (\$8,782,000AUD) in S. Tarawa was \$10,024,000 in 2006 (Table 3.1., pg. 13). Both of these income activities may take place on residential land.

				The number of people in S Tarawa engaged in subsistence activity is 4.1% (Table 2.4, pg. 12). This equals 1,610 people of the 39,186 total S Tarawa population in 2006 (Table 2.1, pg. 11). Subsistence income per person engaged in subsistence activity = \$10,024,000/1,610 people = \$6,226/ person.
DISTRIBUTION_OF_FUNDING_TO_S_TARAWA	0.2		Dimensionless	The proportion of budget has remained fairly constant from 2008-2018 with ~38%:20%:42% of budget to national:South Tarawa: outer islands. Sources: 2009 and 2018 National Budgets
effect_of_land_loss_on_subsistence_livelihoods	GRAPH(Tarawa.Residential_Land_Area/(INIT(Tarawa.Residential_Land_Area))) Points: (0.000, 0.000), (0.100, 0.100), (0.200, 0.200), (0.300, 0.300), (0.400, 0.400), (0.500, 0.500), (0.600, 0.600), (0.700, 0.700), (0.800, 0.800), (0.900, 0.900), (1.000, 1.000)		Dimensionless	This converter estimates a relationship where subsistence livelihoods decrease as land is lost.
financial_cost_to_move_abroad	15000		Dimensionless	Moving cost (\$15,000 AUD) was estimated from international move website and accounts for visa, flights, shipping, and insurance. https://internationalvanlines.com/how-much-does-it-cost-to-move-to-australia/
financial_cost_to_move_internally	300		Dimensionless	Price estimated from airline cost (~\$200 AUD) from South Tarawa to Tabiteuea South with an additional \$100 AUD estimated for shipping.
GOVNT_FUNDING_PER_CAPITA_IN_OUTER_ISLANDS	TOTAL_GOVNT_FUNDING_PER_CAPITA*(0.62-DISTRIBUTION_OF_FUNDING_TO_S_TARAWA)		AUD / (people* year)	Assuming ~38% of the budget will go to national programs. The funding to the outer islands will be 62 minus the percent to South Tarawa.
income_in_S_Tarawa_per_capita	"total_income_in_S_Tarawa"/Demographics.Population_in_Tarawa		AUD/ (people* year)	Per capita income is the total income in South Tarawa divided by the population in a given year.
INTERNATIONAL_REMITTANCE_S_PER_YEAR	GRAPH(TIME) Points: (1990.0, 500000), (2006.0, 6068000), (2019.0, 15477722), (2045.0, 32600000), (2063.33333333, 45600000), (2081.66666667, 61600000), (2100.0, 75000000)		AUD/ year	Points were estimated around historic data points of 2006 (\$6,068,000 AUD) and 2019 (\$15,477,722 AUD). These values are total remittances received for South Tarawa. Sources: 2006 and 2009 Household Income and Expenditures Report
total_cost_of_movement_from_Outer_Islands_abroad	financial_cost_to_move_abroad+Outer_Islands.total_emotional_cost_of_movement_abroad		Dimensionless	Total cost is the sum of financial and emotional cost.
total_cost_of_movement_from_Outer_Islands_to_S_Tarawa	financial_cost_to_move_internally+Outer_Islands.total_emotional_cost_of_movement_internal		Dimensionless	Total cost is the sum of financial and emotional cost.
total_cost_of_movement_from_S_Tarawa_abroad	financial_cost_to_move_abroad+Tarawa.total_emotional_cost_of_movement_abroad		Dimensionless	Total cost is the sum of financial and emotional cost.
total_cost_of_movement_from_S_Tarawa_to_Outer_Islands	financial_cost_to_move_internally+Tarawa.total_emotional_cost_of_movement_internal		Dimensionless	Total cost is the sum of financial and emotional cost.
TOTAL_GOVNT_FUNDING_PER_CAPITA	1000		AUD / (people* year)	Government funding per capita is based on total expenditure and population. It increased from ~\$740/person in 2008 to ~\$1,390/person in 2018. A value of \$1,000 was used here.
total_income_from_subsistence	Demographics.Population_in_Tarawa*ANNUAL_INCOME_FOR_SUSTAINABLE_LIVELIHOODS*percent_of_S_Tarawa_engaged_in_subsistence_activities"		AUD/ year	The total income in South Tarawa from subsistence activities is the population times the percentage of people engaged times the per capita annual income for subsistence livelihoods.
total_other_income	GRAPH(TIME) Points: (1990.0, 300), (1998.46153846, 800), (2006.0, 1120), (2015.38461538, 1800), (2019.0, 2032), (2032.30769231, 3300), (2040.76923077, 4100), (2049.23076923, 5100), (2057.69230769, 6300), (2066.15384615, 7600), (2074.61538462, 9000), (2083.07692308, 10300), (2091.53846154, 11800), (2100.0, 13500)		AUD/ (people* year)	Total other income for 2006 was calculated from the Per Capita total income (\$1,531 AUD) minus income generated from home produce sales (\$32 AUD), subsistence activity (\$224 AUD), and remittances (\$155 AUD) (Table 3.3, pg. 16 in Household Income and Expenditures report 2006). Total other income was calculated to be \$1,120 AUD per capita in 2006. Total other income for 2019 was calculated from the total Average annual per capita income (\$2,915 AUD) (Table 139, pg. 199 in Household Income and Expenditures report 2019) minus Primary industry/activities - composed of home based activities (\$638 per capita per year), Cash gifts, remittances (\$94 per capita per year), and Cash purchased gifts (\$151 per capita per year). Total other income was calculated to be \$2,032 AUD per capita in 2019.

				Other data points were added based on research judgement.
Food:				
ACCESS_TO_IMPORTED_FOOD_OUTER_ISLANDS	0.6		Dimensionless	Access to imported food in the outer islands is estimated to be lower than that of South Tarawa.
ACCESS_TO_IMPORTED_FOOD_S_TARAWA	1		Dimensionless	Access to imported food is estimated to be 100% based on discussions and observations in South Tarawa.
effect_of_temp_on_local_food_supply	GRAPH(Climate_Impacts.PROJECTED_TEMPERATURE//Climate_Impacts.HISTORIC_TEMPERATURE) Points: (1.000, 1.000), (1.100, 0.9973), (1.200, 0.9866), (1.300, 0.9451), (1.400, 0.8055), (1.500, 0.500), (1.600, 0.1945), (1.700, 0.05487), (1.800, 0.01343), (1.900, 0.002742), (2.000, 0.000)		Dimensionless	Relationship estimated from researcher and represents the idea that as temperature increases, local farming will become increasingly more difficult. Effect will be multiplied to the local food supply where a low "effect" leads to lower supply.
imported_food_stock_Outer_Islands	REF_FOOD_SECURITY_OUTER_ISLANDS*ACCESS_TO_IMPORTED_FOOD_OUTER_ISLANDS		food stock	The imported food supply in the outer islands is calculated from a reference value for food security in the outer islands then adjusted from the estimated accessed to imported food.
imported_food_stock_S_Tarawa	REF_FOOD_SECURITY_S_TARAWA*ACCESS_TO_IMPORTED_FOOD_S_TARAWA		food stock	The imported food supply in South Tarawa is calculated from a reference value for food security in South Tarawa then adjusted from the estimated accessed to imported food.
local_food_supply_Outer_Islands	REF_FOOD_SECURITY_OUTER_ISLANDS*effect_of_temp_on_local_food_supply		food stock	The local food supply in the outer islands is calculated from a reference value for food security in the outer islands then dynamically updated from the effect of temperature on food production.
local_food_supply_S_Tarawa	REF_FOOD_SECURITY_S_TARAWA*effect_of_temp_on_local_food_supply		food stock	The local food supply in South Tarawa is calculated from a reference value for food security in South Tarawa then dynamically updated from the effect of temperature on food production.
PREFERENCE_FOR_LOCAL_FOOD_IN_OUTER_ISLANDS	0.2		Dimensionless	Averaged 'share of dietary energy consumed from own production' (Figure 6) from all regions excluding South Tarawa. [value=19.5%] FAO 'Food consumption in Kiribati'
PREFERENCE_FOR_LOCAL_FOOD_IN_S_TARAWA	0.05		Dimensionless	From 'share of dietary energy consumed from own production' (Figure 6) for South Tarawa. [value=5%] FAO 'Food consumption in Kiribati'
REF_FOOD_SECURITY_OUTER_ISLANDS	0.71		food stock	71% of households in the Outer Islands are classified as food secure or mildly food insecure according the the Kiribati 2019/20 Household Income and Expenditures Survey. This value was calculated from the average of all regions excluding South Tarawa. (Figure 36 of FAO Food consumption in Kiribati)
REF_FOOD_SECURITY_S_TARAWA	0.59		food stock	59% of households in South Tarawa are classified as food secure or mildly food insecure according the the Kiribati 2019/20 Household Income and Expenditures Survey. (Figure 36 of FAO Food consumption in Kiribati)
total_food_stock_adequacy_Outer_Islands	(1-PREFERENCE_FOR_LOCAL_FOOD_IN_OUTER_ISLANDS)*imported_food_stock_Outer_Islands+(PREFERENCE_FOR_LOCAL_FOOD_IN_OUTER_ISLANDS)*local_food_supply_Outer_Islands		food stock	The total food adequacy in the outer islands is the combination of local food and imported food availability.
total_food_stock_adequacy_S_Tarawa	(1-PREFERENCE_FOR_LOCAL_FOOD_IN_S_TARAWA)*imported_food_stock_S_Tarawa+(PREFERENCE_FOR_LOCAL_FOOD_IN_S_TARAWA)*local_food_supply_S_Tarawa		food stock	The total food adequacy in South Tarawa is the combination of local food and imported food availability.
Water_Resources:				
	Freshwater Lens (ft ³) = (groundwater recharge	INIT		Changes to the freshwater lens is based on water balance equation where change in freshwater lens storage (S) = precipitation + groundwater inflow - groundwater outflow - evapotranspiration. Runoff was not included in this calculation.

Freshwater_Lens(t)	$\text{Freshwater_Lens}(t - dt) + (\text{groundwater_recharge} - \text{groundwater_abstractions}) * dt$	Freshwater_Lens = 12042762	cu m	The initial freshwater lens volume was roughly estimated from a dome equation where the diameter is the island width (1,000m) and the height is the maximum freshwater thickness for Bonriki over a 12 year period (23m). While in reality, the freshwater lens is asymmetrical, a dome shape was used for simplification. Source: Falkland & Woodroffe, 2004
Water_in_Storage_Tanks(t)	$\text{Water_in_Storage_Tanks}(t - dt) + (\text{water_collection} - \text{tank_withdrawal}) * dt$	INIT Water_in_Storage_Tanks = 56375	cu m	Assuming the initial amount of water tanks in Tarawa start at half capacity. 5,245 tanks in Tarawa * 43% of population using rainwater harvesting = 2,255 tanks. 2,255 tanks (with a max of 50 cu m per tank) at half capacity = 56,375 cu meters
Water_Tanks_in_Tarawa(t)	$\text{Water_Tanks_in_Tarawa}(t - dt) + (\text{new_tank_installations} - \text{discontinued_tank_use}) * dt$	INIT Water_Tanks_in_Tarawa = 2255.35	water tank	The 2005 National Census shows that 43% of households in South Tarawa use rainwater harvesting. Source: Kiribati Tarawa Water Master Plan 2010-2030 (pg 23)
discontinued_tank_use	$\text{DELAY}(\text{Water_Tanks_in_Tarawa}/\text{LIFESPAN_OF_WATER_TANK}, 30)$		water tank/Years	Tank discontinuation rate is based on the lifespan of the tank.
groundwater_abstractions	$\text{pumping_withdrawal} + (\text{INIT}(\text{Freshwater_Lens}) - \text{volume_of_lens_unaffected_by_SLR})/\text{TIME_PERIOD_OF_LENS_VOLUME_CHANGE}$		cu m/year	The rate of groundwater lost from the freshwater lens is the amount from pumping in addition to the amount that is lost to salinisation.
groundwater_recharge	$\text{MIN}(\text{effective_rainfall} * \text{AVG_RECHARGE_RATE}, \text{volume_that_can_infiltrate}/\text{TIME_PERIOD_OF_LENS_VOLUME_CHANGE})$		cu m/year	Recharge rate = precipitation - evapotranspiration +/- the change in soil-moisture store. This calculation assumes soil-moisture store to be constant and only includes precipitation and evapotranspiration. Source: Falkland & Woodroffe, 2004 This is currently assuming that all rainwater that hits non-developed land is soak into the ground for groundwater (no runoff). This is supported by Post et al., 2018 who say that runoff can be "neglected because of the high infiltration capacity of the soils, the flat topography, and the lack of surface flow feature on the island." This is agreed by White (1996) who gives simplified water balance equation, where no soil hydrology needed.
new_tank_installations	$\text{tank_installation_from_new_housing} + \text{new_tanks_funded_by_govt} + \text{tank_replacement_rate}$		water tank/Years	New tank installation rates are based primarily on a constant tank replacement rate to replace discontinued tanks and tank installations from new housing. When the government funding/ tank subsidy switch is on, new tanks can also be added from that.
tank_withdrawal	rainwater_usage		cu m / year	The rate of water withdrawal from tanks is from the usage.
water_collection	$\text{MIN}(\text{supply_from_house_catchment}, \text{volume_that_can_be_collected}) * \text{RAINWATER_HARVESTING_SWITCH}$		cu m/year	The rate of water collection is based on the rainwater able to be collected from a roof surface area, but limited by the amount of tank capacity (or vice versa).
ADDITIONAL_WATER_CONSUMPTION_NEED_PER_CAPITA_PER_DEG_WARMING	2		liter / (people* day*Degrees C)	Estimate taken from Kiribati Tarawa Water Master Plan 2010-2030 (Section 5.2). The projection in the Master Plan was for 1deg C of warming by 2020 and allowed an additional 2L/person/day in demand. Using this, we estimate an increased demand of 2L/person/day for every 1degC of warming.
AVG_RECHARGE_RATE	0.36		Dimensionless	From historical rainfall and recharge data, Falkland & Woodroffe calculated an average recharge rate of 36% of rainfall. Source: Falkland & Woodroffe, 2004

