Reframing global warming for better risk management: climate change, food insecurity and societal collapse

Catherine E. Richards

This thesis is submitted for the degree of

Doctor of Philosophy in Engineering

December 2021

Peterhouse

Department of Engineering

University of Cambridge

[blank page]

Declaration

This thesis is the result of my own work and includes nothing which is the outcome of work done in collaboration except as declared in the preface and specified in the text. It is not substantially the same as any work that has already been submitted for any degree or other qualification except as declared in the preface and specified in the text. This thesis contains 64,822 words and 116 figures, with 39,131 words and 28 figures constituting the main body and the remainder constituting appendices. It does not exceed the prescribed limit of 65,000 words, including appendices, footnotes, tables and equations, but excluding the bibliography, and 150 figures, specified by the Engineering Degree Committee.

Catherine E. Richards

Submitted for examination December 2021.

[blank page]

Abstract

Natural climate change, through its influence on agriculture, has been central to the rise and fall of civilisations throughout history. Anthropogenic climate change poses an unprecedented challenge and existential risk but, unlike natural climate change, it is a threat that contemporary society can prevent if we so choose. Despite consensus amongst climate scientists, concern across society and knowledge of solutions, anthropogenic emissions continue to rise, threatening the welfare of current and future generations globally. The recent failure of COP26 to 'flick the switch' on urgent climate action demonstrates the need for a paradigm shift in the way that we think about the threat of climate change.

Good risk management requires consideration and communication of tangible worst-case impacts. The mainstream framing of 'global warming', in terms of imperceptible temperature increases, does neither. For humanity, tangible worst-case impacts take the form of human suffering, societal collapse or extinction. However, consideration and communication of these concerning outcomes, with respect to climate change, is underdeveloped. This thesis is motivated by the idea that reframing the threat of climate change to embody more tangible risk of everyday relevance to society may support better risk management. And so, a three-part investigation is undertaken to improve our understanding of the complex risk landscape of climate change, food insecurity and societal collapse.

The first contribution looks to the past to examine how systematically documenting historical evidence may improve our understanding of the complex risk landscape. An original empirical evidence base is established and structured using a novel format causal loop diagram. Thousands of feedback loops are unfurled, demonstrating fragile interdependencies that may see climate change undermine agricultural productivity and food supply chains. This may lead to cascading or synchronous sociocultural unrest, economic loss and political dysfunction as well as starvation, migration and conflict, with the potential to trigger a reinforcing 'global systems death spiral'. The novel format enables swift identification of data-

driven methods used to establish empirical evidence and existing gaps. This systematic documentation of multidisciplinary evidence facilitates succinct visual consideration and communication of feedback loops and intervention points critical to managing the threat of climate change.

The second contribution looks to the future to examine how surveying 'end-game' climate change may improve our understanding of the complex risk landscape. An original quantitative model is developed to illustrate an 'extreme global warming' scenario. It is shown that we may face societal collapse as early as 2050, with population plummeting to 32% of current numbers by 2100, under high-range (8°C+) global warming. The distribution of risk will not be equal, with the least prepared countries of the developing Global South hit the hardest, experiencing 93% of cumulative human suffering by 2100. Emerging superpowers have a unique role to play in mitigating climate change, not only in the best interests of the rest of the world but for their own sake, with China and India alone at risk of 1.2 billion and 1.6 billion starvation deaths by 2100. These insights emphasise the danger of societal collapse should we not act with haste to reduce emissions, build resilience and decrease vulnerability.

The third contribution looks to the present to examine how climate policy and socioeconomic development decision-making may influence the complex risk landscape. An original quantitative model is used to conduct a comparative analysis of decision-factors under 15 mainstream scenarios of low- to mid-range (1.5–4.5°C) global warming. Depending on decision-making in the present, up to 2.5 billion people may face starvation, conflict or migration by 2100. Climate policy should prioritise urgent mitigation through behavioural disruption, while supporting slow-burn technological solutions. Socioeconomic development supporting education, gender and income equality, social cohesion and sustainable infrastructure and services is needed to build resilience and decrease vulnerability. High emitters hold a moral responsibility to address inequalities that may manifest global climate injustice. These insights emphasise that strong global coordination and international cooperation is needed to tackle climate change with proactive and well-balanced decisions if we are to minimise human suffering.

Collectively, the contributions to knowledge contained in this thesis provide a systematic and quantitative study of climate change, food insecurity and societal collapse, highlighting the danger of indirect cascading effects and synchronous failures as well as the potential for technological and socio-politico-economic interventions to backfire or have unintended consequences. It demonstrates the importance of future work to develop a deeper understanding of the worst-case impacts of climate change, which has broader implications for society in terms of articulating more tangible risk of everyday relevance to individuals, businesses and governments, to support better risk management.

Acknowledgements

Completing my PhD at Cambridge has been a life changing experience. I sincerely appreciate everyone who has supported me during my PhD and contributed positively to my time at Cambridge.

Firstly, I acknowledge my PhD funders—the General Sir John Monash Foundation, the Origin Foundation, the Cambridge Trust and Cambridge Australia Scholarships—for enabling me to have this incredible experience. I am especially grateful to the General Sir John Monash Foundation, whose interest in me came at a time when I was navigating a 'major fork in the road'. Thanks also to the British Federation of Women Graduates for recognising work contained in this thesis with the award for outstanding research, and to Forbes for recognising me on the 30 Under 30 list for contributions throughout my career in industry as well as my doctoral research.

I thank my PhD Supervisor, Professor Julian Allwood, who challenged me with this 'difficult and risky research brief' in our first meeting and encouraged me into the 88Pianists project, teaching and conducting admissions interviews. I am grateful for his support and guidance throughout my PhD, especially for his kindness in navigating an unexpectedly bumpy ride entailing a fall from a horse, a global pandemic and a personal trauma. I also thank my PhD Examiners, Professor Dick Fenner and Professor Jim Hall, for their time reading this thesis, advice and encouragement.

I acknowledge my Use Less Group and Resource Efficiency Collective colleagues. Thanks to Dr Rick Lupton and Dr Hannes Gauch for their technical support in tackling components of my PhD. Special thanks to Sarah, Simon, Iain, Karla, Harry, Matteo and Leo for their convivial companionship and countless cups of tea over the past four years.

I extend sincere appreciation to my colleagues from the Centre for the Study of Existential Risk, particularly Asaf, Catherine, Shahar, Lara, Sabin, Clarissa, Luke and Lord Martin Rees. Thanks for welcoming me so warmly and the excellent opportunities. The inspiration and happiness that being part of CSER has provided me is astounding, and I look forward to collaborating on postdoctoral research.

I acknowledge my college, Peterhouse. Thanks for providing me a beautiful home and safe place, generously funding my polo, and gifting me with many valuable friendships. Special thanks to Jenny and Alex for the tremendous impact they have had on my life, as well as Daniel, Lucy, Sally and Trev, with whom I share fond memories. I am honoured to have served the MCR as Treasurer. I am grateful to my Tutor, Dr Christopher Lester, for his wise and jovial support throughout my PhD. I will always remember Mr Meade, may he rest in peace, for his warm and cheeky welcomes, along with the kindness of many other people that make Peterhouse brilliant.

Polo has been a highlight of my time at Cambridge. I am grateful to CUPC for the opportunity to try polo having never ridden before, as well as for the support of Selby and Jacqui at Jurassic Park Polo and the Morris-Lowes and co. in Cambridge and Berkshire for getting me up to the standard of playing in the Varsity Match at Guards Polo Club. I am proud to have earned a Full Blue and the Award for Outstanding Contributions from Cambridge University Sport. More than anything, I am thankful to have made so many life-long friends. A special mention goes to Aviv and Charlotte, Olivia and Toby, Camila, Tony, Erik, Zerxes, Tate, Cameron, Chloe and Victoria. I cannot wait to add to our already marvellous collection of memories.

Finally, I acknowledge dear friends and family, near and far, old and new, who I have collected over my lifetime. Heartfelt thanks go to Nicole, Tash, Bret, Jamie, Jacquie, Lorena, Emily and Léa for making a special mark on my life. Joy – my completeness, thank you for making life brighter and entirely more joyful. Lachlan – my dearest friend, I would not be here without you, and I am so thankful for our life adventures. To my mother, Jennifer – thank you for all that you have sacrificed for me and for being a fine example of a genuine, strong and independent woman. I am happy and proud of the person I have become, and that is a product of your influences.

Table of contents

Front matter ..... **i**

1. Introduction: reframing the threat of global warming **1**

1.1. Research motivation **2**

1.1.1. Problem: the escalating threat of anthropogenic climate change 2

1.1.2. Opportunity: a tangible framing of anthropogenic climate change 4

1.1.3. Aim: an investigation of the worst-case impacts of climate change 6

1.2. Research scope **6**

1.2.1. Context: a history of climate, agriculture and complex societies 7

1.2.2. Context: the nascent interdisciplinary study of existential risks 8

1.2.3. Research boundary: systematic and quantitative study of climate change, food insecurity, societal collapse 10

1.3. Research framework **10**

1.3.1. Research Question 1: learning from the past 11

1.3.2. Research Question 2: surveying 'end-game' futures 11

1.3.3. Research Question 3: prioritising decision-factors in the present 12

1.4. Chapter summary: thesis outline **12**

2. Literature review: refining the research objectives **15**

2.1. Studies examining historical evidence of societal collapse **15**

2.1.1. Case studies based on primary sources 16

2.1.2. Meta-theory studies based on primary and secondary sources 20

2.1.3. Foresight studies based on primary, secondary and tertiary sources 23

2.2. Models of societal collapse for illustrating end-game futures **25**

2.2.1. Models of artificial societies for describing theories 25
2.2.2. Models of historical case studies for examining theories 27
2.2.3. Models of the contemporary world for exploring future scenarios 28
2.3. Scenarios for exploring decision-factors in the present 32
2.3.1. Development of the RCP-SSP-SPA framework 32
2.3.2. Studies on isolated components of the framework 36
2.3.3. Studies extending from the framework as a whole 38
2.4. Chapter summary: research objectives 40

3. The past: documenting complex evidence of climate change, food insecurity and societal collapse in contemporary society 43
3.1. Methodology 43
3.1.1. Investigation concept 44
3.1.2. Establishing an empirical evidence base in contemporary society 45
3.1.3. Constructing a novel format causal loop diagram 46
3.1.4. Validation, verification and interpretation 49
3.2. Results 50
3.2.1. New empirical evidence base 50
3.2.2. Novel format causal loop diagram 52
3.3. Discussion 55
3.3.1. Understanding the complex risk landscape depicted 55
3.3.2. Understanding the spread of empirical evidence depicted 57
3.4. Chapter summary: key findings 59

4. The future: illustrating the international risk landscape of climate change, food insecurity and societal collapse under extreme global warming 61
4.1. Methodology 62
4.1.1. Investigation concept 62
4.1.2. Data preparation 65
4.1.3. Simulation workflow 71
4.1.4. Validation, verification and interpretation 75
4.2. Results 76
4.2.1. Global and continental societal collapse dynamics 76
4.2.2. Continental and regional population loss 78

4.2.3. National starvation, development, vulnerability and resilience 80
4.3. Discussion 82
4.3.1. Danger of societal collapse under 'extreme global warming' 82
4.3.2. Geographic distribution of human suffering 83
4.3.3. Preparedness of populations at risk 85
4.4. Chapter summary: key findings 86

5. The present: exploring the influence of climate policy and socioeconomic development decision-factors on climate change, food insecurity and societal collapse 89
5.1. Methodology 90
5.1.1. Investigation concept 90
5.1.2. Computing human suffering in terms of risk of starvation 90
5.1.3. Comparing climate policy and socioeconomic development factors 94
5.1.4. Validation, verification and interpretation 96
5.2. Results 97
5.2.1. Risk of starvation under the 15 RCP-SSP-SPA framework scenarios 97
5.2.2. Future climate policy and socioeconomic development trends 100
5.2.3. Current climate policy and socioeconomic development inequalities 108
5.3. Discussion 110
5.3.1. Danger of human suffering under low- to mid-range global warming 110
5.3.2. Influence of climate policy decision-factors 111
5.3.3. Influence of socioeconomic development decision-factors 113
5.3.4. Inequalities manifesting as global climate injustice 113
5.4. Chapter summary: key findings 114

6. Conclusion: toward better risk management 117
6.1. Research contributions to knowledge 117
6.1.1. Contribution 1: learning from the past 117
6.1.2. Contribution 2: surveying end-game futures 118
6.1.3. Contribution 3: prioritising decision factors in the present 119
6.1.4. Overarching contribution: an investigation of the worst-case impacts of climate change 119
6.2. Future research opportunities 120