BONRIKI_LAND_AREA	9.5		sq km	The area of Bonriki was used before it is the surface area that infiltrates down into the main freshwater lens used for pumping. The water pumped from this area by the public utilities (PUB) supplies 67% of South Tarawa's population. Source: Post et al., 2018
CONVERSION_MM_TO_M	0.001		m / mm	Conversion of mm to m.
CONVERSION_SQ_KM_TO_SQ_M	1000000		sq m/ sq km	Conversion of sq km to sq m
COST_OF_WATER_TANK	1313		Australian Dollars / water tank	Price sourced from tank retailer at \$850USD (\$1313AUD) for a 1000 gallon tank. Price conversion from USD to AUD made on Apr. 15, 2024. Source: https://tankretailer.com/products/quadel-plastic-water-storage-tank?currency=USD&variant=47211282399552&utm_medium=cpc&utm_source=google&utm_campaign=Google+Shopping&stkn=6c7cd00f44c4&srltid=AfmBOoq-36JVc4XSGgwntd93qvlAG_KDGwdEUOhZ6M4zAwkB-bQ2f-VRE&com_cvv=d30042528f072ba8a22b19c81250437cd47a2f30330f0ed03551c4efdaf3409e
DAY_TO_YEAR_CONVERSION	365		day / year	Conversion of day to year
DESAL_SWITCH	0		Dimensionless	Switch turns on scenario for the use of desalination plants. Currently set at 0 as none of the proposed plants are currently in use.
DESALINATION_PLANT_PROPOSED_WATER_PUMPING_RATES_PER_DAY	3000		cu m / (plants *day)	The Environmental and Social Impact Assessment for the 2 proposed desalination plants estimates an additional 6,000 cu m/ day of water supply. It is assumed that each plant will contribute 3,000 cu m/day. Source: Kiribati: South Tarawa Water Supply Project (ADB, 2020)
desalination_water_usage	IF TIME < 2024 THEN 0 ELSE MIN(DESALINATION_PLANT_PROPOSED_WATER_PUMPING_RATES_PER_DAY*NUMBER_OF_DESAL_PLANTS*DAY_TO_YEAR_CONVERSION, total_water_demand_yearly)*DESAL_SWITCH		cu m / year	
effect_of_rainwater_scarcity_on_consumption	GRAPH(IF rainwater_need > 0 THEN (Water_in_Storage_Tanks/rainwater_need) ELSE 1) Points: (0.000, 0.2000), (0.100, 0.2357), (0.200, 0.2775), (0.300, 0.3264), (0.400, 0.3836), (0.500, 0.4506), (0.600, 0.5289), (0.700, 0.6206), (0.800, 0.7278), (0.900, 0.8532), (1.000, 1.0000)		Dimensionless	This relationship represents a behaviour where rainwater tank water is used freely if tanks are full. The use of rainwater becomes more measured if the amount in the tanks is perceived to be inadequate to the usage need. A minimum value was set to indicate that rainwater usage would still continue, even if minimally, at low tank supply.
EFFECT_OF_SEA_LEVEL_RISE_ON_SALINITY	100		m/ (m)	Sherif and Singh (1999) and Werner & Simmons (2009) both found that there may be toe migration "on the order of 5km inland for a 500-mm sea level rise". This assumed a constant head, compared to a constant flux conditions which would be around 50 meters. A rate of 5000meters/ 0.5 meters seems too high after testing. Value lowered to 50meters/0.5meters. Source: Werner&Simmons (2009) Constant head conditions were assumed because water table levels stay relatively constant ("at typical depths of about 1-2 m below groundlevel". Source: Falkland &Woodroffe (2004)
effective_rainfall	IF TIME < 2023 THEN (Climate_Impacts.HISTORIC_RAINFALL-evapotranspiration_rate)*BONRIKI_LAND_AREA*CONVERSION_MM_TO_M*CONVERSION_SQ_KM_TO_SQ_M ELSE (Climate_Impacts.PROJECTED_RAINFALL-evapotranspiration_rate)*BONRIKI_LAND_AREA*CONVERSION_MM_TO_M*CONVERSION_SQ_KM_TO_SQ_M		cu m/ year	

evapotranspiration_rate	IF TIME < 2023 THEN 17.162*LN(Climate_Impacts.HISTORIC_RAINFALL)+26.1 ELSE 17.162*LN(Climate_Impacts.PROJECTED_RAINFALL)+26.1		mm/year	Actual annual evapotranspiration rates (mm) were plotted against month precipitation (mm) in Kiribati using values from 'Table 19-4. Water-balance calculations for 1989-1990, Tarawa.' Data was fit with a logarithmic trend line to determine the equation of $y = 17.162\ln(x) + 26.1$ Water-balance calculations found annual evapotranspiration rates to be higher in wet years than dry years. Source: Falkland & Woodroffe 2004
freshwater_lens_width	1000-inland_migration_of_lens_from_SLR		m	Initial island width was estimated at 1,000m (Falkland & Woodroffe, 2004). Updated island width is initial width minus the width of the freshwater lens lost to sea level rise.
GOVT_FUNDING_SWITCH	0		Dimensionless	Switch turns on scenario for testing government funding.
inland_migration_of_lens_from_SLR	Climate_Impacts.sea_level_rise*EFFECT_OF_SEA_LEVEL_RISE_ON_SALINITY		m	The inland migration of freshwater lens is calculated from the projected sea level rise and the effect relationship between horizontal distance to vertical sea rise.
LENS_THICKNESS	23		m	
LIFESPAN_OF_WATER_TANK	30		year	Based on average lifespan for polyethylene tanks. Source: https://smartwateronline.com/news/how-long-will-my-water-tank-last#:~:text=Summary,well%20maintained%20and%20well%2Dpositioned.
LITER_TO_CU_M_CONVERSION	1000		liter / cu m	Conversion of liter to cubic meter
MIN_DAILY_WATER_CONSUMPTION_NEEDED	65		liter / (people *day)	Water consumption is estimated at 65L/ person/day. Source: Kiribati Tarawa Water Master Plan 2010-2030 (pg 24)
new_tanks_funded_by_govt	(Finances."GOVERNMENT_FUNDING_PER_CAPITA_IN_S_TARAWA"*Demographics.Population_in_Tarawa)*PERCENT_OF_BUDGET_ON_WATER_INFRASTRUCTURE*PERCENT_CONVERSION/COST_OF_WATER_TANK*GOVT_FUNDING_SWITCH		water tank/ year	
NUMBER_OF_DESAL_PLANTS	3		plants	There are currently 3 proposed desalination plants in South Tarawa.
PERCENT_CONVERSION	0.01		Dimensionless	Conversion of percent to decimal value.
PERCENT_OF_BUDGET_ON_WATER_INFRASTRUCTURE	0.6		Dimensionless	Estimated from percent of Infrastructure budget in the Ministry of Public Works and Utilities (\$4,652,123AUD) vs the total budget for 2008 (\$81,881,605). \$500,000 of this was estimated towards rainwater tanks. Source: National Budget 2009 (pg 67) Value is 0.006 (0.6%)
PERCENT_OF_NEW_HOUSES_USING_RAINWATER	1		Dimensionless	This value was calculated through a calibration optimization. COME BACK TO THIS NUMBER.

pumping_withdrawal	$\text{MIN}(\text{groundwater_recharge} * \text{RECHARGE_ABSTRACTION_PERCENT}, \text{MAX}(0, (\text{total_water_demand_yearly} - \text{desalination_water_usage} - \text{rainwater_usage})))$		cu m / year	Water supply will first prioritise desalination plant supply then use groundwater and rainwater if more is needed. The pumping is also affected by the preference between rainwater harvesting and groundwater pumping. The pumping will compensate past the rainwater/groundwater preference if rainwater cannot achieve the set preference ratio. The abstraction rate is limited by the recommendation that only 25-50% of the recharge volume be abstracted.
RAINWATER_HARVESTING_SWITCH	1		Dimensionless	Switch turns on scenario for the use of rainwater harvesting.
rainwater_need	$(\text{total_water_demand_yearly} - \text{desalination_water_usage}) * \text{rainwater_preference_to_groundwater}$		cu m / year	This variable is used to indicate is rainwater harvesting will be used. If yes, then consumption behaviour will be adjusted.
rainwater_preference_to_groundwater	0.5		Dimensionless	The preference value between rainwater harvesting and groundwater pumping is set to 50:50.
rainwater_usage	$\text{MAX}(0, \text{rainwater_need} * \text{effect_of_rainwater_scarcity_on_consumption})$		cu m / year	Water supply will first prioritise desalination plant supply then use groundwater and rainwater if more is needed. The rainwater usage is also affected by the preference between rainwater harvesting and groundwater pumping.
RECHARGE_ABSTRACTION_PERCENT	0.5		Dimensionless	In order to maintain the integrity of the freshwater lens, only 25-50% of the recharge amount should be withdrawn. Source: Management of freshwater lenses on small Pacific islands (White & Falkland, 2009)
ROOF_AREA	140		sq m / housing building	The average roof area (140 sq m) from housing types in Kiribati was used. Source: Foon et al., 2006
supply_from_house_catchment	$\text{IF TIME} < 2023 \text{ THEN}$ $(\text{LOOKUP}(\text{Climate_Impacts.HISTORIC_RAINFALL}, \text{TIME}) * \text{Tarawa.Housing_Units} * \text{ROOF_AREA} / 2 * \text{CONVERSION_MM_TO_M} / (\text{Tarawa.HOUSING_LEVELS}))$ $\text{ELSE}(\text{Climate_Impacts.PROJECTED_RAINFALL} * \text{Tarawa.Housing_Units} * \text{ROOF_AREA} / 2 * \text{CONVERSION_MM_TO_M} / (\text{Tarawa.HOUSING_LEVELS}))$		cubic meter / year	From t=0 until 2020, the volume will be calculated from the historic rainfall amount multiplied by the catchment area. The catchment area is assumed to be half of the house footprint. For future projections, the volume is calculated from projected rainfall (based on RCPs) multiplied by the catchment area. The catchment area is assumed to be half of the house footprint.
TANK_EVALUTION_TIME	1		year	A tank evaluation time of 1 year was chosen to match the interval of rainfall data to make sure that more rainfall is not being collected than available.
tank_installation_from_new_housing	$\text{Tarawa.housing_development} / (\text{IF Tarawa.SWITCH_HOUSING_LEVELS} = 1 \text{ THEN Tarawa.HOUSING_LEVELS ELSE } 1) * \text{WATER_TANK_PER_HOUSE_FOOTPRINT} * \text{PERCENT_OF_NEW_HOUSES_USING_RAINWATER}$		water tank / year	The number of tanks installed from new builds is calculated from the percent of new houses using rainwater harvesting of the new housing units developed (divided by levels if multi-story switch is on). Each new housing build can have a certain number of tanks, based on the 'Water tank per house footprint' variable.
tank_replacement_rate	10		water tank / year	
TANK_VOLUME	50		cu m / (water tank)	A tank volume of 50 cu meters is used from Foon et al. (2006) who advises that this is the maximum size which a normal household can afford.
TIME_PERIOD_OF_LENS_VOLUME_CHANGE	1		year	Period of change was selected to match the rainfall data and other model evaluation increments.
total_additional_water_needed_from_temperature_increase	$\text{ADDITIONAL_WATER_CONSUMPTION_NEED_PER_CAPITA_PER_DEG_WARMING} * \text{Climate_Impacts.degree_of_warming}$		liter / (people* day)	Total additional water needed from temperature increase is calculated from the projected temperature increase and the relationship between temperature and water need increase.
total_capacity_of_tanks	$\text{Water_Tanks_in_Tarawa} * \text{TANK_VOLUME}$		cu m	Total capacity of rainwater tanks in South Tarawa is calculated from the total number of tanks and their volume.
total_water_demand_yearly	$((\text{MIN_DAILY_WATER_CONSUMPTION_NEEDED} + \text{total_additional_water_needed_from_temperature_increase}) * \text{Demographics.Population_in_Tarawa}) * \text{DAY_TO_YEAR_CONVERSION} / \text{LITER_TO_CU_M_CONVERSION}$		cu m / year	The total yearly water demand for South Tarawa is based on the minimum water needed per person, adjusted to increase with temperature, and dynamically updated with population changes.

volume_of_lens_unaffected_by_SLR	$(2/3)*PI*(freshwater_lens_width/2)^2*LENS_THICKNESS$		cu m	The freshwater lens volume was roughly estimated from a dome equation where the diameter is the island width ('freshwater lens width' converter) and the height is the the maximum freshwater thickness for Bonriki over a 12 year period (23m). While in reality, the freshwater lens is assymetrical, a dome shape was used for simplification. A static value of lens thickness was also assumed. Source: Falkland & Woodroffe, 2004
volume_that_can_be_collected	$MAX(0, (total_capacity_of_tanks - Water_in_Storage_Tanks)/TANK_EVALUTION_TIME)$		cu m / year	The total volume of water that can be in the tanks is calculated from the total capacity minus the amount of water that is already in the tanks. Max function ensures that it can't go below 0.
volume_that_can_infiltrate	$MAX(0, volume_of_lens_unaffected_by_SLR - Freshwater_Lens)$		cu m	The volume that can be infiltrated (filled) is the total capacity minus the volume of water that is already in there.
water_adequacy_ratio	$(total_water_demand_yearly - water_demand_deficit) / total_water_demand_yearly$		Dimensionless	
water_demand_deficit	$MAX(0, total_water_demand_yearly - desalination_water_usage - rainwater_usage - pumping_withdrawal)$		cu m / year	
WATER_TANK_PER_HOUSE_FOOTPRINT	2		water tank / housing building	Each house is assumed to have the ability to accommodate up to two water tanks.