6.2.1. Addressing data availability issues 120
6.2.2. Addressing methodological issues 121
6.2.3. Extending beyond the boundaries of this investigation 122
6.3. Broader implications for society 124
6.3.1. Individuals, media and cultural institutions 124
6.3.2. Businesses, universal owners and financial regulators 125
6.3.3. Government, intergovernmental and international institutions 126
6.4. Chapter summary: denouement 127

References 129

Appendix A: Supplementary information for Chapter 3 183

Appendix B: Supplementary information for Chapter 4 and 5 241

List of figures

1.1 Relentless rise in annual CO_2 emissions despite climate action milestones from 1950 to 2021 4

1.2 Intertwined existence of the natural system, natural-system interface and human system 5

1.3 Society depends on the stable Holocene climate niche that has enabled agriculture for millennia. 8

1.4 Existential risks, like climate change, are unprecedented, global and intergenerational risks that may cause human suffering, societal collapse or extinction 10

1.5 Thesis outline 13

2.1 Conceptual model of the overarching process of societal collapse 16

2.2 Primary and secondary determinants of societal collapse 23

2.3 The global scale and granularity real-world system simulated by World3 31

2.4 The scenario matrix architecture of the RCP-SSP-SPA framework 33

2.5 The RCP dimension of the RCP-SSP-SPA framework 33

2.6 The SSP dimension of the RCP-SSP-SPA framework 34

3.1 Methodology overview for the first investigation (RQ1) of the three-part research framework . 44

3.2 One of the i-CLDs created for each of the 41 evidence points in the new empirical evidence base of climate change, food insecurity and societal collapse in contemporary society 47

3.3 Summary and custom colour-coded typology of the new empirical evidence base of climate change, food insecurity and societal collapse in contemporary society 51

3.4 Novel format causal loop diagram of climate change, food insecurity and societal collapse in contemporary society at global scale and national granularity. 54

4.1 Methodology overview for the second investigation (RQ2) of the three-part research framework. 63

4.2 Global and continental climate change, food insecurity and societal collapse dynamics from 2000 to 2100 under 'extreme global warming' 77

4.3 Continental and regional starvation deaths by decade under 'extreme global warming' 79

4.4 National cumulative starvation deaths in 2100 under 'extreme global warming' compared to development status, vulnerability and resilience in 2020 81
5.1 Methodology overview for the third investigation (RQ3) of the three-part framework 91
5.2 Global risk of starvation by continent under each of the 15 RCP-SSP-SPA framework scenarios 98
5.3 Comparison I – Global risk of starvation at 2100 under each of the 15 RCP-SSP-SPA framework scenarios mapped to (a) climate policy challenges space and (b) sustainability challenges space 99
5.4 Comparison II – Global risk of starvation at 2100 compared to future demographic and human development growth trends under each of the 15 RCP-SSP-SPA framework scenarios 101
5.5 Comparison III – Global risk of starvation at 2100 compared to future economic and institutional growth trends under each of the 15 RCP-SSP-SPA framework scenarios. 103
5.6 Comparison IV – Global risk of starvation at 2100 compared to future technology and environmental governance growth trends under each of the 15 RCP-SSP-SPA framework scenarios 105
5.7 Comparison V – Global risk of starvation at 2100 compared to future energy demand and supply growth trends under each of the 15 RCP-SSP-SPA framework scenarios 107
5.8 Comparison VI – (a) Global risk of starvation at 2100 compared to climate forcing for each of the 15 RCP-SSP-SPA framework scenarios. (b)-(e) Country risk of starvation at 2100 compared to current climate policy and socioeconomic development inequalities 109
5.9 Simulation narrative of climate niche shift causing food insecurity and human suffering. Example depicted for staple cereals in Pakistan under SSP5-RCP85 110
A.1 i-CLD for evidence point N1 186
A.2 i-CLD for evidence point N2 187
A.3 i-CLD for evidence point N3 187
A.4 i-CLD for evidence point N4 188
A.5 i-CLD for evidence point N5 188
A.6 i-CLD for evidence point N6 189
A.7 i-CLD for evidence point N7 189
A.8 i-CLD for evidence point N8 190
A.9 i-CLD for evidence point N9 190
A.10 i-CLD for evidence point C1 191
A.11 i-CLD for evidence point C2 191
A.12 i-CLD for evidence point C3 192
A.13 i-CLD for evidence point C4 192

A.14 i-CLD for evidence point C5 193
A.15 i-CLD for evidence point C6 193
A.16 i-CLD for evidence point C7 194
A.17 i-CLD for evidence point C8 194
A.18 i-CLD for evidence point C9 195
A.19 i-CLD for evidence point C10 195
A.20 i-CLD for evidence point C11 196
A.21 i-CLD for evidence point C12 196
A.22 i-CLD for evidence point C13 197
A.23 i-CLD for evidence point C14 197
A.24 i-CLD for evidence point C15 198
A.25 i-CLD for evidence point C16 198
A.26 i-CLD for evidence point C17 199
A.27 i-CLD for evidence point C18 199
A.28 i-CLD for evidence point C19 200
A.29 i-CLD for evidence point C20 200
A.30 i-CLD for evidence point E1 201
A.31 i-CLD for evidence point E2 201
A.32 i-CLD for evidence point E3 202
A.33 i-CLD for evidence point E4 202
A.34 i-CLD for evidence point E5 203
A.35 i-CLD for evidence point E6 203
A.36 i-CLD for evidence point E7 204
A.37 i-CLD for evidence point E8 204
A.38 i-CLD for evidence point E9 205
A.39 i-CLD for evidence point E10 205
A.40 i-CLD for evidence point E11 206
A.41 i-CLD for evidence point E12 206
A.42 Standard format f-CLD 207
A.43 Mapping the i-CLD for evidence point N1 212
A.44 Mapping the i-CLD for evidence point N2 213
A.45 Mapping the i-CLD for evidence point N3 213
A.46 Mapping the i-CLD for evidence point N4 214
A.47 Mapping the i-CLD for evidence point N5 214

A.48 Mapping the i-CLD for evidence point N6 215
A.49 Mapping the i-CLD for evidence point N7 215
A.50 Mapping the i-CLD for evidence point N8 216
A.51 Mapping the i-CLD for evidence point N9 216
A.52 Mapping the i-CLD for evidence point C1 217
A.53 Mapping the i-CLD for evidence point C2 217
A.54 Mapping the i-CLD for evidence point C3 218
A.55 Mapping the i-CLD for evidence point C4 218
A.56 Mapping the i-CLD for evidence point C5 219
A.57 Mapping the i-CLD for evidence point C6 219
A.58 Mapping the i-CLD for evidence point C7 220
A.59 Mapping the i-CLD for evidence point C8 221
A.60 Mapping the i-CLD for evidence point C9 221
A.61 Mapping the i-CLD for evidence point C10 222
A.62 Mapping the i-CLD for evidence point C11 222
A.63 Mapping the i-CLD for evidence point C12 223
A.64 Mapping the i-CLD for evidence point C13 223
A.65 Mapping the i-CLD for evidence point C14 224
A.66 Mapping the i-CLD for evidence point C15 224
A.67 Mapping the i-CLD for evidence point C16 225
A.68 Mapping the i-CLD for evidence point C17 225
A.69 Mapping the i-CLD for evidence point C18 226
A.70 Mapping the i-CLD for evidence point C19 227
A.71 Mapping the i-CLD for evidence point C20 228
A.72 Mapping the i-CLD for evidence point E1 229
A.73 Mapping the i-CLD for evidence point E2 230
A.74 Mapping the i-CLD for evidence point E3 231
A.75 Mapping the i-CLD for evidence point E4 232
A.76 Mapping the i-CLD for evidence point E5 233
A.77 Mapping the i-CLD for evidence point E6 234
A.78 Mapping the i-CLD for evidence point E7 235
A.79 Mapping the i-CLD for evidence point E8 236
A.80 Mapping the i-CLD for evidence point E9 237
A.81 Mapping the i-CLD for evidence point E10 238

A.82 Mapping the i-CLD for evidence point E11 239
A.83 Mapping the i-CLD for evidence point E12 240
B.1 Defining *food_production_growth_cropyield* under 'extreme global warming' 289
B.2 Documentation of *RCP85_climate_forcing* input data 294
B.3 World3-03 BAU-CC output 296
B.4 Documentation of *W3_climate_forcing, W3_population, W3_gdp, W3_food_production, W3_food_demand* input data 297
B.5 Verification of Chapter 5 results – comparison of simulated risk of starvation with current population undernourished 303

[blank page]

List of tables

2.1 Summary of other studies that find declines in crop yields associated with climate change across various geographies over the century 37

5.1 Quantitative 2020 to 2100 growth for climate policy and socioeconomic development decision-factors 95

5.2 Qualitative 2020 to 2100 growth score for climate policy and socioeconomic development decision-factors 95

B.1 List of countries in the model 243

B.2 List of countries excluded from the model 248

B.3 Documentation of shape file 'geounits' mapped to the model countries 248

B.4 Documentation of raw data to final input data cleaning issues for *population_historical* 254

B.5 Documentation of raw data to final input data cleaning issues for *gdp_pc_historical* 256

B.6 Documentation of raw data to final input data cleaning issues for *food_production_historical* 260

B.7 Energy-equivalent-grain-weight conversion factors 263

B.8 Documentation of raw data to final input data cleaning issues for *food_demand_pc_historical* 265

B.9 Documentation of raw to input data cleaning issues for *trade_distance* 268

B.10 Documentation of working data cleaning issues for total land area factors 270

B.11 Documentation of steps in deriving energy-equivalent-grain-weight conversion factors and energy content per unit grain weight factor 275

B.12 Documentation of raw data to final input data cleaning issues for *population_growth* 281

B.13 Documentation of raw data to final input data cleaning issues for *gdp_pc_growth* 283

B.14 Documentation of raw data to final input data cleaning issues for *food_production_growth_cropland* 285

B.15 Documentation of raw data to final input data cleaning issues for *food_production_growth_cropyield*. 290

B.16 Documentation of raw data to final input data cleaning issues for *food_demand_pc_growth* 293
B.17 Verification of Chapter 4 results – current population undernourished groups 298
B.18 Verification of Chapter 4 results – comparison of simulated risk of starvation with current population undernourished groups 299
B.19 Verification of Chapter 5 results – comparison of simulated risk of starvation with current population undernourished 302

Nomenclature and key definitions

Nomenclature

°C	degrees Celsius.
ADER	average dietary energy requirement.
AR1–6	IPCC's First to Sixth Assessment Reports.
BAU-CC	World3 business-as-usual-climate-change-equivalent-collapse scenario.
BCE	before common era.
CE	common era.
CLD	causal loop diagram. f-CLD is final CLD, i-CLD is individual CLD.
CO_2	carbon dioxide.
COP	Conference of the Parties.
ESM	earth system model(ling).
FIT	food insecurity threshold.
FSI	Fragile States Index.
GDP|PPP	gross domestic product at purchasing power parity.
GSD	growth shock discount.
GSP	growth shock period.
GST	growth shock threshold.
GSY	growth shock year.
ha	hectare.
IAM	integrated assessment model(ling).
IAV	impact, adaptation and vulnerability.
IPCC	Intergovernmental Panel on Climate Change.
m	metres.
ppm	parts per million.

MDER	minimum dietary energy requirements.
MLFD	minimum lifestyle food demand.
RCP	Representative Concentration Pathway(s).
RI	Resilience Index.
RPG	role-playing game.
RQ	Research Question. RQ0 is the overarching research question. RQ1-3 are component research questions.
SPA	Shared Climate Policy Assumptions.
SSP	Shared Socioeconomic Pathway(s)
t	tonne.
UNFCCC	United Nations Framework Convention on Climate Change.
W	Watt.

Key Definitions

Climate change	is a long-term shift in climate rather than short-term climate variations. Natural climate change refers to that caused by natural influences, such as solar or volcanic forcing. Anthropogenic climate change refers to that forcing by human influences, such as emissions and land cover change. Where a distinction is not made, climate change refers to anthropogenic climate change as the focus of this thesis.
Existential risk (X-risk)	is a risk that threats the destruction of humanity's long-term potential, be it complete destruction, such as human extinction, or incomplete destruction, such as human suffering or societal collapse.
Extinction	is the termination of a kind or group of organisms.
Food security	is a measure of food availability, accessibility, stability and utilisation.
Global warming	is a human-induced warming of the Earth system, a type of climate change. Low- and mid-range global warming is 1.5–4.5°C by 2100. High-range or 'extreme global warming' is 8°C+ by 2100.
Human suffering	is an unpleasantness, aversion or pain associated with an experience.
Resilience	is the capacity to recover original state quickly following a disturbance.
Societal collapse	is an enduring loss of population or institutional complexity/identity, which may occur abruptly or gradually but is notably transformative and may be experienced by a local, national or global community.
Vulnerability	is the quality of being exposed to a risk.

Chapter 1

Introduction: reframing the threat of global warming

Let us consider two stories. Story 1: civilisation is booming with socioeconomic growth and complex infrastructure, but suddenly a long-term drought coupled with destruction of infrastructure by intermittent extreme floods sees food supply plummet, triggering institutional breakdown, starvation, migration and conflict, eventually leading to societal collapse. Story 2: an ever-prosperous civilisation begins to see the effects of global warming and attempts to intervene using stratospheric aerosol injection, but this backfires catastrophically causing an ice age that kills most of humanity, with the remnants suffering a life confined to the walls of a circumnavigational train. The former is a historical recount of the Akkadian Empire collapse, where natural climate change destabilised the Holocene climate niche on which contemporary society continues to rely. The latter is a dystopian narrative from science fiction film *Snowpiercer,* where anthropogenic climate change destabilises the same climate niche in the future. Anthropogenic climate change poses an unprecedented challenge to society but, unlike natural climate change, it is a threat we can prevent if we so choose. Perhaps if we begin to talk in terms of tangible worst-case impacts, instead of imperceptible temperatures, we can facilitate better risk management to safeguard ourselves from the ever-growing threat of anthropogenic climate change.

This chapter introduces the research contained in this thesis. Section 1.1 presents the motivation, i.e. "The Why", of this research. Section 1.2 scopes a topic and lens boundary, i.e. "The What", to contain this research. Section 1.3 defines a three-part investigation framework, i.e. "The How", for conducting this bounded research. Finally, Section 1.4 provides the outline of this thesis.

1.1 Research motivation

This section introduces the motivation for this research. The problem of anthropogenic climate change is presented in Section 1.1.1. An opportunity to reframe the threat of global warming to make it more tangible is proposed in Section 1.1.2. This leads to formulation of the aim of this thesis in Section 1.1.3.

1.1.1 Problem: the escalating threat of anthropogenic climate change

Society's penchant for a fossil-fuelled lifestyle has seen global atmospheric CO_2 concentration increase from a stable 270–285 ppm baseline prior to the Industrial Revolution (~1760–1840 CE) to well over 400 ppm (Ritchie and Roser 2020). Paleoclimate data shows that in the entirety of humanity's ~300,000 year existence Earth has never experienced a similar level of atmospheric forcing (Bereiter et al. 2015). Today, global emissions exceed 50 billion CO_2-equivalent tonnes per year, following a rapid rebound from a 5% drop during the COVID-19 pandemic (Tollefson 2021a), having increased by ~2000% since 1900 and more than doubled in the last 50 years (Friedlingstein et al. 2021). Temperatures have already surpassed 1°C above pre-industrial levels and are likely to rise 2–5°C (Raftery et al. 2017) by the end of the century, with global warming greater than 8°C not out of the question (Schneider et al. 2019). Such temperatures may translate to very real dangers for society but while climate science is well established, the concerning ramifications of anthropogenic climate change are masked with uncertainty that clouds the solution space for our predicament (Taylor 2020).

Climate science has a long history, dating back to 4th century BCE with ancient philosophers, such a Theophrastus, suspecting that dramatic climate changes occurred over time (Weart 2021). Scientific theories of natural climate forcing, including solar, volcanic and gravitational activity, came about with Fourier's explanation of the atmosphere's role in planetary warming in 1824, Aggasiz's proposal of past ice ages in 1837 and Tyndall's (1859) findings that atmospheric gases can trap solar radiation. Scientific discovery transitioned to anthropogenic climate forcing, including greenhouse gas, aerosol and land surface changes, with Arrhenius' (1896) proposal that CO_2 emitted from the burning of fossils fuels would cause Earth's temperature to increase, further developed by Chamberlin (1899) and coined the 'greenhouse effect' by Poynting (1907). Efforts subsequently increased to understand this phenomenon, with Callendar (1938) and Keeling (1960) presenting evidence that atmospheric CO_2 concentration and temperature were increasing and Budyko (1969) and Sellers (1969) defining the possibility of climate change feedbacks. Through the 1970s and 1980s, scientific consensus increased with the mainstreaming

of climate predictions (Sawyer 1972) and climate models (Manabe and Wetherald 1975), which initiated the evolution of detailed earth system models used today (Steffen et al. 2020). In 1988, the Intergovernmental Panel on Climate Change (IPCC) was established and has since produced six Assessment Reports (AR1–6) summarising the state of climate science (IPCC 1995, 2000, 2001, 2007, 2014, 2021). There exists scientific consensus of over 99% on anthropogenic climate change in peer-reviewed literature (Lynas et al. 2021), with world scientists giving repeat warnings of the threat it poses (Ripple et al. 2020).

Political, economic and social climate concern developed concomitantly with scientific consensus. In 1979, the first World Climate Conference was held, leading to the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 and the first Conference of the Parties (COP1) in 1995 (Weart 2021). The Kyoto Protocol, the first legally binding commitment by countries to reduce emissions, was passed in 1997 at COP13 and then superseded by the Paris Agreement passed in 2015 at COP21 (Hirst 2020). Climate economics kicked into gear in the 1970s (Nordhaus 1975). Notwithstanding pivotal work, such as the *Stern Review on the Economics of Climate Change* (Stern 2006), the treatment of discounting (Yeeles 2019), damages (Schultes et al. 2021) and fat-tailed uncertainty (Weitzman 2011) in quantifying the costs and benefits of climate action remains a unique challenge. In September 2019 we saw the emergence of global climate strikes, with some 6 million people inspired by climate activist Greta Thunberg (2019). Warnings of dystopian climate futures are commonplace (Kareiva and Carranza 2018) in both popular non-fiction, such as *Six Degrees* (Lynas 2007), *The Sixth Extinction* (Kolbert 2014) and *The Uninhabitable Earth* (Wallace-Wells 2019), and fiction, such as *Waterworld* (Reynolds 1995), *The Day After Tomorrow* (Emmerich 2004) and *The Tomorrow War* (McKay 2021). Increasingly, individuals, the media, businesses, governments and international institutions are declaring a climate emergency (UNDP 2021).

Climate solutions have been proposed in response to increasing climate concern. Supply-side interventions rely on slow-burn technological disruption, such as transition to renewable energy sources, energy storage and energy efficiency as well as geoengineering (Allwood et al. 2019). Demand-side interventions rely on behavioural disruption, including reducing the carbon intensity of our lifestyles in terms of travel, material purchases, heating and eating (Stephenson et al. 2021). Books for the layman audience grounded in technical rigour, such as *Sustainable energy - without the hot air* (MacKay 2009), *Sustainable materials - with both eyes open* (Allwood and Cullen 2012), *There's no Planet B* (Berners-Lee 2019), *Food and climate change - without the hot air* (Bridle 2020) and *How to avoid a climate disaster* (Gates 2021), offer an arsenal of solutions to tackle the anthropogenic climate change problem.

Despite the consensus amongst climate scientists, concern across society and knowledge of solutions, anthropogenic emissions continue to rise (Peters et al. 2020), as illustrated in Figure 1.1. Today's lack of climate action threatens the welfare of current and future generations (Rogelj et al. 2016). The ramifications of global warming across the natural and human systems are already signalling danger (Funk 2021): the polar ice caps are melting and sea levels are rising (Slater et al. 2021); the Americas are experiencing unprecedented drought (Chiang et al. 2021) with the same already undermining crop yields in Africa (Sultan et al. 2019); and, the frequency and magnitude of extreme weather events are increasing (Schiermier 2018), including fires in Australia (Canadell et al. 2021), floods in Germany (Else 2021) and heat waves across Asia (Imada et al. 2018). Against this backdrop, the recent failure of COP26 (Hales and Mackay 2021) to 'flick the switch' on urgent climate action demonstrates the need for a paradigm shift in the way that we think about the threat of global warming (Masood 2021).

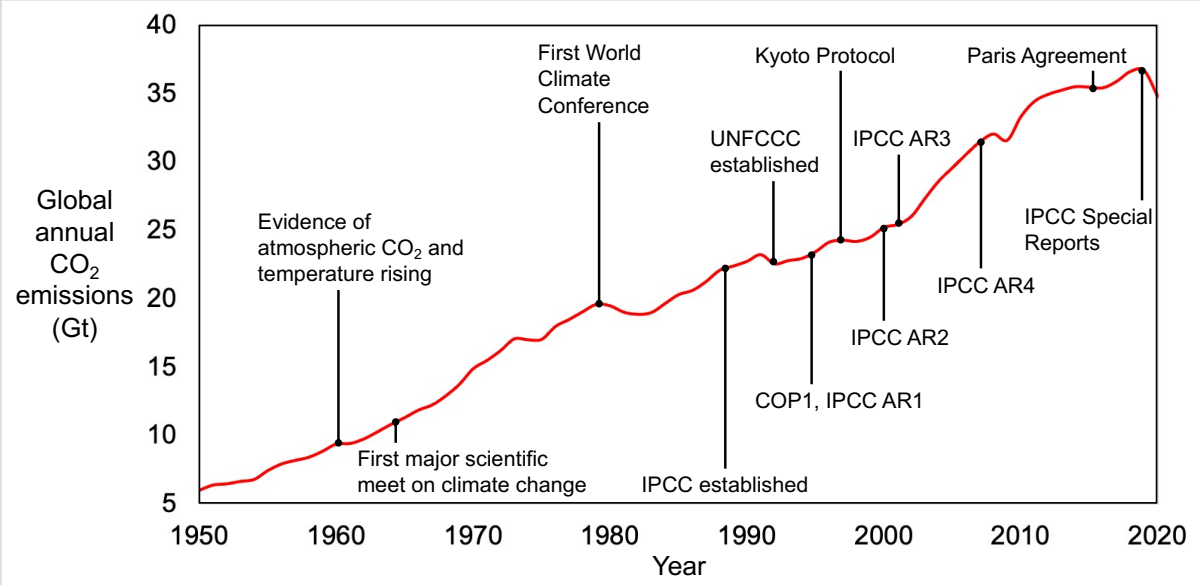


Figure 1.1: Relentless rise in annual CO_2 emissions despite climate action milestones from 1950 to 2021. Data basis: emissions from Friedlingstein et al. (2021); climate action milestones in-text.

1.1.2 Opportunity: a tangible framing of anthropogenic climate change

Our exposure to risk dates back to the beginning of human evolution (Hintze et al. 2015). Individuals manage personal and interpersonal risks, such as shark attacks or car crashes, to prevent harm to themselves. Businesses manage internal and external risks, such as talent loss or market competition, to prevent financial loss. Governments manage domestic and international security risks, such as inequality or military-attacks, to safeguard their citizens and prevent world wars. Humanity's story of risk management is one of success thus far, but anthropogenic climate change poses an unprecedented

challenge. There exists a great dearth of literature debating how to best frame the risk of anthropogenic climate change to motivate action, establishing the need to strike a balance in combating indifference without triggering apathy, denial or fatalism (Hogett 2019). Empirical examples such as the ozone layer hole (Ungar 2000) and COVID-19 pandemic (Gordon 2021) demonstrate society's capacity to urgently act when a risk engenders a balance of understanding and manageable fear, as long as it is not crowded out by other risks (Bostrom et al. 2020). By definition, good risk management necessitates both measured consideration and communication of tangible worst-case impacts (Kunreuther et al. 2013).

In terms of consideration, anthropogenic climate change threatens to impact aspects of human life on Earth across the natural system, natural-human system interface and human system (Beard et al. 2021), which are intertwined as depicted in Figure 1.2. The latest research, embodying IPCC (2018, 2019a, b) Special Reports, considers impacts mostly on the natural system, such as on corals, and to a lesser extent on the natural-human system interface, such as water supply (Magnan et al. 2021). Whereas impacts on the human system have received significantly less treatment, especially compared to attention garnered by 'sexy risks' like artificial intelligence (Kuhlemann 2019), despite evidence of its role in heat-related deaths (Vicedo-Cabrera et al. 2021), migration (Hoffmann et al. 2020) and conflict (Mach et al. 2019).