Run Specs	
Start Time	1990
Stop Time	2100
DT	1/2
Fractional DT	TRUE
Save Interval	1
Sim Duration	1.5
Time Units	Years
Pause Interval	0
Integration Method	Euler
Keep all variable results	TRUE
Run By	Run
Calculate loop dominance information	TRUE
Exhaustive Search Threshold	1000

Custom Unit	Aliases	Equation
Dimensionless	dmnl unitless	1

Appendix VI

Loop Categorisation and Dominance

Loop Categorisation SSP 1-2.6

Loop Label	Categorisation	Loop Details
B1 1 stock 4 variables	Water (consumption)	Water Resources.tank withdrawal→Water Resources.Water in Storage Tanks→Water Resources.effect of rainwater scarcity on consumption→Water Resources.rainwater usage
R1 1 stock 2 variables	Demographics (births)	Demographics.births→Demographics.Population in Tarawa
B2 1 stock 2 variables	Demographics (movement)	Demographics.outer islands to S Tarawa flow→Demographics.Population in Outer Islands
R2 1 stock 2 variables	Demographics (births)	Demographics.outer islands births→Demographics.Population in Outer Islands
B3 1 stock 3 variables	Water (tanks)	Water Resources.water collection→Water Resources.Water in Storage Tanks→Water Resources.volume that can be collected
B4 1 stock 2 variables	Demographics (movement)	Demographics.out-migration from the outer islands→Demographics.Population in Outer Islands
B5 1 stock 2 variables	Demographics (deaths)	Demographics.deaths→Demographics.Population in Tarawa
B6 1 stock 2 variables	Demographics (deaths)	Demographics.outer islands deaths→Demographics.Population in Outer Islands
B7 1 stock 7 variables	Demographics (movement), Water (consumption)	Demographics.outer islands to S Tarawa flow→Demographics.Population in Tarawa→Water Resources.total water demand yearly→Water Resources.water demand deficit→Water Resources.water adequacy ratio→Utility Functions.utility of moving to S Tarawa→Utility Functions.probability of moving to S Tarawa from outer islands
B8 1 stock 3 variables	Land (loss)	Tarawa.residential land loss→Tarawa.Residential Land Area→Tarawa.percent of residential land area
R3 1 stock 6 variables	Demographics (movement), Water (consumption)	Demographics.outer islands to S Tarawa flow→Demographics.Population in Tarawa→Water Resources.total water demand yearly→Water Resources.water adequacy ratio→Utility Functions.utility of moving to S Tarawa→Utility Functions.probability of moving to S Tarawa from outer islands
B9 1 stock 3 variables	Settlements/ Infrastructure (tanks)	Water Resources.Water Tanks in Tarawa→__internal__→Water Resources.discontinued tank use
B10 1 stock 3 variables	Land (loss)	Tarawa.loss of open land→Tarawa.Undeveloped Land Area→Tarawa.percent of land area undeveloped
R4 3 stocks 16 variables	Settlements/Infrastructure (houses), Demographics (movement, births), Water (tanks, consumption)	Water Resources.water collection→Water Resources.Water in Storage Tanks→Water Resources.effect of rainwater scarcity on consumption→Water Resources.rainwater usage→Water Resources.water demand deficit→Water Resources.water adequacy ratio→Utility Functions.utility of moving to S Tarawa→Utility Functions.probability of moving to S Tarawa from outer islands→Demographics.outer islands to S Tarawa flow→Demographics.Population in Tarawa→Demographics.births→Tarawa.new people to Tarawa→Tarawa.housing units needed for new people→Tarawa.housing development→Tarawa.Housing Units→Water Resources.supply from house catchment
B11 3 stocks 18 variables	Settlements/Infrastructure (houses), Demographics (movement, births), Water (tanks, consumption)	Water Resources.water collection→Water Resources.Water in Storage Tanks→Water Resources.effect of rainwater scarcity on consumption→Water Resources.rainwater usage→Water Resources.water demand deficit→Water Resources.water adequacy ratio→Utility Functions.utility of moving to S Tarawa→Utility Functions.probability of moving to S Tarawa from outer islands→Demographics.outer islands to S Tarawa flow→Demographics.Population in Tarawa→Tarawa."population density in S. Tarawa"→Tarawa.birthrate in Tarawa→Demographics.births→Tarawa.new people to Tarawa→Tarawa.housing units needed for new people→Tarawa.housing development→Tarawa.Housing Units→Water Resources.supply from house catchment
B12 1 stock 4 variables	Demographics (births)	Demographics.births→Demographics.Population in Tarawa→Tarawa."population density in S. Tarawa"→Tarawa.birthrate in Tarawa
B13 1 stock 6 variables	Land (development), Settlements/Infrastructure (housing)	Tarawa.developing open land→Tarawa.Undeveloped Land Area→Tarawa.function of effect of land availability on moving in with family→Tarawa.percent of new people moving in with family→Tarawa.housing units needed for new people→Tarawa.housing development
B14 1 stock 5 variables	Demographics (movement), Economic	Demographics.outer islands to S Tarawa flow→Demographics.Population in Tarawa→Finances.income in S Tarawa per capita→Utility Functions.utility of moving to S Tarawa→Utility Functions.probability of moving to S Tarawa from outer islands
R5 2 stocks 14 variables	Settlements/Infrastructure (houses), Demographics (movement), Water (tanks, consumption)	Water Resources.water collection→Water Resources.Water in Storage Tanks→Water Resources.effect of rainwater scarcity on consumption→Water Resources.rainwater usage→Water Resources.water demand deficit→Water Resources.water adequacy ratio→Utility Functions.utility of moving to S Tarawa→Utility Functions.probability of moving to S Tarawa from outer islands→Demographics.outer islands to S Tarawa flow→Tarawa.new people to Tarawa→Tarawa.housing units needed for new people→Tarawa.housing development→Tarawa.Housing Units→Water Resources.supply from house catchment
R6 1 stock 6 variables	Demographics (movement), Economic	Demographics.outer islands to S Tarawa flow→Demographics.Population in Tarawa→Finances."total income in S. Tarawa"→Finances.income in S Tarawa per capita→Utility Functions.utility of moving to S Tarawa→Utility Functions.probability of moving to S Tarawa from outer islands

Loop Categorisation SSP 5-8.5

Loop Label	Categorisation	Loop Details
R1 1 stock 2 variables	Demographics (births)	Demographics.births→Demographics.Population in Tarawa
B1 1 stock 4 variables	Water (consumption)	Water Resources.tank withdrawal→Water Resources.Water in Storage Tanks→Water Resources.effect of rainwater scarcity on consumption→Water Resources.rainwater usage
B2 1 stock 2 variables	Demographics (movement)	Demographics.outer islands to S Tarawa flow→Demographics.Population in Outer Islands
R2 1 stock 2 variables	Demographics (births)	Demographics.outer islands births→Demographics.Population in Outer Islands
B3 1 stock 3 variables	Water (tanks)	Water Resources.water collection→Water Resources.Water in Storage Tanks→Water Resources.volume that can be collected
B4 1 stock 2 variables	Demographics (movement)	Demographics.out-migration from the outer islands→Demographics.Population in Outer Islands
B5 1 stock 2 variables	Demographics (deaths)	Demographics.deaths→Demographics.Population in Tarawa
B6 1 stock 2 variables	Demographics (deaths)	Demographics.outer islands deaths→Demographics.Population in Outer Islands
B7 1 stock 3 variables	Land (loss)	Tarawa.residential land loss→Tarawa.Residential Land Area→Tarawa.percent of residential land area
B8 1 stock 3 variables	Settlements/Infrastructure (tanks)	Water Resources.Water Tanks in Tarawa→_internal_→Water Resources.discontinued tank use
R3 3 stocks 19 variables	Settlements/Infrastructure (tanks, houses), Demographics (movement, births), Water (tanks)	Water Resources.new tank installations→Water Resources.Water Tanks in Tarawa→Water Resources.total capacity of tanks→Water Resources.volume that can be collected→Water Resources.water collection→Water Resources.Water in Storage Tanks→Water Resources.effect of rainwater scarcity on consumption→Water Resources.rainwater usage→Water Resources.water demand deficit→Water Resources.water adequacy ratio→Utility Functions.utility of moving to S Tarawa→Utility Functions.probability of moving to S Tarawa from outer islands→Demographics.outer islands to S Tarawa flow→Demographics.Population in Tarawa→Demographics.births→Tarawa.new people to Tarawa→Tarawa.housing units needed for new people→Tarawa.housing development→Water Resources.tank installation from new housing
B9 1 stock 7 variables	Demographics (movement), Water (consumption)	Demographics.outer islands to S Tarawa flow→Demographics.Population in Tarawa→Water Resources.total water demand yearly→Water Resources.water demand deficit→Water Resources.water adequacy ratio→Utility Functions.utility of moving to S Tarawa→Utility Functions.probability of moving to S Tarawa from outer islands
B10 1 stock 3 variables	Land (loss)	Tarawa.loss of open land→Tarawa.Undeveloped Land Area→Tarawa.percent of land area undeveloped
R4 1 stock 6 variables	Demographics (movement), Water (consumption)	Demographics.outer islands to S Tarawa flow→Demographics.Population in Tarawa→Water Resources.total water demand yearly→Water Resources.water adequacy ratio→Utility Functions.utility of moving to S Tarawa→Utility Functions.probability of moving to S Tarawa from outer islands
B11 1 stock 6 variables	Land (development), Settlements/Infrastructure (housing)	Tarawa.developing open land→Tarawa.Undeveloped Land Area→Tarawa.function of effect of land availability on moving in with family→Tarawa.percent of new people moving in with family→Tarawa.housing units needed for new people→Tarawa.housing development
B12 1 stock 5 variables	Demographics (movement), Economic	Demographics.outer islands to S Tarawa flow→Demographics.Population in Tarawa→Finances.income in S Tarawa per capita→Utility Functions.utility of moving to S Tarawa→Utility Functions.probability of moving to S Tarawa from outer islands
R5 3 stocks 16 variables	Settlements/Infrastructure (houses), Demographics (movement, births), Water (tanks, consumption)	Water Resources.water collection→Water Resources.Water in Storage Tanks→Water Resources.effect of rainwater scarcity on consumption→Water Resources.rainwater usage→Water Resources.water demand deficit→Water Resources.water adequacy ratio→Utility Functions.utility of moving to S Tarawa→Utility Functions.probability of moving to S Tarawa from outer islands→Demographics.outer islands to S Tarawa flow→Demographics.Population in Tarawa→Demographics.births→Tarawa.new people to Tarawa→Tarawa.housing units needed for new people→Tarawa.housing development→Tarawa.Housing Units→Water Resources.supply from house catchment
R6 2 stocks 14 variables	Settlements/Infrastructure (houses), Demographics (movement), Water (tanks, consumption)	Water Resources.water collection→Water Resources.Water in Storage Tanks→Water Resources.effect of rainwater scarcity on consumption→Water Resources.rainwater usage→Water Resources.water demand deficit→Water Resources.water adequacy ratio→Utility Functions.utility of moving to S Tarawa→Utility Functions.probability of moving to S Tarawa from outer islands→Demographics.outer islands to S Tarawa flow→Tarawa.new people to Tarawa→Tarawa.housing units needed for new people→Tarawa.housing development→Tarawa.Housing Units→Water Resources.supply from house catchment
B13 1 stock 4 variables	Demographics (births)	Demographics.births→Demographics.Population in Tarawa→Tarawa."population density in S. Tarawa"→Tarawa.birthrate in Tarawa
B14 3 stocks 18 variables	Settlements/Infrastructure (houses), Demographics (movement, births), Water (tanks, consumption)	Water Resources.water collection→Water Resources.Water in Storage Tanks→Water Resources.effect of rainwater scarcity on consumption→Water Resources.rainwater usage→Water Resources.water demand deficit→Water Resources.water adequacy ratio→Utility Functions.utility of moving to S Tarawa→Utility Functions.probability of moving to S Tarawa from outer islands→Demographics.outer islands to S Tarawa flow→Demographics.Population in Tarawa→Tarawa."population density in S. Tarawa"→Tarawa.birthrate in Tarawa→Demographics.births→Tarawa.new people to Tarawa→Tarawa.housing units needed for new people→Tarawa.housing development→Tarawa.Housing Units→Water Resources.supply from house catchment

Loop Dominance SSP 1-2.6

Loop Label	2025	2025.5	2026	2026.5	2027	2027.5	2028	2028.5	2029	2029.5
B1 1 stock 4 variables	2%	42%	48%	14%	5%	2%	18%	25%	19%	21%
R1 1 stock 2 variables	49%	28%	25%	44%	49%	51%	42%	38%	41%	39%
B2 1 stock 2 variables	1%	0%	0%	0%	0%	0%	0%	0%	1%	1%
R2 1 stock 2 variables	2%	1%	1%	1%	0%	0%	0%	1%	1%	2%
B3 1 stock 3 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B4 1 stock 2 variables	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B5 1 stock 2 variables	13%	7%	7%	12%	13%	14%	11%	10%	11%	10%
B6 1 stock 2 variables	1%	0%	0%	0%	0%	0%	0%	0%	0%	1%
B7 1 stock 7 variables	9%	5%	4%	8%	9%	9%	7%	6%	7%	6%
B8 1 stock 3 variables	1%	0%	0%	1%	1%	1%	1%	1%	1%	1%
R3 1 stock 6 variables	6%	4%	3%	6%	6%	7%	5%	5%	5%	5%
B9 1 stock 3 variables	5%	3%	3%	5%	5%	5%	4%	4%	4%	4%
B10 1 stock 3 variables	4%	2%	2%	3%	4%	4%	3%	3%	3%	3%
R4 3 stocks 16 variables	0%	1%	2%	0%	0%	0%	1%	1%	1%	1%
B11 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B13 1 stock 6 variables	2%	1%	1%	1%	2%	2%	2%	1%	1%	1%
B14 1 stock 5 variables	3%	2%	2%	3%	3%	3%	3%	2%	3%	2%
R5 2 stocks 14 variables	0%	1%	1%	0%	0%	0%	1%	1%	1%	1%
R6 1 stock 6 variables	3%	1%	1%	2%	3%	3%	2%	2%	2%	2%

Normalised

Settlements and Infrastructure	6%	6%	6%	6%	6%	6%	6%	5%	6%	6%
Freshwater Supply	14%	45%	50%	23%	17%	14%	26%	31%	26%	28%
Habitable Land	5%	3%	3%	5%	5%	5%	5%	5%	5%	4%
Economic Activities	5%	3%	2%	4%	5%	5%	4%	4%	4%	4%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	71%	44%	40%	62%	68%	70%	59%	55%	60%	59%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 1-2.6

Loop Label	2030	2030.5	2031	2031.5	2032	2032.5	2033	2033.5	2034	2034.5
B1 1 stock 4 variables	15%	1%	16%	12%	1%	9%	0%	24%	37%	13%
R1 1 stock 2 variables	42%	49%	41%	43%	48%	42%	47%	36%	29%	41%
B2 1 stock 2 variables	1%	1%	1%	1%	2%	2%	2%	2%	2%	2%
R2 1 stock 2 variables	2%	3%	3%	3%	4%	5%	5%	4%	3%	5%
B3 1 stock 3 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B4 1 stock 2 variables	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
B5 1 stock 2 variables	11%	13%	11%	11%	13%	11%	13%	9%	8%	11%
B6 1 stock 2 variables	1%	1%	1%	1%	1%	2%	2%	1%	1%	2%
B7 1 stock 7 variables	7%	8%	7%	7%	7%	7%	7%	5%	4%	6%
B8 1 stock 3 variables	1%	2%	1%	2%	2%	2%	2%	2%	1%	2%
R3 1 stock 6 variables	5%	6%	5%	5%	5%	5%	5%	4%	3%	4%
B9 1 stock 3 variables	5%	5%	4%	4%	5%	5%	5%	4%	3%	4%
B10 1 stock 3 variables	3%	3%	3%	3%	3%	2%	3%	2%	2%	2%
R4 3 stocks 16 variables	0%	0%	1%	0%	0%	0%	0%	1%	1%	0%
B11 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B13 1 stock 6 variables	1%	2%	1%	1%	1%	1%	1%	1%	1%	1%
B14 1 stock 5 variables	3%	3%	3%	3%	3%	3%	3%	2%	2%	2%
R5 2 stocks 14 variables	0%	0%	0%	0%	0%	0%	0%	1%	1%	0%
R6 1 stock 6 variables	2%	3%	2%	2%	3%	2%	2%	2%	2%	2%

Normalised

Settlements and Infrastructure	6%	6%	6%	5%	6%	6%	6%	5%	5%	5%
Freshwater Supply	23%	12%	24%	20%	11%	18%	11%	30%	40%	21%
Habitable Land	5%	5%	5%	5%	5%	4%	5%	4%	3%	5%
Economic Activities	4%	5%	4%	4%	5%	4%	4%	3%	3%	4%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	63%	72%	62%	65%	73%	68%	74%	58%	49%	66%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 1-2.6

Loop Label	2035	2035.5	2036	2036.5	2037	2037.5	2038	2038.5	2039	2039.5
B1 1 stock 4 variables	1%	23%	23%	4%	9%	20%	15%	35%	37%	69%
R1 1 stock 2 variables	46%	34%	34%	43%	41%	36%	38%	28%	27%	12%
B2 1 stock 2 variables	3%	3%	3%	4%	4%	3%	4%	3%	3%	1%
R2 1 stock 2 variables	6%	6%	5%	7%	6%	6%	6%	5%	5%	2%
B3 1 stock 3 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B4 1 stock 2 variables	2%	2%	2%	2%	2%	2%	2%	2%	2%	1%
B5 1 stock 2 variables	12%	9%	9%	11%	11%	9%	10%	7%	7%	3%
B6 1 stock 2 variables	2%	2%	2%	3%	2%	2%	2%	2%	2%	1%
B7 1 stock 7 variables	7%	5%	5%	6%	6%	5%	5%	4%	4%	2%
B8 1 stock 3 variables	2%	2%	2%	2%	2%	2%	2%	2%	2%	1%
R3 1 stock 6 variables	5%	4%	4%	4%	4%	4%	4%	3%	3%	1%
B9 1 stock 3 variables	5%	5%	4%	5%	5%	4%	4%	3%	3%	1%
B10 1 stock 3 variables	2%	2%	1%	2%	2%	1%	1%	1%	1%	0%
R4 3 stocks 16 variables	0%	1%	1%	0%	0%	1%	0%	1%	1%	2%
B11 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B13 1 stock 6 variables	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%
B14 1 stock 5 variables	3%	2%	2%	3%	2%	2%	2%	2%	2%	1%
R5 2 stocks 14 variables	0%	1%	1%	0%	0%	1%	0%	1%	1%	2%
R6 1 stock 6 variables	2%	2%	2%	2%	2%	2%	2%	1%	1%	1%

Normalised

Settlements and Infrastructure	6%	6%	6%	6%	5%	5%	5%	5%	5%	5%
Freshwater Supply	10%	28%	28%	13%	17%	26%	21%	38%	40%	68%
Habitable Land	5%	3%	3%	4%	4%	4%	4%	3%	3%	1%
Economic Activities	4%	3%	3%	4%	4%	3%	4%	3%	3%	1%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	75%	59%	59%	73%	70%	62%	66%	51%	50%	25%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 1-2.6

Loop Label	2040	2040.5	2041	2041.5	2042	2042.5	2043	2043.5	2044	2044.5
B1 1 stock 4 variables	71%	2%	15%	41%	43%	94%	90%	14%	6%	10%
R1 1 stock 2 variables	11%	42%	36%	25%	24%	0%	2%	36%	39%	36%
B2 1 stock 2 variables	1%	5%	5%	3%	3%	0%	0%	6%	7%	7%
R2 1 stock 2 variables	2%	9%	7%	5%	5%	0%	0%	8%	10%	10%
B3 1 stock 3 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B4 1 stock 2 variables	1%	3%	2%	2%	2%	0%	0%	3%	3%	4%
B5 1 stock 2 variables	3%	11%	10%	7%	6%	0%	1%	10%	10%	10%
B6 1 stock 2 variables	1%	3%	3%	2%	2%	0%	0%	3%	4%	4%
B7 1 stock 7 variables	1%	6%	5%	3%	3%	0%	0%	5%	5%	5%
B8 1 stock 3 variables	1%	3%	3%	2%	2%	0%	0%	3%	3%	3%
R3 1 stock 6 variables	1%	4%	3%	2%	2%	0%	0%	3%	3%	3%
B9 1 stock 3 variables	1%	6%	5%	3%	3%	0%	0%	4%	5%	5%
B10 1 stock 3 variables	0%	1%	1%	1%	0%	0%	0%	1%	0%	0%
R4 3 stocks 16 variables	2%	0%	0%	1%	1%	3%	3%	0%	0%	0%
B11 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B13 1 stock 6 variables	0%	1%	1%	0%	0%	0%	0%	0%	0%	0%
B14 1 stock 5 variables	1%	2%	2%	1%	1%	0%	0%	2%	2%	2%
R5 2 stocks 14 variables	2%	0%	0%	1%	1%	3%	2%	0%	0%	0%
R6 1 stock 6 variables	1%	2%	2%	1%	1%	0%	0%	2%	2%	2%

Normalised

Settlements and Infrastructure	5%	6%	5%	5%	5%	5%	5%	5%	5%	5%
Freshwater Supply	69%	11%	21%	43%	45%	90%	86%	20%	13%	16%
Habitable Land	1%	4%	4%	2%	2%	0%	0%	3%	3%	3%
Economic Activities	1%	4%	3%	2%	2%	0%	0%	3%	4%	3%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	24%	76%	67%	47%	46%	5%	8%	68%	75%	72%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 1-2.6

Loop Label	2045	2045.5	2046	2046.5	2047	2047.5	2048	2048.5	2049	2049.5
B1 1 stock 4 variables	1%	1%	16%	16%	5%	22%	32%	6%	3%	15%
R1 1 stock 2 variables	40%	39%	35%	36%	38%	28%	24%	33%	37%	33%
B2 1 stock 2 variables	8%	8%	6%	6%	8%	8%	7%	10%	9%	8%
R2 1 stock 2 variables	11%	11%	9%	8%	11%	10%	9%	13%	12%	10%
B3 1 stock 3 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B4 1 stock 2 variables	4%	4%	3%	3%	4%	4%	4%	5%	5%	4%
B5 1 stock 2 variables	11%	10%	9%	9%	10%	8%	6%	9%	10%	9%
B6 1 stock 2 variables	4%	4%	3%	3%	4%	4%	4%	5%	5%	4%
B7 1 stock 7 variables	5%	5%	4%	4%	4%	3%	3%	4%	4%	4%
B8 1 stock 3 variables	3%	3%	3%	3%	3%	3%	2%	3%	4%	3%
R3 1 stock 6 variables	3%	3%	3%	3%	3%	2%	2%	3%	3%	3%
B9 1 stock 3 variables	6%	6%	4%	4%	5%	4%	4%	5%	4%	3%
B10 1 stock 3 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
R4 3 stocks 16 variables	0%	0%	1%	0%	0%	1%	1%	0%	0%	0%
B11 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B13 1 stock 6 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B14 1 stock 5 variables	2%	2%	2%	2%	2%	2%	1%	2%	2%	2%
R5 2 stocks 14 variables	0%	0%	0%	0%	0%	1%	1%	0%	0%	0%
R6 1 stock 6 variables	2%	2%	2%	2%	2%	1%	1%	2%	2%	2%

Normalised

Settlements and Infrastructure	5%	5%	5%	4%	4%	5%	5%	5%	4%	4%
Freshwater Supply	8%	8%	22%	21%	11%	26%	35%	12%	9%	20%
Habitable Land	3%	3%	3%	3%	3%	2%	2%	3%	4%	4%
Economic Activities	4%	4%	3%	3%	4%	3%	2%	3%	3%	3%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	80%	80%	68%	69%	78%	64%	56%	77%	80%	70%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 1-2.6

Loop Label	2050	2050.5	2051	2051.5	2052	2052.5	2053	2053.5	2054	2054.5
B1 1 stock 4 variables	30%	17%	9%	1%	10%	7%	4%	15%	28%	12%
R1 1 stock 2 variables	27%	33%	34%	35%	28%	23%	31%	30%	25%	30%
B2 1 stock 2 variables	6%	8%	9%	12%	12%	16%	13%	10%	8%	11%
R2 1 stock 2 variables	8%	9%	11%	14%	14%	18%	15%	11%	9%	12%
B3 1 stock 3 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B4 1 stock 2 variables	3%	4%	5%	6%	6%	8%	6%	5%	4%	5%
B5 1 stock 2 variables	7%	9%	9%	9%	7%	6%	8%	8%	7%	8%
B6 1 stock 2 variables	3%	4%	5%	6%	6%	7%	6%	5%	4%	5%
B7 1 stock 7 variables	3%	4%	4%	4%	3%	3%	3%	3%	3%	3%
B8 1 stock 3 variables	3%	3%	3%	4%	3%	2%	3%	3%	3%	3%
R3 1 stock 6 variables	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
B9 1 stock 3 variables	3%	3%	4%	4%	4%	4%	4%	3%	3%	3%
B10 1 stock 3 variables	0%	1%	1%	1%	1%	0%	1%	1%	1%	1%
R4 3 stocks 16 variables	1%	0%	0%	0%	0%	0%	0%	0%	1%	0%
B11 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B13 1 stock 6 variables	0%	0%	0%	1%	0%	0%	1%	1%	1%	1%
B14 1 stock 5 variables	1%	2%	2%	2%	1%	1%	2%	1%	1%	1%
R5 2 stocks 14 variables	1%	0%	0%	0%	0%	0%	0%	0%	1%	0%
R6 1 stock 6 variables	1%	2%	2%	2%	1%	1%	1%	1%	1%	1%

Normalised

Settlements and Infrastructure	4%	4%	4%	4%	5%	5%	4%	4%	4%	4%
Freshwater Supply	33%	21%	14%	7%	15%	11%	9%	19%	31%	16%
Habitable Land	3%	4%	4%	4%	3%	3%	4%	4%	4%	5%
Economic Activities	2%	3%	3%	3%	2%	2%	3%	3%	2%	3%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	58%	68%	75%	82%	75%	80%	80%	70%	59%	72%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 1-2.6