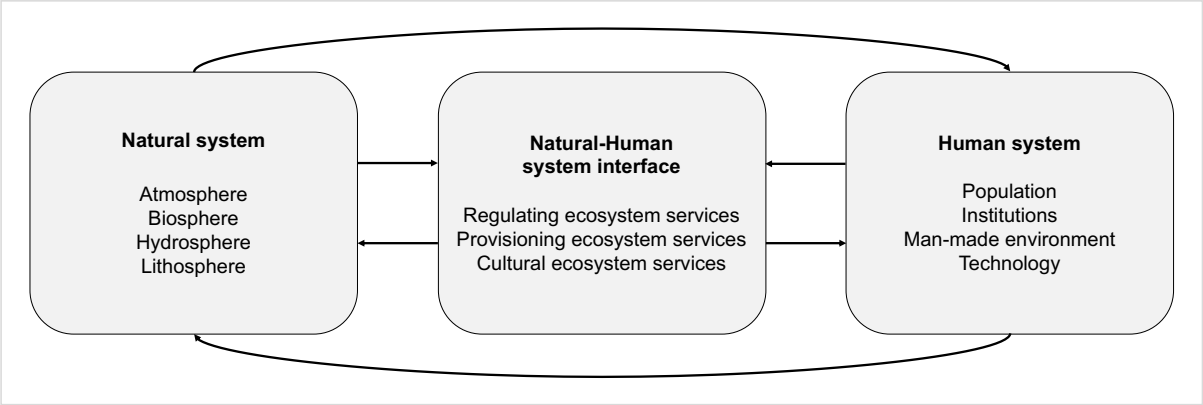


Figure 1.2: Intertwined existence of the natural system, natural-human system interface and human system.

In terms of communication, the mainstream framing of anthropogenic climate change is that of 'global warming' (Briggs et al. 2015). Given that many people seek vacations in warmer climates or experience daily fluctuations of several degrees, this description of long-term temperature increases of a few degrees does not convey tangible risk nor urgency (Weber 2006). The terminology of 'climate emergency' and 'climate crisis' is more helpful in communicating urgency, but does not express tangible impact that would encourage prioritisation of anthropogenic climate change above the many other crises that society has to deal with (Hung and Bayrak 2020). At the other end of the spectrum, doomsday narratives describing a 'climate apocalypse' similarly do not articulate tangible risk and have been shown

to undermine urgency due to prophetic misalignment with ingrained beliefs of reality (Feinberg and Willer 2010) or fatalist resignation (Mayer and Smith 2019). These framings fail to put humanity at the centre of risk management (Erisman et al. 2015) and do not provide well-balanced narratives that engender both understanding and fear necessary to motivate action (Hinkel et al. 2020).

Treatment of anthropogenic climate change to date escapes what is needed for good risk management (Schubert et al. 2019). For humanity, tangible worst-case impacts take the form of human suffering (Althaus and Gloor 2016), societal collapse (Weiss and Bradley 2001) or extinction (Leslie 1996). However, the consideration and communication of these concerning outcomes, a 'climate endgame' so to speak, is underdeveloped (Kemp et al. 2022). Ergo, there may exist an opportunity to facilitate more urgent climate action by reframing anthropogenic climate change to embody tangible risk of everyday relevance for individuals, businesses and governments (Wagner and Weitzman 2015).

1.1.3 Aim: an investigation of the worst-case impacts of climate change

Section 1.1.1 established that today's climate action is deficient, despite widespread concern and available solutions. As emissions continue to rise, the threat of anthropogenic climate change escalates. There is need for a paradigm shift in the way that we think about 'global warming'.

Section 1.1.2 identified that this current framing does not engender understanding nor fear to motivate urgency. Good risk management requires consideration and communication of worst-case climate change impacts, including human suffering and societal collapse, that are currently understudied.

This thesis aims to investigate the worst-case impacts of anthropogenic climate change, with the motivation that such reframing of the threat of global warming may facilitate better risk management by articulating tangible risk of everyday relevance to individuals, businesses and governments.

1.2 Research scope

Various topics and lenses may apply in addressing the aim established in Section 1.1 and this thesis certainly does not tackle them all. As such, this section introduces the scope for this research. The history of climate, agriculture and complex societies is sketched in Section 1.2.1. The nascent interdisciplinary study of X-risk is outlined in Section 1.2.2. This contextualisation scopes a topic and

lens boundary, in order to contain the aim of this thesis in making an incremental contribution to knowledge, defined in Section 1.2.3.

1.2.1 Context: a history of climate, agriculture and complex societies

Earth formed ~4.5 billion years ago, over which time its atmosphere, biosphere, hydrosphere and lithosphere have dramatically evolved (Hazen 2012). Unicellular life first emerged ~4 billion years ago (Dodd et al. 2017) and multicellular life proliferated in the Cambrian Explosion ~540 million years ago (Erwin and Valentine 2013). Amongst the evolution of plants, arthropods, molluscs, dinosaurs, mammals, flowers and birds in the Phanerozoic eon, five mass extinction events occurred between 440 and 66 million years ago with natural climate change evidenced as a contributing factor (Brannen 2017).

Then came human evolution from the primate order, with Hominoidea diverging from Old World monkeys ~44–40 million years ago. Anatomically modern humans (*Homo sapiens*) emerged ~300,000 years ago and behavioural modernity occurred ~40,000 years ago (Stringer and Galway-Witham 2017). For 96% of our ~300,000 year existence, regular Pleistocene climate fluctuations (~50 ppm or ~4°C from average) from warm periods to ice ages made agriculture impossible, so humans lived in simple hunter-gatherer societies, growing and shrinking in response to wild food availability (Gowdy 2020).

Human life dramatically changed ~12,000 years ago, when the Earth's climate shifted to unprecedented warm and stable conditions of the Holocene, as shown in Figure 1.3, that made agriculture possible (Richerson et al. 2001). Traditional hunting and gathering transitioned to systematic cultivation of wild cereals, which gave rise to complex agrarian societies across the Fertile Crescent ~11,700 years ago (Bar-Yosef et al. 2017), as well as dispersal of Neolithic populations to more favourable agriculture conditions ~6,600–6,000 years ago (Weninger and Clare 2017). The explosion of agriculture through the Neolithic Revolution eventually saw the arrival of civilisation (Mazoyer 2006), including the Sumer of Mesopotamia and Egyptians of the Nile River in ~3000 BCE followed by the Harappans of Indus River Valley in ~2500 BCE and Chinese cultures along the Yellow and Yangtze Rivers in ~2200 BCE (Roberts and Westad 2013).

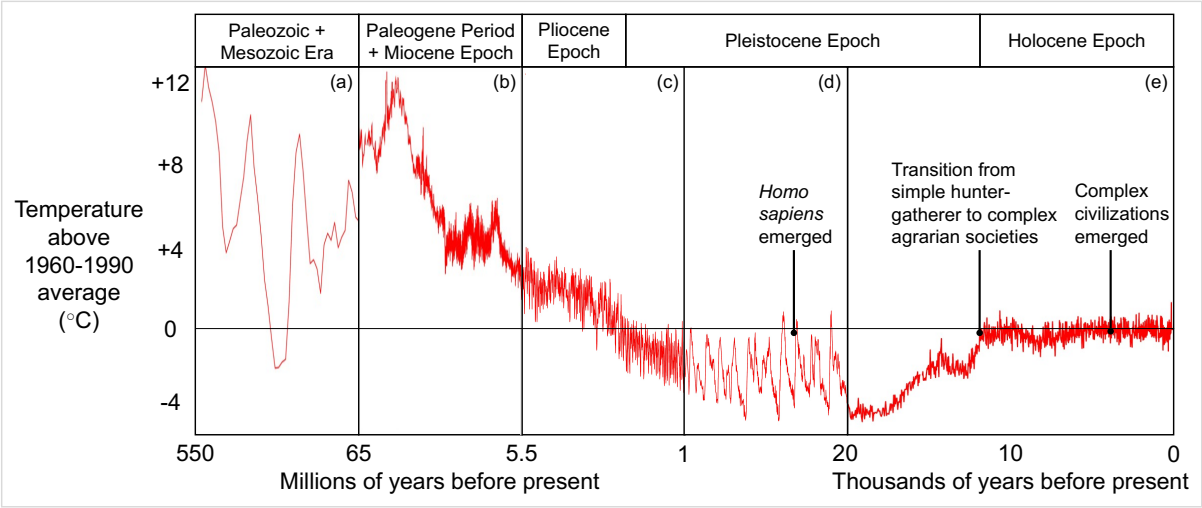


Figure 1.3: Society depends on the stable Holocene climate niche that has enabled agriculture for millennia. Data basis: (a) from Royer et al. (2004); (b) from Zachos et al. (2008) and Hansen et al. (2013); (c)-(d) from Lisiecki and Raymon (2005) and Hansen et al. (2013); (e) from Jouzel and Masson-Delmotte (2007).

The Scientific (16th–17th century CE), Industrial (18th–19th century CE), Technological (19th–20th century CE) and Digital (20th century CE – present) Revolutions of modern history (1500 CE – present) yielded significant productivity increases in open-environment agriculture through improved crop yields, irrigation systems and fertilizers (Mazoyer 2006), distinct from the relatively recent boom of fossil-fuelled energy and water infrastructure (Pain 2017). Meanwhile, globalisation has resulted in a complex web of food supply chains, which introduce resilience benefits of delocalised distribution but also unprecedented vulnerability to climate related shocks (Davis et al. 2021). Today's globalised civilisation continues to rely on the stable climate niche of the Holocene for food security (Xu et al. 2020). This relationship between climate and food is central to humanity's existence (Brooke 2014).

1.2.2 Context: the nascent interdisciplinary study of existential risks

The scholarly study of natural hazards dates back to the earliest recorded history (Bernstein 1996). Philosophical prognoses of the risk of human extinction dates back to 18th century CE (Moynihan 2020). Scientific concern over the potential for technology—namely, nuclear weapons—to cause a global catastrophe dates back to 1939, with the founding of *The Bulletin of Atomic Scientists* in 1945 and Doomsday Clock in 1949 (Beard and Torres 2020). However, the formalised field of study on 'existential risks', coined 'X-risks', is more nascent having emerged in the last few decades with seminal works by Bostrom (2002, 2013) and Rees (2003, 2018), the founding of dedicated research centres, such as the Future of Humanity Institute in 2005 (FHI 2021) and Centre for the Study of Existential Risk (CSER 2021a) in 2012, and the inception of annual reports on Global Catastrophic Risks in 2016 (GCF

2016, 2017, 2018, 2019, 2020, 2021). X-risk studies emerged due to increasing concern that some risks, including engineered pandemics, artificial intelligence and anthropogenic climate change, will cause human suffering, societal collapse or extinction of our species (Bostrom and Ćirković 2008).

X-risks, distinct from everyday risks, prove a major challenge as they do not conform to traditional risk analysis and assessment conventions (Posner 2004), as depicted in Figure 1.4. This is particularly relevant to those of anthropogenic origin (Bostrom 2002b), including climate change. Specifically, X-risks are complex and interdependent, intergenerational and global and unprecedented with exposure to survivorship bias (Ord 2020). X-risk management requires interdisciplinary coordination (Craig 2018), long-term international collaboration (Jones et al. 2018) and foresight in decision-making under uncertainty (Currie and Ó hÉigeartaigh 2018); there is no room for 'trial and error' (Matheny 2007). The limited consideration and communication of X-risks, including anthropogenic climate change, to date has mostly been philosophical and qualitative (Beard et al. 2021). In the words of Bostrom (2002):

"There is more scholarly work on the life-habits of the dung fly than on existential risks."

Only recently has attention shifted toward systematic consideration, such as classifying spread mechanisms across critical systems (Avin et al. 2018) and means of intervention (Cotton-Barratt et al. 2020), and quantification (Beard et al. 2020) of X-risks. The *A Science of Global Risk* project (CSER 2021b) demonstrates the need for systematic and quantitative study of the potential for anthropogenic climate change to cause human suffering, societal collapse or extinction. As noted by Rees (2013) with respect to the important implications of X-risk studies for social ethics, business governance and policy:

"True, it is hard to quantify the potential "existential" threats … But we should at least start figuring out what can be left in the sci-fi bin (for now) and what has moved beyond the imaginary."