Loop Label	2055	2055.5	2056	2056.5	2057	2057.5	2058	2058.5	2059	2059.5
B1 1 stock 4 variables	26%	55%	63%	16%	11%	1%	8%	10%	9%	4%
R1 1 stock 2 variables	26%	15%	12%	29%	29%	30%	24%	21%	24%	26%
B2 1 stock 2 variables	9%	5%	4%	11%	13%	16%	17%	18%	17%	17%
R2 1 stock 2 variables	9%	5%	4%	11%	13%	15%	16%	17%	16%	16%
B3 1 stock 3 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B4 1 stock 2 variables	4%	3%	2%	5%	6%	7%	8%	9%	8%	8%
B5 1 stock 2 variables	7%	4%	3%	8%	8%	8%	6%	6%	6%	7%
B6 1 stock 2 variables	4%	2%	2%	5%	5%	6%	7%	7%	7%	7%
B7 1 stock 7 variables	3%	2%	1%	3%	3%	3%	2%	2%	2%	3%
B8 1 stock 3 variables	3%	2%	1%	3%	3%	4%	3%	3%	3%	3%
R3 1 stock 6 variables	2%	1%	1%	2%	2%	2%	1%	1%	2%	2%
B9 1 stock 3 variables	2%	1%	1%	3%	3%	3%	3%	3%	3%	3%
B10 1 stock 3 variables	1%	1%	0%	1%	1%	1%	1%	1%	1%	1%
R4 3 stocks 16 variables	1%	2%	2%	0%	0%	0%	0%	0%	0%	0%
B11 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B13 1 stock 6 variables	1%	0%	0%	1%	1%	1%	1%	1%	1%	1%
B14 1 stock 5 variables	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
R5 2 stocks 14 variables	1%	1%	2%	0%	0%	0%	0%	0%	0%	0%
R6 1 stock 6 variables	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%

Normalised

Settlements and Infrastructure	4%	4%	5%	4%	4%	4%	4%	4%	4%	4%
Freshwater Supply	29%	55%	62%	20%	15%	6%	12%	13%	12%	8%
Habitable Land	4%	2%	2%	5%	5%	5%	4%	4%	5%	5%
Economic Activities	2%	1%	1%	2%	2%	2%	2%	2%	2%	2%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	61%	37%	30%	69%	74%	83%	78%	78%	77%	81%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 1-2.6

Loop Label	2060	2060.5	2061	2061.5	2062	2062.5	2063	2063.5	2064	2064.5
B1 1 stock 4 variables	3%	7%	18%	58%	68%	27%	38%	14%	10%	1%
R1 1 stock 2 variables	27%	27%	24%	11%	8%	20%	17%	24%	24%	24%
B2 1 stock 2 variables	17%	16%	14%	7%	5%	13%	11%	15%	17%	21%
R2 1 stock 2 variables	16%	14%	12%	6%	4%	11%	9%	13%	14%	17%
B3 1 stock 3 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B4 1 stock 2 variables	8%	7%	6%	3%	2%	6%	5%	7%	8%	10%
B5 1 stock 2 variables	7%	7%	6%	3%	2%	5%	5%	6%	6%	6%
B6 1 stock 2 variables	7%	6%	5%	2%	2%	5%	4%	6%	6%	7%
B7 1 stock 7 variables	3%	3%	2%	1%	1%	2%	2%	2%	2%	2%
B8 1 stock 3 variables	3%	4%	3%	2%	1%	3%	3%	4%	4%	4%
R3 1 stock 6 variables	2%	2%	2%	1%	0%	1%	1%	1%	1%	1%
B9 1 stock 3 variables	3%	3%	2%	1%	1%	2%	2%	2%	2%	2%
B10 1 stock 3 variables	1%	1%	1%	1%	0%	1%	1%	2%	2%	2%
R4 3 stocks 16 variables	0%	0%	1%	2%	2%	1%	1%	0%	0%	0%
B11 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B13 1 stock 6 variables	1%	1%	1%	1%	0%	1%	1%	1%	1%	1%
B14 1 stock 5 variables	1%	1%	1%	0%	0%	1%	1%	1%	1%	1%
R5 2 stocks 14 variables	0%	0%	0%	1%	2%	1%	1%	0%	0%	0%
R6 1 stock 6 variables	1%	1%	1%	0%	0%	1%	1%	1%	1%	1%

Normalised

Settlements and Infrastructure	4%	4%	4%	4%	4%	4%	4%	4%	4%	4%
Freshwater Supply	7%	11%	21%	57%	67%	29%	39%	16%	13%	4%
Habitable Land	6%	6%	5%	3%	2%	5%	4%	6%	6%	6%
Economic Activities	2%	2%	2%	1%	1%	2%	1%	2%	2%	2%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	82%	77%	68%	35%	27%	60%	51%	72%	75%	84%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 1-2.6

Loop Label	2065	2065.5	2066	2066.5	2067	2067.5	2068	2068.5	2069	2069.5
B1 1 stock 4 variables	4%	0%	6%	11%	10%	3%	2%	20%	75%	4%
R1 1 stock 2 variables	15%	2%	25%	26%	20%	20%	17%	8%	2%	13%
B2 1 stock 2 variables	26%	37%	16%	12%	17%	23%	27%	26%	7%	29%
R2 1 stock 2 variables	20%	29%	12%	9%	13%	17%	19%	18%	5%	20%
B3 1 stock 3 variables	0%	0%	5%	9%	11%	0%	0%	0%	0%	0%
B4 1 stock 2 variables	12%	17%	8%	6%	8%	11%	12%	12%	3%	13%
B5 1 stock 2 variables	4%	1%	7%	7%	5%	5%	4%	2%	1%	4%
B6 1 stock 2 variables	9%	13%	6%	4%	6%	8%	9%	8%	2%	9%
B7 1 stock 7 variables	1%	0%	2%	2%	2%	2%	1%	1%	0%	1%
B8 1 stock 3 variables	2%	0%	4%	4%	3%	3%	3%	1%	0%	2%
R3 1 stock 6 variables	1%	0%	1%	1%	1%	1%	1%	0%	0%	1%
B9 1 stock 3 variables	2%	0%	2%	2%	2%	2%	2%	1%	0%	1%
B10 1 stock 3 variables	1%	0%	2%	2%	1%	2%	1%	1%	0%	1%
R4 3 stocks 16 variables	0%	0%	0%	0%	0%	0%	0%	1%	2%	0%
B11 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B13 1 stock 6 variables	1%	0%	2%	2%	1%	2%	1%	1%	0%	1%
B14 1 stock 5 variables	1%	0%	1%	1%	1%	1%	1%	0%	0%	0%
R5 2 stocks 14 variables	0%	0%	0%	0%	0%	0%	0%	0%	2%	0%
R6 1 stock 6 variables	1%	0%	1%	1%	1%	1%	1%	0%	0%	0%

Normalised

Settlements and Infrastructure	3%	1%	4%	4%	3%	3%	3%	3%	4%	3%
Freshwater Supply	6%	1%	14%	22%	22%	5%	4%	21%	73%	6%
Habitable Land	4%	1%	7%	8%	6%	6%	5%	2%	1%	4%
Economic Activities	1%	0%	2%	2%	1%	1%	1%	1%	0%	1%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	86%	98%	73%	65%	68%	84%	86%	73%	22%	86%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 1-2.6

Loop Label	2070	2070.5	2071	2071.5	2072	2072.5	2073	2073.5	2074	2074.5
B1 1 stock 4 variables	2%	2%	3%	1%	4%	13%	14%	7%	1%	1%
R1 1 stock 2 variables	16%	19%	16%	14%	19%	19%	15%	19%	14%	3%
B2 1 stock 2 variables	27%	25%	27%	30%	24%	21%	15%	23%	31%	41%
R2 1 stock 2 variables	18%	17%	18%	19%	16%	13%	9%	14%	18%	24%
B3 1 stock 3 variables	0%	0%	0%	0%	0%	0%	21%	3%	0%	0%
B4 1 stock 2 variables	12%	12%	12%	14%	11%	9%	7%	10%	14%	18%
B5 1 stock 2 variables	4%	5%	4%	4%	5%	5%	4%	5%	4%	1%
B6 1 stock 2 variables	8%	8%	8%	9%	7%	6%	4%	6%	9%	11%
B7 1 stock 7 variables	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%
B8 1 stock 3 variables	3%	3%	3%	3%	4%	4%	3%	4%	3%	1%
R3 1 stock 6 variables	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%
B9 1 stock 3 variables	2%	2%	2%	1%	2%	2%	1%	2%	1%	0%
B10 1 stock 3 variables	1%	2%	1%	1%	2%	2%	1%	2%	1%	0%
R4 3 stocks 16 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B13 1 stock 6 variables	1%	2%	2%	1%	2%	2%	2%	2%	2%	0%
B14 1 stock 5 variables	1%	1%	1%	1%	1%	1%	1%	1%	0%	0%
R5 2 stocks 14 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
R6 1 stock 6 variables	1%	1%	1%	0%	1%	1%	0%	1%	0%	0%

Normalised

Settlements and Infrastructure	3%	3%	3%	3%	4%	4%	3%	3%	3%	1%
Freshwater Supply	4%	4%	5%	3%	7%	15%	36%	11%	3%	1%
Habitable Land	6%	6%	6%	5%	7%	7%	6%	7%	5%	1%
Economic Activities	1%	1%	1%	1%	1%	1%	1%	1%	1%	0%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	86%	85%	85%	88%	82%	73%	55%	77%	88%	97%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 1-2.6

Loop Label	2075	2075.5	2076	2076.5	2077	2077.5	2078	2078.5	2079	2079.5
B1 1 stock 4 variables	1%	0%	5%	5%	2%	0%	3%	6%	16%	0%
R1 1 stock 2 variables	6%	9%	12%	13%	7%	1%	8%	4%	1%	0%
B2 1 stock 2 variables	38%	36%	32%	31%	37%	44%	35%	36%	28%	46%
R2 1 stock 2 variables	22%	20%	18%	17%	20%	23%	18%	19%	14%	23%
B3 1 stock 3 variables	0%	0%	0%	0%	0%	0%	4%	7%	21%	0%
B4 1 stock 2 variables	17%	16%	14%	14%	17%	19%	15%	16%	12%	20%
B5 1 stock 2 variables	2%	2%	3%	3%	2%	0%	2%	1%	0%	0%
B6 1 stock 2 variables	10%	10%	8%	8%	10%	11%	9%	9%	7%	11%
B7 1 stock 7 variables	0%	1%	1%	1%	0%	0%	0%	0%	0%	0%
B8 1 stock 3 variables	1%	2%	2%	3%	2%	0%	2%	1%	0%	0%
R3 1 stock 6 variables	0%	0%	1%	1%	0%	0%	0%	0%	0%	0%
B9 1 stock 3 variables	1%	1%	1%	1%	1%	0%	1%	0%	0%	0%
B10 1 stock 3 variables	1%	1%	1%	1%	1%	0%	1%	0%	0%	0%
R4 3 stocks 16 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B13 1 stock 6 variables	1%	1%	1%	2%	1%	0%	1%	0%	0%	0%
B14 1 stock 5 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
R5 2 stocks 14 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
R6 1 stock 6 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Normalised

Settlements and Infrastructure	1%	2%	3%	3%	2%	0%	2%	1%	0%	0%
Freshwater Supply	2%	1%	6%	7%	3%	0%	8%	13%	37%	0%
Habitable Land	2%	4%	5%	5%	3%	1%	4%	2%	1%	0%
Economic Activities	0%	1%	1%	1%	0%	0%	0%	0%	0%	0%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	94%	93%	86%	84%	92%	99%	86%	84%	62%	100%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 1-2.6

Loop Label	2080	2080.5	2081	2081.5	2082	2082.5	2083	2083.5	2084	2084.5
B1 1 stock 4 variables	2%	3%	0%	6%	1%	4%	1%	3%	0%	1%
R1 1 stock 2 variables	11%	19%	5%	7%	2%	6%	9%	14%	13%	11%
B2 1 stock 2 variables	34%	27%	42%	33%	44%	37%	38%	32%	35%	37%
R2 1 stock 2 variables	17%	13%	20%	15%	20%	16%	17%	14%	15%	15%
B3 1 stock 3 variables	0%	0%	0%	9%	1%	6%	0%	0%	0%	1%
B4 1 stock 2 variables	15%	12%	18%	15%	19%	16%	17%	14%	15%	16%
B5 1 stock 2 variables	3%	5%	1%	2%	1%	2%	2%	4%	3%	3%
B6 1 stock 2 variables	8%	6%	10%	8%	10%	8%	8%	7%	7%	8%
B7 1 stock 7 variables	1%	1%	0%	0%	0%	0%	1%	1%	1%	1%
B8 1 stock 3 variables	3%	5%	1%	2%	1%	2%	2%	4%	4%	3%
R3 1 stock 6 variables	0%	1%	0%	0%	0%	0%	0%	1%	0%	0%
B9 1 stock 3 variables	1%	3%	1%	1%	0%	1%	1%	2%	1%	1%
B10 1 stock 3 variables	1%	2%	1%	1%	0%	1%	1%	2%	2%	2%
R4 3 stocks 16 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B13 1 stock 6 variables	2%	3%	1%	1%	0%	1%	2%	2%	2%	2%
B14 1 stock 5 variables	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%
R5 2 stocks 14 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
R6 1 stock 6 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Normalised

Settlements and Infrastructure	3%	5%	1%	2%	1%	2%	2%	4%	4%	3%
Freshwater Supply	3%	5%	1%	16%	2%	11%	2%	4%	1%	2%
Habitable Land	6%	9%	3%	4%	1%	3%	5%	8%	7%	6%
Economic Activities	1%	1%	0%	0%	0%	0%	0%	1%	1%	1%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	88%	80%	95%	78%	96%	84%	90%	83%	87%	88%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 1-2.6

Loop Label	2085	2085.5	2086	2086.5	2087	2087.5	2088	2088.5	2089	2089.5
B1 1 stock 4 variables	2%	7%	20%	28%	37%	32%	7%	2%	10%	26%
R1 1 stock 2 variables	6%	10%	7%	4%	1%	3%	16%	17%	12%	6%
B2 1 stock 2 variables	40%	30%	17%	10%	3%	7%	29%	29%	24%	11%
R2 1 stock 2 variables	16%	12%	7%	4%	1%	3%	11%	11%	8%	4%
B3 1 stock 3 variables	3%	11%	31%	42%	55%	47%	1%	3%	15%	38%
B4 1 stock 2 variables	17%	13%	7%	4%	1%	3%	13%	13%	10%	5%
B5 1 stock 2 variables	2%	3%	2%	1%	0%	1%	4%	4%	3%	2%
B6 1 stock 2 variables	8%	6%	3%	2%	1%	1%	6%	5%	4%	2%
B7 1 stock 7 variables	0%	1%	0%	0%	0%	0%	1%	1%	1%	0%
B8 1 stock 3 variables	2%	3%	2%	1%	0%	1%	5%	6%	4%	2%
R3 1 stock 6 variables	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%
B9 1 stock 3 variables	1%	1%	1%	1%	0%	0%	2%	2%	2%	1%
B10 1 stock 3 variables	1%	2%	1%	1%	0%	1%	3%	3%	2%	1%
R4 3 stocks 16 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B13 1 stock 6 variables	1%	2%	1%	1%	0%	1%	3%	3%	3%	1%
B14 1 stock 5 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
R5 2 stocks 14 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
R6 1 stock 6 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Normalised

Settlements and Infrastructure	2%	3%	2%	1%	0%	1%	5%	5%	4%	2%
Freshwater Supply	6%	18%	50%	70%	92%	78%	8%	6%	25%	63%
Habitable Land	4%	6%	4%	3%	1%	2%	11%	11%	9%	5%
Economic Activities	0%	0%	0%	0%	0%	0%	1%	1%	0%	0%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	89%	72%	43%	26%	7%	18%	76%	77%	61%	30%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 1-2.6

Loop Label	2090	2090.5	2091	2091.5	2092	2092.5	2093	2093.5	2094	2094.5
B1 1 stock 4 variables	37%	29%	38%	22%	35%	35%	40%	2%	1%	3%
R1 1 stock 2 variables	1%	5%	1%	8%	2%	2%	0%	20%	21%	22%
B2 1 stock 2 variables	2%	8%	2%	13%	4%	4%	0%	25%	23%	20%
R2 1 stock 2 variables	1%	3%	1%	4%	1%	1%	0%	8%	7%	6%
B3 1 stock 3 variables	55%	43%	56%	33%	53%	52%	59%	0%	0%	0%
B4 1 stock 2 variables	1%	4%	1%	6%	2%	2%	0%	11%	10%	9%
B5 1 stock 2 variables	0%	1%	0%	2%	1%	1%	0%	5%	6%	6%
B6 1 stock 2 variables	0%	1%	0%	2%	1%	1%	0%	4%	4%	3%
B7 1 stock 7 variables	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%
B8 1 stock 3 variables	1%	2%	0%	4%	1%	1%	0%	11%	13%	14%
R3 1 stock 6 variables	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%
B9 1 stock 3 variables	0%	1%	0%	1%	0%	0%	0%	4%	4%	5%
B10 1 stock 3 variables	0%	1%	0%	2%	0%	0%	0%	4%	4%	4%
R4 3 stocks 16 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B13 1 stock 6 variables	0%	1%	0%	2%	1%	1%	0%	5%	6%	6%
B14 1 stock 5 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
R5 2 stocks 14 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
R6 1 stock 6 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Normalised

Settlements and Infrastructure	1%	2%	0%	3%	1%	1%	0%	8%	9%	10%
Freshwater Supply	92%	71%	94%	54%	87%	87%	99%	3%	3%	4%
Habitable Land	1%	4%	1%	7%	2%	2%	0%	19%	21%	22%
Economic Activities	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	6%	23%	5%	36%	10%	10%	1%	70%	67%	63%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 1-2.6

Loop Label	2095	2095.5	2096	2096.5	2097	2097.5	2098	2098.5	2099	2099.5
B1 1 stock 4 variables	1%	6%	4%	0%	5%	18%	8%	24%	35%	26%
R1 1 stock 2 variables	19%	17%	19%	21%	20%	11%	16%	8%	2%	6%
B2 1 stock 2 variables	25%	26%	23%	21%	20%	11%	15%	7%	2%	5%
R2 1 stock 2 variables	7%	7%	6%	6%	5%	3%	4%	2%	0%	1%
B3 1 stock 3 variables	0%	0%	0%	0%	0%	27%	11%	36%	53%	39%
B4 1 stock 2 variables	11%	11%	10%	9%	8%	5%	6%	3%	1%	2%
B5 1 stock 2 variables	5%	5%	5%	6%	5%	3%	4%	2%	1%	2%
B6 1 stock 2 variables	4%	4%	3%	3%	3%	2%	2%	1%	0%	1%
B7 1 stock 7 variables	1%	1%	1%	1%	1%	0%	1%	0%	0%	0%
B8 1 stock 3 variables	13%	11%	14%	17%	17%	11%	18%	10%	3%	10%
R3 1 stock 6 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B9 1 stock 3 variables	4%	3%	4%	5%	5%	3%	5%	3%	1%	3%
B10 1 stock 3 variables	4%	4%	4%	5%	4%	3%	4%	2%	1%	2%
R4 3 stocks 16 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B13 1 stock 6 variables	5%	5%	6%	6%	6%	3%	5%	3%	1%	2%
B14 1 stock 5 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
R5 2 stocks 14 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
R6 1 stock 6 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Normalised

Settlements and Infrastructure	9%	8%	9%	11%	11%	7%	10%	5%	2%	5%
Freshwater Supply	2%	6%	4%	2%	6%	44%	19%	58%	88%	64%
Habitable Land	21%	19%	23%	26%	26%	16%	25%	14%	4%	13%
Economic Activities	1%	0%	1%	1%	1%	0%	0%	0%	0%	0%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	68%	67%	63%	62%	58%	33%	46%	23%	6%	18%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 1-2.6

Loop Label	2100
B1 1 stock 4 variables	37%
R1 1 stock 2 variables	1%
B2 1 stock 2 variables	1%
R2 1 stock 2 variables	0%
B3 1 stock 3 variables	55%
B4 1 stock 2 variables	1%
B5 1 stock 2 variables	0%
B6 1 stock 2 variables	0%
B7 1 stock 7 variables	0%
B8 1 stock 3 variables	3%
R3 1 stock 6 variables	0%
B9 1 stock 3 variables	1%
B10 1 stock 3 variables	0%
R4 3 stocks 16 variables	0%
B11 3 stocks 18 variables	0%
B12 1 stock 4 variables	0%
B13 1 stock 6 variables	0%
B14 1 stock 5 variables	0%
R5 2 stocks 14 variables	0%
R6 1 stock 6 variables	0%

Normalised

Settlements and Infrastructure	1%
Freshwater Supply	91%
Habitable Land	3%
Economic Activities	0%
Food Supply	0%
Societal Conditions	4%
Total	100%

Loop Dominance SSP 5-8.5

Loop Label	2025	2025.5	2026	2026.5	2027	2027.5	2028	2028.5	2029	2029.5
B1 1 stock 4 variables	43%	63%	70%	22%	36%	47%	50%	51%	56%	7%
R1 1 stock 2 variables	31%	20%	16%	43%	35%	28%	26%	25%	23%	49%
B2 1 stock 3 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B3 1 stock 2 variables	0%	0%	0%	0%	0%	0%	0%	1%	1%	2%
R2 1 stock 2 variables	1%	0%	0%	1%	1%	1%	1%	1%	1%	3%
B4 1 stock 2 variables	8%	5%	4%	12%	9%	8%	7%	7%	6%	13%
B5 1 stock 2 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%
R7 3 stocks 19 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
R3 3 stocks 19 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B6 1 stock 2 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%
B7 1 stock 7 variables	6%	4%	3%	8%	6%	5%	5%	4%	4%	8%
R4 3 stocks 16 variables	1%	2%	2%	1%	1%	1%	1%	1%	2%	0%
R5 1 stock 6 variables	4%	3%	2%	6%	5%	4%	3%	3%	3%	6%
B8 1 stock 3 variables	0%	0%	0%	1%	1%	1%	1%	1%	1%	2%
B9 1 stock 3 variables	3%	2%	1%	3%	3%	2%	2%	2%	2%	3%
B10 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 1 stock 3 variables	3%	2%	2%	4%	3%	3%	3%	2%	2%	5%
R6 2 stocks 17 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Normalised										
Settlements and Infrastructure	4%	3%	3%	4%	4%	4%	4%	4%	3%	4%
Freshwater Supply	48%	64%	71%	31%	42%	51%	54%	55%	58%	19%
Habitable Land	3%	2%	1%	4%	3%	3%	2%	2%	2%	4%
Economic Activities	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	45%	30%	25%	61%	51%	43%	40%	39%	36%	72%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 5-8.5

Loop Label	2030	2030.5	2031	2031.5	2032	2032.5	2033	2033.5	2034
B1 1 stock 4 variables	23%	21%	36%	14%	1%	19%	15%	14%	27%
R1 1 stock 2 variables	40%	41%	33%	45%	50%	39%	41%	42%	35%
B2 1 stock 3 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B3 1 stock 2 variables	1%	2%	1%	2%	3%	3%	3%	3%	3%
R2 1 stock 2 variables	3%	3%	3%	4%	6%	5%	6%	6%	5%
B4 1 stock 2 variables	11%	11%	9%	12%	13%	11%	11%	11%	9%
B5 1 stock 2 variables	1%	1%	1%	1%	2%	2%	2%	2%	2%
R7 3 stocks 19 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
R3 3 stocks 19 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B6 1 stock 2 variables	1%	1%	1%	1%	2%	2%	2%	2%	2%
B7 1 stock 7 variables	7%	7%	5%	7%	8%	6%	7%	7%	6%
R4 3 stocks 16 variables	1%	1%	1%	0%	0%	1%	0%	0%	1%
R5 1 stock 6 variables	5%	5%	4%	5%	5%	4%	5%	5%	4%
B8 1 stock 3 variables	1%	1%	1%	2%	2%	2%	2%	2%	2%
B9 1 stock 3 variables	3%	3%	2%	3%	3%	2%	2%	2%	2%
B10 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 1 stock 3 variables	4%	4%	3%	4%	5%	4%	4%	4%	4%
R6 2 stocks 17 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%

Normalised

Settlements and Infrastructure	4%	4%	4%	4%	4%	4%	4%	4%	4%
Freshwater Supply	31%	29%	41%	23%	13%	27%	24%	23%	33%
Habitable Land	4%	4%	3%	4%	4%	3%	4%	4%	3%
Economic Activities	0%	0%	0%	0%	0%	0%	0%	0%	0%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	61%	63%	52%	69%	78%	65%	68%	69%	59%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 5-8.5

Loop Label	2034.5	2035	2035.5	2036	2036.5	2037	2037.5	2038	2038.5
B1 1 stock 4 variables	4%	11%	36%	36%	11%	3%	10%	1%	11%
R1 1 stock 2 variables	46%	43%	31%	31%	42%	44%	40%	44%	40%
B2 1 stock 3 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B3 1 stock 2 variables	4%	4%	3%	3%	4%	5%	6%	6%	5%
R2 1 stock 2 variables	7%	6%	4%	5%	7%	9%	9%	9%	8%
B4 1 stock 2 variables	12%	11%	8%	8%	11%	12%	11%	12%	11%
B5 1 stock 2 variables	2%	2%	1%	2%	2%	3%	3%	3%	3%
R7 3 stocks 19 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
R3 3 stocks 19 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B6 1 stock 2 variables	3%	2%	2%	2%	3%	3%	3%	3%	3%
B7 1 stock 7 variables	7%	7%	5%	5%	6%	7%	6%	7%	6%
R4 3 stocks 16 variables	0%	0%	1%	1%	0%	0%	0%	0%	0%
R5 1 stock 6 variables	5%	5%	3%	3%	4%	4%	4%	5%	4%
B8 1 stock 3 variables	2%	2%	2%	2%	3%	3%	2%	3%	3%
B9 1 stock 3 variables	2%	2%	2%	1%	2%	2%	1%	1%	1%
B10 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 1 stock 3 variables	5%	4%	3%	3%	4%	5%	5%	5%	4%
R6 2 stocks 17 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
Normalised									
Settlements and Infrastructure	5%	4%	3%	3%	4%	4%	5%	4%	4%
Freshwater Supply	15%	21%	41%	40%	20%	13%	18%	11%	19%
Habitable Land	4%	4%	3%	3%	4%	4%	3%	4%	4%
Economic Activities	0%	0%	0%	0%	0%	0%	0%	0%	0%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	77%	71%	52%	53%	73%	79%	74%	80%	73%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 5-8.5

Loop Label	2039	2039.5	2040	2040.5	2041	2041.5	2042	2042.5	2043
B1 1 stock 4 variables	25%	44%	48%	11%	3%	66%	79%	5%	5%
R1 1 stock 2 variables	34%	25%	23%	40%	41%	13%	7%	37%	40%
B2 1 stock 3 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B3 1 stock 2 variables	4%	3%	3%	6%	8%	3%	2%	9%	8%
R2 1 stock 2 variables	7%	5%	5%	9%	11%	4%	2%	12%	11%
B4 1 stock 2 variables	9%	7%	6%	11%	11%	3%	2%	10%	11%
B5 1 stock 2 variables	2%	2%	2%	3%	4%	2%	1%	5%	4%
R7 3 stocks 19 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
R3 3 stocks 19 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B6 1 stock 2 variables	3%	2%	2%	3%	4%	1%	1%	4%	4%
B7 1 stock 7 variables	5%	4%	3%	5%	6%	2%	1%	5%	6%
R4 3 stocks 16 variables	1%	1%	1%	0%	0%	2%	3%	0%	0%
R5 1 stock 6 variables	3%	2%	2%	3%	4%	1%	1%	4%	4%
B8 1 stock 3 variables	2%	2%	2%	3%	3%	1%	1%	3%	3%
B9 1 stock 3 variables	1%	1%	1%	1%	1%	0%	0%	0%	0%
B10 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 1 stock 3 variables	3%	2%	2%	4%	5%	2%	1%	5%	5%
R6 2 stocks 17 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%