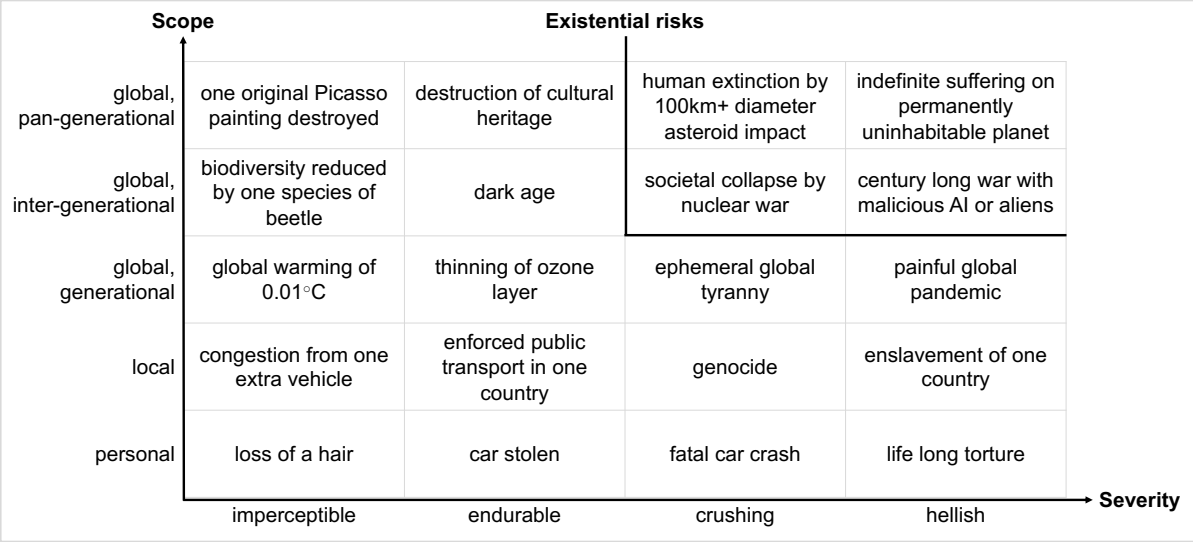


Figure 1.4: Existential risks, like anthropogenic climate change, are unprecedented, global and intergenerational risks that may cause human suffering, societal collapse or extinction. Based on: Bostrom (2002a, 2013), Liu et al. (2018), Turchin and Denkenberger (2018).

1.2.3 Research boundary: systematic and quantitative study of climate change, food insecurity and societal collapse

Section 1.2.1 established that the evolution of civilisations has been governed by the influence of climate on food availability, and the stable Holocene climate niche remains essential for the agriculture that underpins society today. Additionally, our globalised civilisation relies on an unprecedented network of food supply chains that are susceptible to climate change. Ergo, this research focuses on the relationship between climate change, food insecurity and society.

Section 1.2.2 identified the need for systematic and quantitative study of X-risks. Ergo, this research applies an engineering mindset to the study of human suffering, societal collapse and extinction, focusing on the former two as most tangible given historical precedence, as worst-case impacts of climate change.

To this end, the bounded aim of this thesis is to contribute a systematic and quantitative investigation of the relationship between climate change, food insecurity and societal collapse.

1.3 Research framework

Various approaches may contribute to addressing the bounded aim defined in Section 1.2 and this thesis certainly does not implement them all. As such, this section introduces a framework for this research, in

the form of a three-part investigation prompted by research questions that look to the past (Section 1.3.1), future (Section 1.3.2) and present (Section 1.3.3).

1.3.1 Research Question 1: learning from the past

The complexity of society today is unprecedented (Fisher 2021). Globalisation and technological advancement influence both societal resilience and vulnerability to climate change (McMichael 2012). Our highly interconnected civilisation is uniquely exposed to cascading effects (Buldyrev et al. 2010) and synchronous failures (Homer-Dixon et al. 2015). These fragile interdependencies may see localised events trigger an avalanche of system wide catastrophes (Vespignani 2010).

Causal loop diagrams can be used to unpick such interdependencies and give clear visual structure to relationships between variables in a complex system (Randers 2000). However, the causal pathways through which climate change may act independently or as a risk multiplier to, directly or indirectly, impact the human system remain clouded (Nicoll and Zerboni 2020). Good risk management requires learning from the past (Turchin 2008), leading to the first research question:

RQ1. How can systematically documenting historical evidence improve our understanding of the complex risk landscape of climate change, food insecurity and societal collapse?

1.3.2 Research Question 2: surveying 'end-game' futures

Anthropogenic climate change is unprecedented and the magnitude of its ramifications is uncertain (Harrington et al. 2021). As greenhouse gas emissions continue to rise, we have breached 'planetary boundaries' (Rockström et al. 2009a) and risk destabilisation to a 'hothouse Earth' (Steffen et al. 2015, 2018). There is increasing evidence of accelerating amplifying feedbacks, such as methane release from thawing permafrost (Natali 2019), and decelerating dampening feedbacks, such as declining rates of uptake by tropical forest carbon sinks (Hubau et al. 2020). These feedbacks propel us toward tipping points (Lenton et al. 2019) that may see global warming exceed 8°C by 2100 (Fischer et al. 2021).

Quantitative models can be used to simulate the real world and clearly illustrate the distribution of risk in such uncertain futures (Edmonds et al. 2019). However, low- to mid-range global warming (1.5–4.5°C) is over-represented in climate change research, with high-range 'extreme global warming'

(8°C+) receiving minimal attention (Jehn et al. 2021). Good risk management requires surveying 'end-game' futures (Kemp et al. 2022), leading to the second research question:

RQ2. What insights into the future international risk landscape can be gained by illustrating climate change, food insecurity and societal collapse under 'extreme global warming'?

1.3.3 Research Question 3: prioritising decision factors in the present

The global cooperation and coordination required to address the evolving challenge of anthropogenic climate change is unprecedented (Tollefson 2019). Even the impacts of low- to mid-range global warming may prove devastating for our globalised contemporary society (Hausfather and Peters 2020). Well-balanced climate policy and action cannot occur in a vacuum, as a plethora of socioeconomic confounding factors influence the threat of anthropogenic climate change (Robinson and Shine 2018). Decisions made by one nation of individuals may govern the fate of other nations of individuals, which raises ethical concerns about global climate justice (Sovacool 2013).

Expert-informed climate policy and socioeconomic development scenarios can be used for exploration of such decision factors (Weber et al. 2018). However, there remains a lack of agreement on interventions for tackling anthropogenic climate change (Peng et al. 2021) and existing inequalities that may manifest global climate injustice (Tollefson 2021b). Good risk management requires prioritisation of decision factors in the present (O'Neill et al. 2020), leading to the third research question:

RQ3. How might decisions in the present regarding climate policy and socioeconomic development influence climate change, food insecurity and societal collapse?

1.4 Chapter summary: thesis outline

This chapter introduced the motivation, boundary and three-part investigation framework for the research contained in this thesis. The three research questions (RQ1,2,3) provide direction for the literature review (Chapter 2) to refine research objectives that address succinct gaps in the existing body of knowledge relevant to each. These refined objectives provide the basis for three original research chapters (Chapter 3,4,5) containing original methodologies, results and discussions that provide

incremental contributions to knowledge in response to each research question. Collectively, these contributions to knowledge provide opportunities for future research and have broader implications for society (Chapter 6). The outline of this thesis is summarised in Figure 1.5.

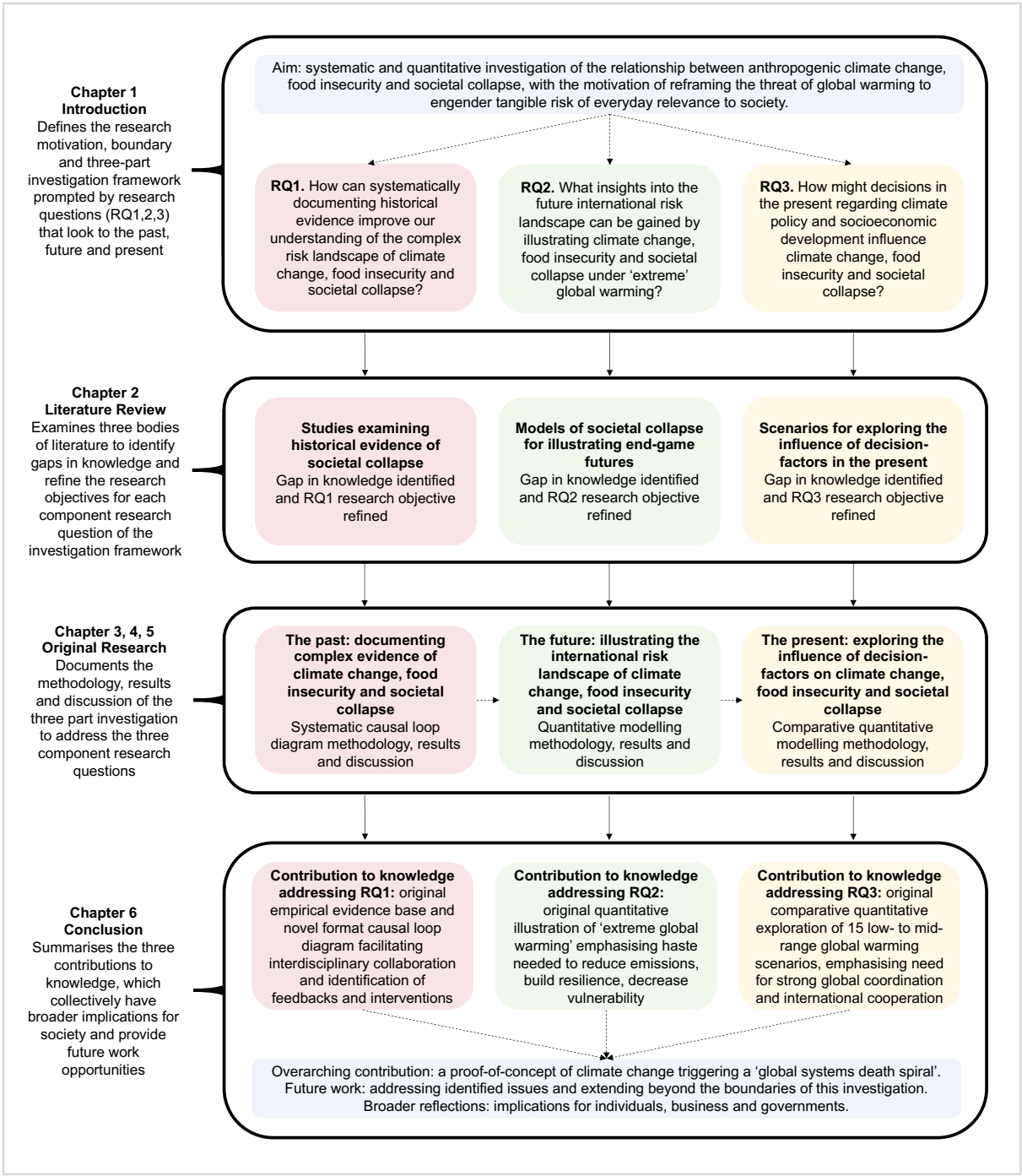


Figure 1.5: Thesis outline.

[blank page]

Chapter 2

Literature review: refining the research objectives

Having established a three-part investigation framework in Chapter 1, this chapter reviews three bodies of literature to establish partial answers and identify remaining gaps in the existing body of knowledge relevant to each research question (RQ1,2,3). Section 2.1 reviews studies examining historical evidence of societal collapse to refine the research objective for RQ1. Section 2.2 reviews models of societal collapse for illustrating end-game futures to refine the research objective for RQ2. Section 2.3 reviews scenarios for exploring the influence of decision factors in the present to refine the research objective for RQ3. Section 2.4 summarises the gaps in knowledge and refined research objectives for RQ1,2,3.

2.1. Studies examining historical evidence of societal collapse

The rise and fall of civilisations has been documented since the earliest recordings of history and is increasingly studied to inform our understanding of the risk of societal collapse in the present (Butzer and Endfield 2012). This section examines the body of literature on historical societal collapse, and the extent to which evidence has been systematically documented using causal loop diagrams to inform understanding of the complex risk landscape of climate change, food insecurity and societal collapse for today's globalised civilization. Three types of studies are considered in turn, namely: case studies based on primary sources (Section 2.1.1); meta-theory studies based on primary and secondary sources (Section 2.1.2); and, foresight studies based on primary, secondary and tertiary sources (Section 2.1.3).