Normalised

Settlements and Infrastructure	4%	3%	3%	4%	5%	4%	3%	5%	4%
Freshwater Supply	31%	47%	51%	18%	11%	66%	78%	13%	13%
Habitable Land	3%	2%	2%	4%	4%	1%	1%	3%	3%
Economic Activities	0%	0%	0%	0%	0%	0%	0%	0%	0%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	62%	47%	44%	74%	81%	29%	18%	79%	79%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 5-8.5

Loop Label	2043.5	2044	2044.5	2045	2045.5	2046	2046.5	2047	2047.5
B1 1 stock 4 variables	55%	57%	21%	15%	10%	1%	5%	7%	5%
R1 1 stock 2 variables	19%	18%	33%	35%	36%	39%	36%	35%	36%
B2 1 stock 3 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B3 1 stock 2 variables	4%	4%	7%	8%	9%	11%	11%	11%	11%
R2 1 stock 2 variables	5%	5%	9%	10%	11%	13%	13%	12%	13%
B4 1 stock 2 variables	5%	5%	9%	9%	10%	10%	10%	9%	10%
B5 1 stock 2 variables	2%	2%	4%	4%	5%	5%	6%	5%	6%
R7 3 stocks 19 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
R3 3 stocks 19 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B6 1 stock 2 variables	2%	2%	3%	4%	4%	5%	5%	5%	5%
B7 1 stock 7 variables	3%	2%	4%	4%	5%	5%	4%	4%	4%
R4 3 stocks 16 variables	2%	2%	1%	0%	0%	0%	0%	0%	0%
R5 1 stock 6 variables	2%	2%	3%	3%	3%	3%	3%	3%	3%
B8 1 stock 3 variables	2%	2%	3%	3%	3%	4%	3%	3%	4%
B9 1 stock 3 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B10 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 1 stock 3 variables	2%	2%	3%	4%	4%	5%	5%	4%	4%
R6 2 stocks 17 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%

Normalised

Settlements and Infrastructure	3%	3%	4%	4%	4%	4%	4%	4%	4%
Freshwater Supply	56%	58%	26%	21%	16%	8%	11%	14%	12%
Habitable Land	2%	2%	3%	3%	3%	3%	3%	3%	4%
Economic Activities	0%	0%	0%	0%	0%	0%	0%	0%	0%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	39%	37%	67%	72%	77%	84%	81%	79%	81%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 5-8.5

Loop Label	2048	2048.5	2049	2049.5	2050	2050.5	2051	2051.5	2052
B1 1 stock 4 variables	20%	59%	64%	9%	5%	10%	7%	0%	14%
R1 1 stock 2 variables	31%	16%	13%	35%	32%	27%	31%	35%	32%
B2 1 stock 3 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B3 1 stock 2 variables	9%	4%	4%	11%	14%	15%	14%	14%	11%
R2 1 stock 2 variables	10%	5%	4%	12%	15%	16%	14%	14%	11%
B4 1 stock 2 variables	8%	4%	3%	9%	9%	7%	8%	9%	8%
B5 1 stock 2 variables	5%	2%	2%	5%	7%	7%	7%	7%	6%
R7 3 stocks 19 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
R3 3 stocks 19 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B6 1 stock 2 variables	4%	2%	2%	5%	6%	6%	6%	6%	4%
B7 1 stock 7 variables	4%	2%	2%	4%	4%	3%	4%	4%	4%
R4 3 stocks 16 variables	1%	2%	2%	0%	0%	0%	0%	0%	0%
R5 1 stock 6 variables	2%	1%	1%	2%	2%	2%	2%	3%	2%
B8 1 stock 3 variables	3%	2%	1%	4%	4%	3%	4%	4%	4%
B9 1 stock 3 variables	0%	0%	0%	1%	1%	1%	1%	1%	1%
B10 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 1 stock 3 variables	3%	1%	1%	3%	4%	4%	4%	4%	3%
R6 2 stocks 17 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
Normalised									
Settlements and Infrastructure	3%	3%	3%	3%	4%	4%	4%	3%	3%
Freshwater Supply	25%	59%	64%	14%	10%	14%	13%	6%	19%
Habitable Land	3%	2%	2%	4%	4%	3%	4%	5%	4%
Economic Activities	0%	0%	0%	0%	0%	0%	0%	0%	0%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	69%	36%	31%	78%	83%	78%	80%	86%	74%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 5-8.5

Loop Label	2052.5	2053	2053.5	2054	2054.5	2055	2055.5	2056	2056.5
B1 1 stock 4 variables	16%	9%	15%	23%	5%	4%	6%	18%	18%
R1 1 stock 2 variables	31%	32%	27%	24%	29%	30%	30%	26%	26%
B2 1 stock 3 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B3 1 stock 2 variables	11%	13%	14%	13%	16%	16%	16%	14%	14%
R2 1 stock 2 variables	10%	13%	13%	12%	15%	15%	14%	12%	12%
B4 1 stock 2 variables	8%	8%	7%	6%	8%	8%	8%	7%	7%
B5 1 stock 2 variables	5%	6%	7%	6%	8%	8%	8%	7%	7%
R7 3 stocks 19 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
R3 3 stocks 19 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B6 1 stock 2 variables	4%	5%	5%	5%	6%	6%	6%	5%	5%
B7 1 stock 7 variables	3%	3%	3%	3%	3%	3%	3%	3%	3%
R4 3 stocks 16 variables	0%	0%	1%	1%	0%	0%	0%	1%	1%
R5 1 stock 6 variables	2%	2%	2%	2%	2%	2%	2%	2%	2%
B8 1 stock 3 variables	4%	4%	3%	3%	4%	4%	4%	4%	4%
B9 1 stock 3 variables	1%	1%	1%	1%	1%	1%	1%	1%	1%
B10 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 1 stock 3 variables	3%	3%	3%	2%	3%	3%	3%	2%	2%
R6 2 stocks 17 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%

Normalised

Settlements and Infrastructure	3%	3%	3%	3%	3%	3%	3%	3%	3%
Freshwater Supply	21%	14%	19%	26%	10%	9%	11%	22%	22%
Habitable Land	5%	5%	4%	4%	5%	5%	5%	4%	5%
Economic Activities	0%	0%	0%	0%	0%	0%	0%	0%	0%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	72%	78%	74%	67%	83%	84%	82%	71%	71%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 5-8.5

Loop Label	2057	2057.5	2058	2058.5	2059	2059.5	2060	2060.5	2061
B1 1 stock 4 variables	17%	19%	19%	1%	14%	11%	15%	26%	36%
R1 1 stock 2 variables	25%	23%	23%	27%	25%	22%	16%	8%	1%
B2 1 stock 3 variables	0%	0%	0%	0%	0%	13%	19%	33%	46%
B3 1 stock 2 variables	15%	15%	16%	20%	17%	14%	13%	7%	1%
R2 1 stock 2 variables	13%	13%	13%	16%	13%	10%	10%	5%	1%
B4 1 stock 2 variables	7%	6%	6%	7%	7%	6%	4%	2%	0%
B5 1 stock 2 variables	7%	7%	8%	10%	8%	6%	6%	3%	0%
R7 3 stocks 19 variables	0%	0%	0%	0%	0%	0%	1%	1%	2%
R3 3 stocks 19 variables	0%	0%	0%	0%	0%	1%	3%	6%	8%
B6 1 stock 2 variables	5%	5%	5%	7%	5%	4%	4%	2%	0%
B7 1 stock 7 variables	2%	2%	2%	3%	2%	2%	2%	1%	0%
R4 3 stocks 16 variables	1%	1%	1%	0%	0%	0%	0%	0%	0%
R5 1 stock 6 variables	2%	1%	1%	2%	1%	1%	1%	0%	0%
B8 1 stock 3 variables	4%	3%	3%	4%	4%	4%	3%	1%	0%
B9 1 stock 3 variables	1%	1%	1%	1%	1%	1%	1%	0%	0%
B10 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 1 stock 3 variables	2%	2%	2%	3%	2%	2%	1%	1%	0%
R6 2 stocks 17 variables	0%	0%	0%	0%	0%	1%	2%	4%	6%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
Normalised									
Settlements and Infrastructure	3%	3%	3%	3%	3%	4%	6%	9%	11%
Freshwater Supply	20%	22%	22%	5%	18%	28%	37%	58%	75%
Habitable Land	5%	4%	4%	5%	5%	4%	3%	2%	0%
Economic Activities	0%	0%	0%	0%	0%	0%	0%	0%	0%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	73%	71%	71%	87%	75%	64%	54%	31%	14%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 5-8.5

Loop Label	2061.5	2062	2062.5	2063	2063.5	2064	2064.5	2065	2065.5
B1 1 stock 4 variables	33%	36%	36%	37%	35%	3%	9%	8%	0%
R1 1 stock 2 variables	3%	1%	1%	1%	1%	21%	17%	17%	17%
B2 1 stock 3 variables	42%	46%	46%	47%	45%	0%	0%	0%	0%
B3 1 stock 2 variables	3%	1%	1%	1%	2%	25%	26%	26%	29%
R2 1 stock 2 variables	2%	1%	1%	0%	1%	16%	16%	16%	18%
B4 1 stock 2 variables	1%	0%	0%	0%	0%	6%	4%	4%	5%
B5 1 stock 2 variables	1%	0%	0%	0%	1%	12%	12%	12%	13%
R7 3 stocks 19 variables	1%	2%	2%	2%	2%	0%	0%	0%	0%
R3 3 stocks 19 variables	7%	7%	7%	7%	7%	0%	0%	0%	0%
B6 1 stock 2 variables	1%	0%	0%	0%	0%	7%	7%	7%	8%
B7 1 stock 7 variables	0%	0%	0%	0%	0%	2%	1%	1%	1%
R4 3 stocks 16 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
R5 1 stock 6 variables	0%	0%	0%	0%	0%	1%	1%	1%	1%
B8 1 stock 3 variables	1%	0%	0%	0%	0%	5%	4%	4%	5%
B9 1 stock 3 variables	0%	0%	0%	0%	0%	2%	1%	1%	1%
B10 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 1 stock 3 variables	0%	0%	0%	0%	0%	2%	2%	2%	2%
R6 2 stocks 17 variables	5%	5%	5%	5%	5%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%

Normalised

Settlements and Infrastructure	10%	11%	11%	11%	11%	2%	2%	2%	2%
Freshwater Supply	70%	75%	75%	76%	73%	6%	11%	10%	3%
Habitable Land	1%	0%	0%	0%	0%	6%	5%	5%	6%
Economic Activities	0%	0%	0%	0%	0%	0%	0%	0%	0%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	19%	13%	14%	13%	16%	86%	82%	83%	90%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 5-8.5

Loop Label	2066	2066.5	2067	2067.5	2068	2068.5	2069	2069.5	2070
B1 1 stock 4 variables	8%	13%	29%	2%	0%	1%	8%	5%	10%
R1 1 stock 2 variables	18%	12%	4%	16%	13%	6%	15%	13%	8%
B2 1 stock 3 variables	10%	16%	37%	0%	0%	1%	12%	7%	13%
B3 1 stock 2 variables	20%	19%	7%	30%	34%	38%	22%	27%	26%
R2 1 stock 2 variables	12%	11%	4%	17%	18%	21%	12%	14%	13%
B4 1 stock 2 variables	5%	3%	1%	4%	3%	2%	4%	4%	2%
B5 1 stock 2 variables	9%	9%	3%	13%	15%	17%	10%	12%	12%
R7 3 stocks 19 variables	0%	1%	2%	0%	0%	0%	0%	0%	1%
R3 3 stocks 19 variables	1%	3%	6%	0%	0%	0%	1%	1%	2%
B6 1 stock 2 variables	5%	5%	2%	7%	8%	9%	5%	6%	6%
B7 1 stock 7 variables	2%	1%	0%	1%	1%	1%	1%	1%	1%
R4 3 stocks 16 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
R5 1 stock 6 variables	1%	1%	0%	1%	1%	0%	1%	1%	0%
B8 1 stock 3 variables	5%	3%	1%	5%	4%	3%	5%	5%	4%
B9 1 stock 3 variables	2%	1%	0%	1%	1%	1%	1%	1%	1%
B10 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 1 stock 3 variables	2%	1%	0%	2%	1%	1%	1%	1%	1%
R6 2 stocks 17 variables	1%	2%	4%	0%	0%	0%	1%	1%	2%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
Normalised									
Settlements and Infrastructure	4%	6%	10%	2%	1%	1%	4%	3%	5%
Freshwater Supply	21%	32%	63%	4%	2%	2%	23%	15%	25%
Habitable Land	6%	4%	1%	6%	5%	3%	6%	6%	4%
Economic Activities	0%	0%	0%	0%	0%	0%	0%	0%	0%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	70%	59%	26%	88%	91%	93%	68%	75%	66%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 5-8.5