To refine the research objective for RQ1, this review is bounded to literature applicable to the relationship between climate, agriculture and society as the focus of this thesis. It should be noted, however, that there exists a dearth of literature on the rise and fall of civilisations debating the role of different mechanisms—including ecocide, volcanic eruption, foreign invasion, loss of trade partners, infectious disease, socio-politico-economic turmoil and disrupted demographic cycles—in any given event (McAnany and Yoffee 2012), and it is widely recognised that societal collapse is a complex phenomenon involving multiple confounding factors (Weiss 2017a). Synthesising this broader literature, as well as the literature detailed below, Figure 2.1 presents a conceptual model of societal collapse to provide contextual definition alongside this review.

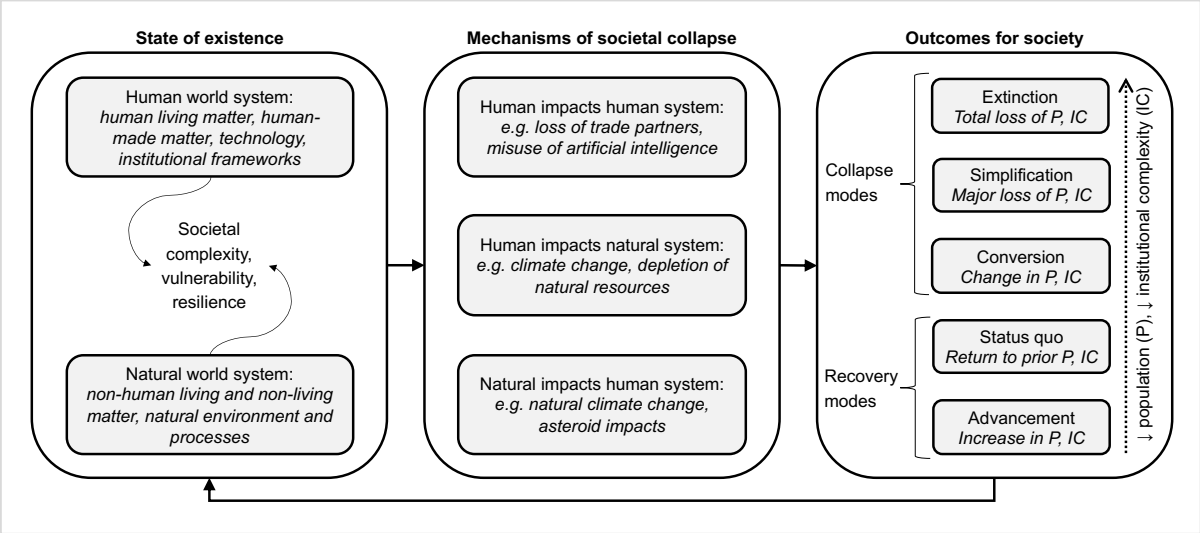


Figure 2.1: Conceptual model of the overarching process of societal collapse.

2.1.1 Case studies based on primary sources

The first type of study includes case studies that empirically investigate the mechanism (see Figure 2.1) of a particular societal collapse event using primary sources, including anthropological, archaeological and palaeontological data. The influence of natural climate change on agriculture is asserted as a mechanism of societal collapse in many of these case studies, as established by DeMenocal (2001), Butzer (2012) and Weiss (2017b). This review moves through history sequentially, detailing five exemplar events that have received notable attention.

The 4.2-kiloyear event that occurred during ~22nd century BCE is one of the worst natural climate change events of the Holocene. It caused both floods and droughts that coincided with agricultural

failures and societal collapses across multiple continents, especially Asia, as described by Gibbons (1993), Lawler (2008) and Choi (2020).

The collapse of the Akkadian Empire in Mesopotamia (present day Iraq, Iran, Syria, Turkey) due to 4.2-kiloyear climate-related drought has received considerable attention (Christie 2008). Using multi-stack proxy data Weiss et al. (1993, 2017c) show that increased aridity and wind circulation, associated with climate destabilisation due to volcanic forcing, may be linked to rain-fed agriculture losses. Watanabe et al.'s (2019) study of fossil corals finds that altered winter shamal seasons caused salinization of irrigated fields contributing to agricultural failures. Kerr (1998) and Cullen et al. (2000) use deep sea sediment cores and Carolin et al. (2019) and Bar-Matthews and Ayalon (2011) use speleothem data to further evidence the role of drought in the Akkadian Empire collapse.

This event and related famines have also been implicated in the collapse of the Harappan Civilisation in Indus Valley (present day Afghanistan, India and Pakistan) using stalagmite records by Griffiths et al. (2020), planktonic oxygen isotopes by Staubwasser et al. (2003) and palaeohydrological records by MacDonald (2011) and Giosan et al. (2012). The collapse of Old Kingdom Egypt has been attributed to altered Nile River flows using sediment cores by Stanley et al. (2003), Welc and Marks (2014) and Hamdan et al. (2019). Wenxiang and Tungsheng (2004) and Dang et al. (2020) use paleoclimate data to show that the collapse of Neolithic cultures across China coincided with droughts in the north and floods in the south. Specifically, climate-induced decline in rice-based agriculture has been linked to collapse of cultures on the Yangtze River by Li et al. (2018) and Innes et al. (2014), Yellow River by Huang et al. (2011) and Yishu River by Gao et al. (2007) and Wang et al. (2016). This climate event also been linked with agriculture-related cultural transitions in the Arabian Peninsula by Parker et al. (2006) and Japan by Kawahata et al. (2009) using sediment cores, and in the Iberian Peninsula by Lillios et al. (2016) using pollen records.

One millennium later in ~12th century BCE, a natural climate change known as the 3.2-kiloyear event triggered the Late Bronze Age Collapse. Multiple Mediterranean societies (present day Europe and Middle East), such as the Assyrians, Babylonians, Cypriots, Canaanites, Egyptians, Hittites, Minoans and Mycenaeans, experienced sudden, violent and complex transitions as detailed by Cline (2014).

Using paleoclimate and archaeological data, Drake (2012) and Kaniewski and Van Campo (2017) link the abrupt 3.2-kiloyear climate shift and associated drought to records of famine, migration and political and economic turmoil as a contributing factor to the widespread collapse. Specifically, Kaniewski et al.

(2013) shows that climate change-driven crop yield failures and disrupted food trade coincided with destructive invasions by the Sea Peoples across Cyprus, Egypt and Hittite. Furthermore, Finné et al. (2017) use high-resolution oxygen and carbon isotope data to detail the fall of Mycenaean Kingdoms, while Tsonis et al. (2010) details the demise of the Minoan civilisation.

The Late Antique Little Ice Age, spanning ~6th–7th century CE, is another natural climate change event that coincided with agricultural failure and societal collapse across multiple continents (Büntgen et al. 2016). The destabilisation is associated with three large volcanic eruptions that gave rise to initial extreme weather events followed by a long cooling period.

Lachniet et al. (2012) and Lachniet and Bernal-Uruchurtu (2017) pair stalagmite oxygen isotopes with rainfall reconstructions to show that drought conditions associated with the Late Antique Little Ice Age coincide with collapse of the Mesoamerican Teotihuacan society (in present day Mexico), which relied on rain- and spring-fed irrigation for staple crops. Further complex transitions across around the Mediterranean (present day Europe and Middle East) have also been attributed to the climate shift. For instance, based on tree ring chronologies from the Russian Altai and European Alps, Büntgen et al. (2016) suggest that the cold period weakened the Byzantine Empire (McCormick et al. 2012) and Sassanid Empire (Gunn 2000) by undermining agriculture, against the backdrop of the Justinian plague (Harper 2017), while concurrently boosting agricultural productivity in the Arabian Peninsula, and therefore contributed to the Arab Empire expansion through conquest of the Levant (Bar-Oz et al. 2019). Similarly, Heather (2009) suggests the quest for more fertile lands may have contributed to the migrations out of the Eurasian Steppe. Fei et al. (2007) also implicates the Late Antique Little Ice Age in the collapse of the Eastern Turkic Khanate, the then most powerful empire in Northeast Asia.

Moving forward again in time and across continents, case studies in the Americas spanning the 9th–13th century CE, concurrent with the Medieval Warm Period, have also attracted significant attention.

For example, climate factors were first implicated in the ~9th century CE Classic Maya Collapse in the southern lowlands of Mesoamerica (spanning present day Central America) by Gann and Thompson (1931). Since then, numerous studies have found coinciding evidence of severe drought conditions driven by climate change likely due to solar forcing (Douglas et al. 2016). Such evidence includes radiometric dating of sediments from Lake Chichancanab by Hodell et al. (1995), Lake Punta by Curtis et al. (1996) and Cariaco Basin by Haug et al. (2003). Similarly evidence from radiometric dating of stalagmites has been established from Yok Balum Cave by Kennett et al. (2012), and a stalagmite with

sediments from three lakes paired across the Yucátan Peninsula by Medina-Elizalde and Rohling (2012). Douglas et al. (2015)'s analysis of plant wax carbon isotopes further implies that agricultural adaptations initially successful then failed as severity of the drought increased. Recently, Kennett and Hodell (2017) collated multiple paleoclimatic proxies with primary historical sources to link population expansion and agricultural degradation exacerbated by drought with famine and warfare between Mayan polities.

Thompson and Kolata (2017) analyse paleoclimate data from the Quelccaya ice cap in Peru to find that El Niño-Southern Oscillation (ENSO) temperature and precipitation fluctuations played a critical role in the evolution of pre-Hispanic agrarian cultures in the coastal deserts, highlands and altiplano regions of Andean South America. For example, the disintegration of Tiwanaku in ~10th century CE has been linked to the ENSO climate variations undermining intensified agricultural systems that relied on monsoonal rain by Ortloff and Kolata (1993) and Arnold et al. (2021) using sediment cores from Lake Titicaca and Lake Orurillo respectively.

The depopulation of the Mesa Verde region of North America by the Ancestral Pueblo culture in 13th century CE, described by Monastersky (2015), has been attributed to loss of dry-land maize cultivation under prolonged drought across the Colorado Plateau using tree-ring chronologies by Stahle et al. (2017). Evidence supporting this theory has also been provided by Schwindt et al. (2016) using population density and maize-niche reconstructions.

Travelling through time and space once more, the 15th century CE collapse of the Khmer Empire capital, Angkor, in Southeast Asia has received significant attention. Angkor was the most expansive low-density agrarian-urban society at the time, famous for its advanced water infrastructure that provided capacity to ride out dry spells as detailed by Fletcher et al. (2017).

Buckley et al. (2010) and Day et al. (2012) show that this collapse coincides with protracted drought interspersed with floods—associated with the long transition from Medieval Warm Period (~10th to 13th century CE) to Little Ice Age (~15th to 19th century CE) alongside short ENSO fluctuations—based on hydroclimate reconstructions from Vietnamese tree rings and sediment cores from West Baray reservoir. Using similar data combined with LiDAR (light detection and sensing) forensics, Buckley et al. (2014) conclude that it was a double blow of drought undermining crop productivity alongside rain damage to water management systems for irrigation that ultimately led to Angkor's collapse.

Further to these major events, the role of climate induced food insecurity has been linked to other societal transitions peppered throughout history, including: the growth and decline of Pacific Islands societies in 6th century BCE to 13th century CE by Nunn and Carson (2015); the establishment and collapse of Norse Viking colonies from 4th century BCE to 17th century CE by Patterson et al. (2010); the rise and fall of oasis civilisations along the Silk Road from 4th to 8th century CE by Li et al. (2016); the demise of the Easter Island population in ~16th century CE by Flenley and King (1984) and Lima et al. (2020); Chinese dynastic cycles by Zhang et al. (2006) and Gao et al. (2021), such as the decline of the Tang Dynasty in 10th century CE (Yancheva et al. 2007) and Ming Dynasty in 17th century CE (Han and Yang 2021); and transitions in the 1st century BCE to 15th century CE (Eastern and Western) Roman Empire by Büntgen et al. (2011) and Xoplaki et al. (2016) and 13th to 20th century CE Ottoman Empire by Kaniewski et al. (2012).

These first type of studies establish empirical evidence of natural climate change as a mechanism of societal collapse, which is useful in considering anthropogenic climate change as a similar mechanism (Scheffer 2016). However, the events examined date back in history to when societies were relatively disconnected, so these studies do not provide empirical evidence detailing the complex risk landscape of today's highly interconnected society. Additionally, these studies establish relatively isolated causal relationships, rather than the overarching process of societal collapse, which have not been systematically documented using causal loop diagrams.

2.1.2 Meta-theory studies based on primary and secondary sources

The second type of study takes the form of tomes that collate primary sources and derivative secondary sources (see Section 2.1.1) to develop meta-theories regarding the overarching process of societal collapse (see Figure 2.1). Some studies have taken a quantitative statistical approach while others have taken a qualitative approach to examination. The former has evidenced one and the latter has evidenced three predominant meta-theories, which are addressed in turn below.

A limited number of studies have quantitatively examined collections of case studies in attempts to define statistical relationships. To date, intricate confounding factors have precluded statistical evaluation of the frequency and significance of one mechanism versus other mechanisms of societal collapse (Kemp 2019a). Examining the natural climate change mechanism in isolation, Zhang et al. (2007, 2011) finds statistical significance between climate fluctuations, agricultural failures, war outbreak and population loss throughout history using societal collapse chronologies alongside high-

resolution paleoclimate data. Researchers have also been able to broadly question whether aspects of time or space influence occurrence of societal collapse. Arbesman (2011)'s foundational analysis using a data set spanning three millennia concludes that rate of collapse is independent of a society's age. To facilitate further statistical analyses, Kemp (2021) is developing a database of ~500 civilisations, based on extensive research to build on existing lists spanning 2000 BCE – 600 CE by Taagepera (1978a, b) and a crowd sourced survey by Freeman (2020). Kemp (2019b)'s initial examination of this database concludes that societal collapse occurs independent of both civilisation life span and size.

These quantitative examinations observe no apparent temporal or spatial influence on the process of societal collapse. The process of societal collapse is recognised as occurring due to labyrinthine mechanisms, whether they be anticipated 'white-swan' or surprise 'black swan' events Taleb (2007)—or any of the 'risk zoo' in between (Lin 2020)—in different geographic locations, geologic times and states of existence (see Figure 2.1) with different outcomes for any given society throughout history. Much like the findings of Žliobaitė and Fortelius (2020) for non-human societies, these quantitative examinations conclude that any human society may be susceptible to collapse. This first meta-theory of societal collapse is much in-line with the *Red Queen hypothesis* of the *Law of Extinction* established by Van Valen (1973), whereby "if species are constantly fighting for survival in a changing environment with numerous competitors, extinction is a consistent possibility."

Most tertiary studies have involved qualitative examinations of collections of 10–30 case studies by scholars to develop overarching theories detailed in prose. These studies are grouped below by consistent considerations of natural system, natural-human system and internal human system mechanisms, which have evidenced three predominant meta-theories respectively. Additionally, the detailed descriptions of empirical evidence provided by these scholars provides for identification of primary and secondary determinants of societal collapse outcomes (see Figure 2.1).

Focusing on societal collapse mechanisms with a natural system origin, Huntington (1915), Fagan (2008) and McMichael (2017) conclude that natural climate change played a principal role in the process of societal collapse throughout history. These scholars reflect on multiple case studies against the backdrop of the relationship between climate, agriculture and complex societies. Over the past 12,000 years, the natural and human systems co-evolved within the stable climate niche of the Holocene Epoch, and the associated geographic endowments governed human transition from band societies based on foraging to complex societies based on agriculture as documented in detail by Runciman (2001). Unfavourable subtle and drastic shifts in climate have influenced the collapse of multiple complex

societies due to food insecurity, with Fagan (2009) documenting key determinants of de-population via famine, migration or conflict. This second meta-theory of societal collapse aligns with Zhang et al.'s (2007, 2011) statistical analysis above and Xu et al.'s (2020) call to prevent anthropogenic forcing from destabilising the Holocene climate niche on which humanity has relied for millennia.

Examining societal collapse mechanisms originating from human impact on the natural system, Ponting (1991), Wright (2004) and Diamond (2005) conclude that human overpopulation and overexploitation relative to the carrying capacity of the environment have played a principal role in the process of societal collapse through history. Societal collapse via environmental degradation is linked to unsustainable agriculture exacerbated by natural climate change. Redman (1999) notes key determinants in the form of institutional breakdown via loss of economic stability and socio-political dysfunction due to magnified inequality. This third meta-theory of societal collapse is much in-line with the theories of 'Malthusian catastrophe' established by Malthus (1798), 'tragedy of the commons' established by Lloyd (1833) and Hardin (1968) and 'overshoot-and-collapse' established by Catton (1980).

In their 12-volume magnum opus examining 28 civilisations, Toynbee (1961) concludes that "great civilisations are not murdered [but rather] they take their own lives" (Kemp 2019a). Tainter (1988), Acemoglu and Robinson (2012) and Johnson (2017) build from this in their examinations of societal collapse mechanisms of internal human system origin. These scholars conclude that societal complexity in relation to problem-solving inability (e.g. environmental degradation) and institutional dysfunction (e.g. inequality and oligarchy internally, trade ally and hostile neighbour relations externally) has played a principal role in the process of societal collapse throughout history. Tainter (1988) describes that as a society becomes more complex, it reaches a point beyond which "continued investment in complexity as a problem-solving strategy yields a declining marginal return" and it will be at risk of collapsing under its own weight via both institutional breakdown and de-population determinants. This 'diminishing returns on complexity' theory has been extensively detailed by Tainter (1995, 2000, 2006, 2011, 2014), as has its relevance to institutional cooperation and coordination within and across societies for problem solving by Taylor (2008) and Strathern (2019). This fourth meta-theory of societal collapse aligns with 'energy returned on energy invested' theory established by Cleveland et al. (1984), which has also been applied to explore societal collapse by Homer-Dixon (2006).

Supporting these four meta-theories with a contrasting approach, Diamond (1997), Turchin (2006) and Schwartz and Nichols (2010) examine why some civilisations have been able to thrive or recover, rather than collapse. These scholars similarly conclude that societies have flourished due to combinations of

good luck, favourable geographic endowment, managing their existence within the carrying capacity of the natural system and cooperative and coordinated action in problem-solving (Middleton 2017). Additionally, these meta-theories may apply independently or in combination to a given societal collapse process. For instance, Storey and Storey (2017), (Heather 2006) and Gibbon (1789) detail how all four are applicable to the Mayan Civilisation and Roman Empire collapses.

These second type of studies establish that the process of societal collapse involves a complex conglomeration of variables and causal relationships (Ehrlich and Ehrlich 2013) and the four meta-theories are useful in considering anthropogenic climate change in the process of societal collapse, both as an independent mechanism and in context of synchronous mechanisms, as described by Yoffee and Cowgill (1988), Redman et al. (2004) and Pearson and Pearson (2012). However, the case study basis of these theories still dates to history when societies were relatively disconnected, so these studies do not provide empirical evidence detailing the complex risk landscape of today's highly interconnected society. Additionally, the causal relationships described by these studies have not been systematically documented using causal loop diagrams. A synthesis of the details provided in these studies identified the primary and secondary determinants presented in Figure 2.2, which define the outcomes in the process of societal collapse shown in Figure 2.1.

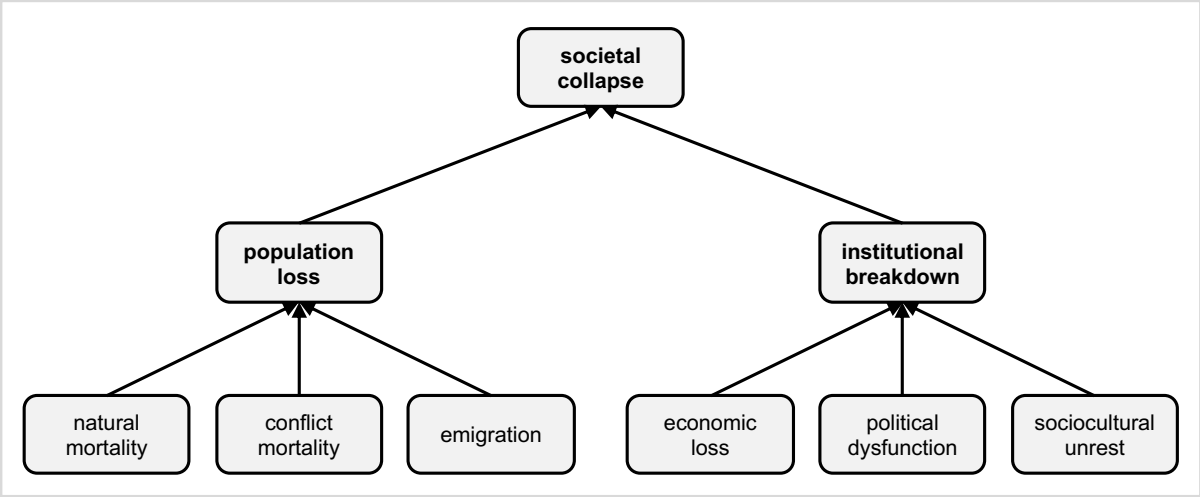


Figure 2.2: Primary and secondary determinants of societal collapse. These determinants are defined considering a single bounded society.

2.1.3 Foresight studies based on primary, secondary and tertiary sources

The third type of study collates information from primary, secondary sources (see Section 2.1.1) and tertiary sources (see Section 2.1.2) to describe possible future processes of societal collapse applicable to

contemporary society. These 'futures studies' or 'foresight studies' (Rios Rojas et al. 2021) are relatively nascent but increasingly recognised in the existential risk field as a valuable means to explore alternate scenarios of uncertain futures using pattern-based understanding of the past and present (Hines et al. 2017). The limited number of existing foresight studies are grouped into quantitative or qualitative approach, addressed in turn below.

Scholars taking a quantitative approach have focused on defining thresholds at which states of existence may transition to mechanisms (see Figure 2.1) triggering societal collapse. The Planetary Boundaries, first proposed by Rockström et al. (2009a, b) and subsequently updated by Steffen et al. (2015), define thresholds in relation to the natural system's state of existence based on expert opinion. Nine Planetary Boundaries have been established, seven of which have been quantified. Anthropogenic climate change is one, with an atmospheric CO_2 boundary of 350 ppm and radiative forcing boundary of 1 W/m^2, both of which have been breached. In a similar vein, Raworth (2017) defines 12 Social Boundaries, one of which is food security, largely based on the Sustainable Development Goals (UNDESA 2021). Despite being titled as "boundaries", these are expressed as a percentage population shortfall and no thresholds are quantified; food insecurity is described by percentage population undernourished. Due to intricate confounding factors, quantifying such thresholds in relation to the human system's state of existence remains a grand challenge, as does quantification of thresholds at which the determinants of societal collapse (see Figure 2.2) trigger an outcome for society (see Figure 2.1) (Baum and Handoh 2014).

Scholars taking a qualitative approach, such as McMichael (1993) and Gowdy (2020), construct non-fiction narratives of hypothetical futures under best- to worst-case scenarios. Martin et al. (2021) focuses on feedbacks within the natural system that could worsen, and the potential for humans to mitigate, anthropogenic climate change. Gore (2007) details how climate change induced shifts in average weather (e.g., temperature) and natural disasters (e.g., floods) could impact human mortality directly. These two effects, coupled with sea level rise due to melting of ice caps, could indirectly impact human mortality via degradation of the natural world system (e.g., land quality) and the human world system (e.g., infrastructure damage) resulting in resource (e.g., water, food) and service (e.g., energy, healthcare) insecurity as narrated by Lynas (2007). This insecurity could cascade through globalised supply chains to impact institutional stability, resulting in economic loss, political dysfunction and social unrest, as well as migration and conflict according to Spratt (2019). Across these scenarios, the outcomes for contemporary society under anthropogenic climate change range from dystopian (e.g., collapse by simplification) to utopian (e.g., recovery by advancement) (Wagner and Weitzman 2015).

These third type of studies in quantitative form emphasise the urgent need for climate action, given that some Planetary Boundaries have already been breached. They also emphasise the need for further work to quantify the process of societal collapse but do provide a measure for food insecurity within the process. In qualitative form, these third type of studies provide narratives of anthropogenic climate change as a mechanism of societal collapse, which facilitates consideration of the contemporary risk landscape (Pancost 2017). However, as these narratives—distinct from data-driven analyses or validated models—provide a hypothetical description they do not establish empirical evidence detailing the complex risk landscape of today's highly interconnected society. Additionally, the causal relationships described by these studies have not been systematically documented using causal loop diagrams. A synthesis of information in these studies suggests that the determinants in Figure 2.2 provide 'proxies' of societal collapse in contemporary society for which there exists no explicit empirical evidence.

2.2. Models of societal collapse for illustrating end-game futures

This section examines the literature on quantitative computational models of societal collapse, and the extent to which such models been used to illustrate the international risk landscape of climate change, food insecurity and societal collapse under 'extreme global warming' into the future. Three types of studies are considered in turn, namely: models of artificial societies for describing theories (Section 2.2.1); models of historical case studies for examining theories (Section 2.2.2); and, models of the contemporary world for exploring future scenarios (Section 2.2.3), with the latter most relevant to refining the research objective for RQ2.