Loop Label	2070.5	2071	2071.5	2072	2072.5	2073	2073.5	2074	2074.5
B1 1 stock 4 variables	27%	36%	29%	0%	0%	3%	1%	2%	3%
R1 1 stock 2 variables	2%	0%	2%	7%	4%	9%	2%	1%	1%
B2 1 stock 3 variables	35%	46%	38%	0%	1%	5%	1%	3%	4%
B3 1 stock 2 variables	9%	0%	8%	38%	29%	30%	30%	44%	42%
R2 1 stock 2 variables	5%	0%	4%	18%	13%	14%	13%	19%	18%
B4 1 stock 2 variables	1%	0%	0%	2%	1%	2%	0%	0%	0%
B5 1 stock 2 variables	4%	0%	3%	17%	13%	13%	13%	19%	19%
R7 3 stocks 19 variables	2%	3%	2%	0%	0%	0%	0%	0%	0%
R3 3 stocks 19 variables	7%	9%	7%	0%	0%	1%	0%	0%	1%
B6 1 stock 2 variables	2%	0%	2%	8%	6%	6%	6%	9%	8%
B7 1 stock 7 variables	0%	0%	0%	1%	0%	1%	0%	0%	0%
R4 3 stocks 16 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
R5 1 stock 6 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B8 1 stock 3 variables	1%	0%	1%	8%	32%	14%	33%	3%	3%
B9 1 stock 3 variables	0%	0%	0%	1%	0%	1%	0%	0%	0%
B10 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 1 stock 3 variables	0%	0%	0%	1%	1%	1%	0%	0%	0%
R6 2 stocks 17 variables	4%	6%	4%	0%	0%	0%	0%	0%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
Normalised									
Settlements and Infrastructure	10%	13%	11%	1%	1%	2%	1%	1%	1%
Freshwater Supply	60%	74%	63%	1%	2%	9%	3%	5%	8%
Habitable Land	1%	0%	1%	9%	32%	15%	33%	3%	3%
Economic Activities	0%	0%	0%	0%	0%	0%	0%	0%	0%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	29%	13%	25%	89%	66%	74%	64%	91%	88%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 5-8.5

Loop Label	2075	2075.5	2076	2076.5	2077	2077.5	2078	2078.5	2079
B1 1 stock 4 variables	7%	9%	24%	7%	19%	13%	26%	21%	29%
R1 1 stock 2 variables	1%	4%	2%	4%	2%	5%	2%	4%	1%
B2 1 stock 3 variables	11%	14%	35%	11%	29%	19%	39%	31%	44%
B3 1 stock 2 variables	38%	30%	11%	34%	19%	26%	8%	14%	3%
R2 1 stock 2 variables	16%	12%	4%	13%	7%	9%	3%	5%	1%
B4 1 stock 2 variables	0%	1%	1%	1%	0%	1%	1%	1%	0%
B5 1 stock 2 variables	17%	13%	5%	15%	8%	11%	3%	6%	1%
R7 3 stocks 19 variables	1%	1%	3%	1%	2%	2%	4%	3%	4%
R3 3 stocks 19 variables	2%	3%	7%	2%	5%	4%	8%	6%	9%
B6 1 stock 2 variables	7%	6%	2%	6%	3%	5%	1%	2%	1%
B7 1 stock 7 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
R4 3 stocks 16 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
R5 1 stock 6 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B8 1 stock 3 variables	1%	4%	1%	3%	1%	2%	1%	1%	0%
B9 1 stock 3 variables	0%	1%	0%	1%	0%	1%	0%	1%	0%
B10 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 1 stock 3 variables	0%	1%	0%	1%	0%	1%	0%	1%	0%
R6 2 stocks 17 variables	1%	2%	4%	1%	3%	2%	5%	4%	5%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
Normalised									
Settlements and Infrastructure	3%	5%	11%	4%	8%	7%	12%	11%	14%
Freshwater Supply	20%	26%	57%	21%	49%	34%	61%	51%	67%
Habitable Land	1%	4%	1%	3%	1%	3%	1%	1%	0%
Economic Activities	0%	0%	0%	0%	0%	0%	0%	0%	0%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	76%	65%	31%	73%	42%	57%	26%	37%	19%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 5-8.5

Loop Label	2079.5	2080	2080.5	2081	2081.5	2082	2082.5	2083	2083.5
B1 1 stock 4 variables	23%	29%	25%	30%	28%	30%	21%	28%	26%
R1 1 stock 2 variables	4%	1%	3%	1%	2%	0%	5%	1%	2%
B2 1 stock 3 variables	34%	44%	37%	45%	41%	45%	31%	41%	39%
B3 1 stock 2 variables	10%	2%	8%	2%	4%	1%	12%	3%	4%
R2 1 stock 2 variables	3%	1%	3%	1%	1%	0%	3%	1%	1%
B4 1 stock 2 variables	1%	0%	1%	0%	0%	0%	1%	0%	1%
B5 1 stock 2 variables	4%	1%	3%	1%	2%	0%	5%	1%	2%
R7 3 stocks 19 variables	4%	5%	4%	5%	5%	6%	5%	7%	7%
R3 3 stocks 19 variables	8%	10%	8%	10%	9%	11%	8%	11%	11%
B6 1 stock 2 variables	2%	0%	1%	0%	1%	0%	2%	0%	1%
B7 1 stock 7 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
R4 3 stocks 16 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
R5 1 stock 6 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B8 1 stock 3 variables	1%	0%	0%	0%	0%	0%	1%	0%	0%
B9 1 stock 3 variables	1%	0%	0%	0%	0%	0%	1%	0%	0%
B10 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 1 stock 3 variables	1%	0%	0%	0%	0%	0%	1%	0%	0%
R6 2 stocks 17 variables	5%	6%	5%	6%	5%	6%	4%	6%	6%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%

Normalised

Settlements and Infrastructure	13%	15%	13%	15%	15%	16%	13%	16%	16%
Freshwater Supply	55%	66%	59%	68%	63%	67%	52%	63%	60%
Habitable Land	1%	0%	1%	0%	0%	0%	1%	0%	0%
Economic Activities	0%	0%	0%	0%	0%	0%	0%	0%	0%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	31%	19%	27%	17%	22%	17%	34%	20%	23%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 5-8.5

Loop Label	2084	2084.5	2085	2085.5	2086	2086.5	2087	2087.5	2088
B1 1 stock 4 variables	28%	14%	21%	14%	21%	15%	15%	11%	7%
R1 1 stock 2 variables	0%	9%	3%	10%	2%	5%	1%	4%	0%
B2 1 stock 3 variables	42%	22%	32%	20%	32%	22%	22%	16%	10%
B3 1 stock 2 variables	1%	15%	4%	16%	3%	7%	1%	6%	0%
R2 1 stock 2 variables	0%	4%	1%	4%	1%	2%	0%	1%	0%
B4 1 stock 2 variables	0%	2%	1%	3%	1%	1%	0%	1%	0%
B5 1 stock 2 variables	0%	6%	2%	7%	1%	3%	1%	2%	0%
R7 3 stocks 19 variables	9%	6%	11%	7%	13%	14%	22%	20%	33%
R3 3 stocks 19 variables	12%	9%	15%	8%	15%	16%	24%	21%	32%
B6 1 stock 2 variables	0%	2%	1%	2%	0%	1%	0%	1%	0%
B7 1 stock 7 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
R4 3 stocks 16 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
R5 1 stock 6 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B8 1 stock 3 variables	0%	1%	0%	1%	0%	0%	0%	0%	0%
B9 1 stock 3 variables	0%	2%	1%	2%	0%	1%	0%	1%	0%
B10 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 1 stock 3 variables	0%	3%	1%	3%	1%	3%	1%	5%	1%
R6 2 stocks 17 variables	7%	5%	8%	4%	8%	8%	12%	11%	16%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%

Normalised

Settlements and Infrastructure	18%	16%	21%	16%	21%	24%	27%	28%	31%
Freshwater Supply	63%	40%	52%	39%	52%	43%	44%	39%	37%
Habitable Land	0%	2%	0%	2%	0%	1%	0%	1%	0%
Economic Activities	0%	0%	0%	0%	0%	0%	0%	0%	0%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	19%	42%	27%	43%	26%	33%	29%	33%	31%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 5-8.5

Loop Label	2088.5	2089	2089.5	2090	2090.5	2091	2091.5	2092	2092.5
B1 1 stock 4 variables	9%	15%	14%	21%	13%	22%	20%	26%	18%
R1 1 stock 2 variables	1%	0%	10%	3%	10%	2%	6%	1%	12%
B2 1 stock 3 variables	13%	22%	21%	31%	20%	33%	30%	38%	26%
B3 1 stock 2 variables	1%	0%	9%	3%	10%	2%	5%	1%	9%
R2 1 stock 2 variables	0%	0%	2%	1%	2%	0%	1%	0%	2%
B4 1 stock 2 variables	0%	0%	3%	1%	3%	1%	2%	0%	3%
B5 1 stock 2 variables	1%	0%	4%	1%	4%	1%	2%	0%	4%
R7 3 stocks 19 variables	30%	26%	14%	17%	14%	19%	15%	17%	10%
R3 3 stocks 19 variables	28%	24%	12%	14%	11%	13%	10%	11%	6%
B6 1 stock 2 variables	0%	0%	1%	0%	1%	0%	0%	0%	1%
B7 1 stock 7 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
R4 3 stocks 16 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
R5 1 stock 6 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B8 1 stock 3 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B9 1 stock 3 variables	0%	0%	3%	1%	3%	1%	2%	0%	4%
B10 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 1 stock 3 variables	2%	0%	4%	1%	4%	1%	2%	0%	2%
R6 2 stocks 17 variables	14%	11%	5%	6%	5%	6%	4%	5%	2%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%

Normalised

Settlements and Infrastructure	30%	28%	21%	22%	21%	22%	20%	20%	15%
Freshwater Supply	39%	44%	41%	51%	40%	53%	50%	58%	46%
Habitable Land	0%	0%	2%	1%	2%	0%	1%	0%	3%
Economic Activities	0%	0%	0%	0%	0%	0%	0%	0%	0%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	31%	28%	36%	26%	37%	25%	29%	21%	36%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 5-8.5

Loop Label	2093	2093.5	2094	2094.5	2095	2095.5	2096	2096.5	2097
B1 1 stock 4 variables	26%	27%	29%	17%	27%	15%	24%	15%	27%
R1 1 stock 2 variables	4%	4%	2%	16%	4%	20%	8%	20%	5%
B2 1 stock 3 variables	38%	40%	43%	25%	41%	22%	36%	22%	41%
B3 1 stock 2 variables	3%	2%	1%	10%	2%	10%	4%	9%	2%
R2 1 stock 2 variables	0%	0%	0%	1%	0%	1%	0%	1%	0%
B4 1 stock 2 variables	1%	1%	0%	4%	1%	5%	2%	5%	1%
B5 1 stock 2 variables	1%	1%	0%	4%	1%	4%	2%	4%	1%
R7 3 stocks 19 variables	14%	14%	14%	8%	14%	7%	13%	8%	15%
R3 3 stocks 19 variables	8%	7%	7%	4%	6%	3%	4%	3%	4%
B6 1 stock 2 variables	0%	0%	0%	1%	0%	1%	0%	1%	0%
B7 1 stock 7 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
R4 3 stocks 16 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
R5 1 stock 6 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B8 1 stock 3 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B9 1 stock 3 variables	1%	1%	1%	6%	1%	8%	4%	9%	2%
B10 3 stocks 18 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%
B11 1 stock 3 variables	1%	0%	0%	2%	0%	2%	1%	1%	0%
R6 2 stocks 17 variables	3%	3%	2%	1%	2%	1%	1%	1%	1%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%	0%	0%	0%

Normalised

Settlements and Infrastructure	17%	16%	16%	12%	15%	10%	14%	10%	15%
Freshwater Supply	59%	61%	65%	43%	63%	39%	58%	40%	63%
Habitable Land	1%	1%	0%	5%	1%	7%	3%	8%	2%
Economic Activities	0%	0%	0%	0%	0%	0%	0%	0%	0%
Food Supply	0%	0%	0%	0%	0%	0%	0%	0%	0%
Societal Conditions	23%	22%	19%	40%	21%	44%	26%	42%	21%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

Loop Dominance SSP 5-8.5

Loop Label	2097.5	2098	2098.5	2099	2099.5	2100
B1 1 stock 4 variables	26%	28%	26%	26%	23%	17%
R1 1 stock 2 variables	7%	3%	5%	3%	6%	13%
B2 1 stock 3 variables	38%	42%	39%	39%	37%	30%
B3 1 stock 2 variables	2%	1%	1%	1%	1%	2%
R2 1 stock 2 variables	0%	0%	0%	0%	0%	0%
B4 1 stock 2 variables	2%	1%	1%	1%	2%	4%
B5 1 stock 2 variables	1%	0%	1%	0%	0%	1%
R7 3 stocks 19 variables	15%	18%	18%	22%	23%	22%
R3 3 stocks 19 variables	4%	4%	4%	4%	4%	4%
B6 1 stock 2 variables	0%	0%	0%	0%	0%	0%
B7 1 stock 7 variables	0%	0%	0%	0%	0%	0%
R4 3 stocks 16 variables	0%	0%	0%	0%	0%	0%
R5 1 stock 6 variables	0%	0%	0%	0%	0%	0%
B8 1 stock 3 variables	0%	0%	0%	0%	0%	0%
B9 1 stock 3 variables	4%	2%	3%	2%	3%	8%
B10 3 stocks 18 variables	0%	0%	0%	0%	0%	0%
B11 1 stock 3 variables	0%	0%	0%	0%	0%	0%
R6 2 stocks 17 variables	1%	1%	1%	1%	1%	0%
B12 1 stock 4 variables	0%	0%	0%	0%	0%	0%

Normalised

Settlements and Infrastructure	14%	16%	16%	17%	18%	17%
Freshwater Supply	60%	64%	60%	60%	57%	48%
Habitable Land	3%	1%	2%	1%	2%	5%
Economic Activities	0%	0%	0%	0%	0%	0%
Food Supply	0%	0%	0%	0%	0%	0%
Societal Conditions	23%	19%	22%	21%	23%	30%
Total	100%	100%	100%	100%	100%	100%