2.2.1 Models of artificial societies for describing theories

The first type of study uses quantitative models of artificial societies for theoretical exposition of societal collapse dynamics. These studies are grouped by focus on Malthusian-Ricardian dynamics, 'diminishing returns on complexity' theory and other theoretical expositions, addressed in turn below.

Several scholars, such as Brander and Taylor (1998) and Erickson and Gowdy (2000), use models based on predator-prey theory (Lotka-Volterra equations) to examine Malthusian-Ricardian population and natural resource dynamics. Motesharrei et al. (2014) develop a mathematical model of a dynamically coupled human and natural system, including accumulated wealth and inequality, to explore how mechanisms of economic stratification and ecological strain can lead to different modes of societal

collapse. They also establish a measure of 'carrying capacity', which is the population that can be supported by nature, as a means for early detection of collapse. In contrast, Lopes and Fontanari (2019) use a Beverton-Holt model to examine the role of technology and resource management in buffering intra-societal 'feast and famine' cycles typically seen in predator-prey models. Guzmán et al. (2018) use an agent-based model to explore Malthusian-Ricardian dynamics at the intra-societal level and incorporate warfare and territorial dynamics at the inter-societal level. Much in line with history, their model identifies three consecutive eras with agriculture being the key driver of social and geographical dynamics in the progression from simple to complex societies.

Bardi et al. (2019) create a biophysical model of Tainter's (1988) 'diminishing returns of complexity' theory, demonstrating that society's success depends on its problem solving ability but "continued investment in complexity as a problem-solving strategy yields a declining marginal return" that leads to collapse. Using a game-based model, Derex et al. (2013) show that larger population size tends to yield greater diversity, frequency of innovation and transmission of knowledge in facilitating adaptive societal evolution, but subsequent group-size reduction reflects maladaptive losses as seen in collapse. Janssen and Scheffer's (2004) examination of the 'sunk-cost effect' in human decision-making highlights an unwillingness to abandon existing investments despite declining returns, which explains why overexploitation of natural resources contributed to the collapse of historical complex societies.

Various other theoretical expositions have been conducted using quantitative models, including: Yegorov et al.'s (2020) dynamic optimization model of economy, military strength and geography in the spatial evolution of societies; Feichtinger and Novak's (1994) game-based model of dynastic cycles; Lawson and Oak's (2014) game-theory model showing that concealment of political instability at the height of a state's power can lead to abrupt collapse; Jusup et al.'s (2014) model examining the role of ideological rigidity and barriers to cooperation in social collapse; and, Livni's (2019) classical stability theory model showing that increasing complexity invariably leads to a collapse even if the transition from a stable to unstable state takes centuries, again, much in line with Tainter (1988)'s 'diminishing returns on complexity' theory.

This first type of study yields valuable insights into societal evolution and collapse dynamics, such as the role of carrying capacity, diminishing returns on complexity and problem-solving ability, that may be applicable today in tackling the problem of climate change. However, due to their specific modelling purpose (Edmonds et al. 2019), these have not been transformed into models of the contemporary world for exploring future scenarios of climate change.

2.2.2 Models of historical case studies for examining theories

The second type of study uses models of historical case studies to explain theories of societal collapse. These studies are grouped by examinations of cyclical dynamics by Turchin, popular societal collapse events by Roman and other historical case studies by various scholars, addressed in turn below.

Turchin (2003) uses mathematical models alongside empirical data to shed light on historical cyclical dynamics, such as the growth and decline of population, the expansion and collapse of empires and the spread and wither of religions. In their study of 'secular cycles', Turchin and Nefedov (2009) demonstrate that historical processes exhibit recurrent long-term oscillations by modelling societies from the Roman Empire to medieval and early modern France and Russia. For instance, Turchin and Korotayev (2006) find that population density and warfare intensity oscillate in phase-shifted cycles in case studies of early modern England and the Han and Tang Dynasties of China. Turchin et al. (2013) employ an agent-based model to predict the evolution of Old-World complex societies across the Afro-Eurasian landmass based on mechanisms of 'ultra-sociality' and cultural multilevel selection, echoing Ibn Khaldun's 'asabiyyah' concept of cyclical social solidarity that is strongest at the birth and diminishes with the death of a civilisation.

Several 'popular' case studies of societal collapse have recently been investigated using dynamical systems models by Roman. In a similar vein to Turchin, Roman (2021) investigates territorial patterns of Chinese dynasties during periods of unification and upheaval, arriving at a quantitative measure for 'asabiyyah' with secular cycles matching the historical record over 1,800 years. Roman and Palmer (2019) model the growth dynamics of military, territory and coinage over the period 500 BCE – 500 CE, concluding that a high degree of centralized control was necessary to stabilise and prevent decline of the Western Roman Empire. Modelling 1,400 years of Southern Lowlands development, Roman et al. (2018) examine the role of climate induced drought and intensive agriculture management in the Classic Maya collapse. Roman et al. (2017) suggest that coupled societies are more robust against collapse, based on exploration of population growth and natural resource extraction dynamics within the Easter Island archaeological record.

Various other case studies have been examined using quantitative models, including: Yaroshenko et al.'s (2015) predictive wavelet model of stable and chaotic conditions of the Roman Empire from 400 BCE – 400 CE and European Union from 1957–2007 CE; Reuveny and Decker's (2000) model of "Malthusian" population and technological dynamics on Easter Island; DiNapoli et al.'s (2020)'s Bayesian model

demonstrating the 'tempo' of Easter Island collapse events; Allen and Heldring's (2021) model of the southern Mesopotamia collapse based on digitized archaeological data; and, Jones' (2021) game-based model of 'barbarigenesis' in the decline of late Antiquity and Middle Age complex societies. Flores (2015) uses numerical simulations to demonstrate climate-induced phase-transitions, associated with agriculture and fishery, between states of disorder and organisation in the Andean Caral collapse, while Flores et al.'s (2011) model suggests that a 95% loss of population in Tiwanaku may have occurred due to climate-induced drought. In a similar vein, Zhang et al. (2011) and Cookson et al. (2019) reveal that climate related agricultural failures contributed to large scale human crises in 16th– 17th century CE Europe and in the demise of the Akkadian Empire in 22nd century BCE, further demonstrating the role of climate change in historical societal collapse.

This second type of study yields valuable insights into the dynamics of the rise and fall of historical civilisations that may be applicable today, such as the role of social cohesion and collective action in tackling the problem of climate change. However, due to their specific modelling purpose (Edmonds et al. 2019), these have not been transformed into models of the contemporary world for exploring future scenarios of climate change.

2.2.3 Models of the contemporary world for exploring future scenarios

The third type of study uses models of the contemporary real world to illustrate possible future scenarios. To refine the research objective for RQ2, this review is bounded to literature on World3, and derivative studies, as the most eminent and accessible model central to the explicit study of societal collapse. It should be noted, however, that the field of integrated global modelling has vastly expanded since the development of World3, as documented by Castro and Jacovkis (2015). Subsequent models, such as the Mesarovic-Pestel (Mesarović and Pestel 1974), Bariloche (Herrera et al. 1976), FUGI (Onishi 1977), MOIRA (Linneman et al. 1979) and International Futures (Hughes 1985) models, have made important contributions to our understanding of world dynamics. An overview of the history of World3 and debate associated with *The Limits to Growth* is provided before addressing the model itself and models derived from it, in turn below.

The 'World' model was conceptualised by Forrester, the father of system dynamics, which is a modelling approach that was first applied to business problems (Forrester 1961) and urban planning (Forrester 1969). In 1970, the Club of Rome asked Forrester to apply system dynamics to study the 'predicament of mankind', following which Forrester created 'World1' soon thereafter refined into

'World2' (Forrester 1971). The model was further refined into 'World3' by Meadows et al. (1974), used to produce *The Limits to Growth* (Meadows et al. 1972) as a report to the Club of Rome. The study simulated 12 scenarios from 1900 to 2100, to explore the potential for 'collapse' should socioeconomic growth 'overshoot' the planet's 'carrying capacity' under different population, resource, technology, and policy assumptions. Recognising the limitations inherent in modelling, Meadows et al. (1972) nonetheless came to concerning but hopeful conclusions about humanity's future:

"If … trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years. The most probable result will be a rather sudden and uncontrollable decline in both population and industrial capacity."

The Limits to Growth sold ~30 million copies in over 30 languages (Nørgård et al. 2016), with many viewing it as a founding text of the environment movement and the initiator of the integrated global modelling paradigm (Meadows et al. 1982). It has created fierce debate, attracting three main themes of criticism, namely, that the model: 'oversimplifies' the real world, such as by grouping all non-renewable resources as noted by Smil (2005); is 'unduly pessimistic' in key assumptions as argued by Simon (1981), such as underestimating the power of technology (Wallich 1982), with weak foundation of data (Solow 1973) and high parameter sensitivity (Vermeulen and de Jongh 1976); and, is 'unrealistically deterministic' as described by Cole et al. (1973), with a rigid overshoot-and-collapse mode giving little credence to human adaptability (Bray 1972). While some critics, such as Bonnet and Woltjer (2008), have taken a balanced approach to addressing limitations while recognising the overall message as valid, others have relegated the "empty and misleading work" (Passell et al. 1972) to "the dustbin of history" (Lomborg and Rubin 2002) based on misinterpretations of the study (Bardi 2011). In response, Meadows et al. (1973) demonstrated that many criticisms had misunderstood or misrepresented their study, while Meadows et al. (1992), Meadows et al. (2004) and Randers (2012) updated World3 and ran refined scenarios to bolster the original conclusions in *The Limits to Growth*.

While the criticisms dominating its first three decades of existence linger in a more neutral form (Castro 2012), the turn of the century has seen a positive 're-appraisal' of *The Limits to Growth* emerge (MacKenzie 2012). Proponents, such as Schoijet (1999), have suggested a biased agenda of critics. Others, like Woodwell (1998) and Heath et al. (2019), have conducted comparative studies to demonstrate that the model's overall trends are stable despite criticisms of high parameter sensitivity. Several scholars, including Randers (2000), Turner (2008, 2012, 2014) and Pasqualino et al. (2015), have compared World3's output against up-to-date data, which has led scientists, such as Hall and Day

(2009), and economists, such as Simmons (2000), alike to recognise the validity of the study. The most recent of such studies is one by Herrington (2021), which shows that two scenarios align closely not only with observed data but also contemporary climate change debate. One is the climate change equivalent scenario that leads to collapse due to pollution (#2 by Meadows et al. (2004)), reflective of the argument that we must urgently correct our broach of planetary boundaries to avoid climate tipping points (Lenton et al. 2008). The other scenario sees gradual decline to stabilisation under rising costs of high technological progress (#6 by Meadows et al. (2004)), reflective of the argument that humanity can innovate past its problems (Häggström 2016). The utility of World3 is further evidenced by the current U.K. All-Party Parliamentary Group on *Limits to Growth* (Jackson and Webster 2016).

World3 is a system dynamics model of the real world depicted at global scale and global granularity. It describes dynamic relationships within and between five major sub-systems, namely: population, capital, agriculture, pollution and non-renewable resources. In terms of 'content', World3 implicitly accounts for climate change as part of the pollution sub-system, including impacts on agricultural production. It explicitly accounts for food insecurity via food production and food demand as part of the agriculture and population sub-systems. Societal collapse is explicitly evaluated in the form of population loss as a function of food availability, pollution, health services and crowding. In terms of 'structure', World3 does not distinguish heterogenous characteristics of regions, nations or localities, such as geographic endowment of arable land and climate favourable for crop yields, nor does it account for international interactions, such as trade, conflict and migration, due to its global granularity. The system represented in World3 is shown in Figure 2.3 for context.

A limited number of studies have directly extended World3 to gain new insights. Some scholars have focused on altering World3 'content'. Acharya and Saeed (1996) incorporate additional policy space to examine the operationalization of sustainable policies within existing institutions. Simonovic (2002) add a water resource sub-system to account for the growing scarcity of water quantity and quality. Ansell and Cayzer (2018) alter the pollution and resource sub-systems to explicitly examine energy mix and climate change economics. Pasqualino et al. (2019) examine the economic dynamics of households, firms and governments by adding a financial sub-system. While affecting the integrity of the original World3 dynamics for specific purposes, these studies demonstrate World3's utility as a foundation for examining different aspects of world dynamics.

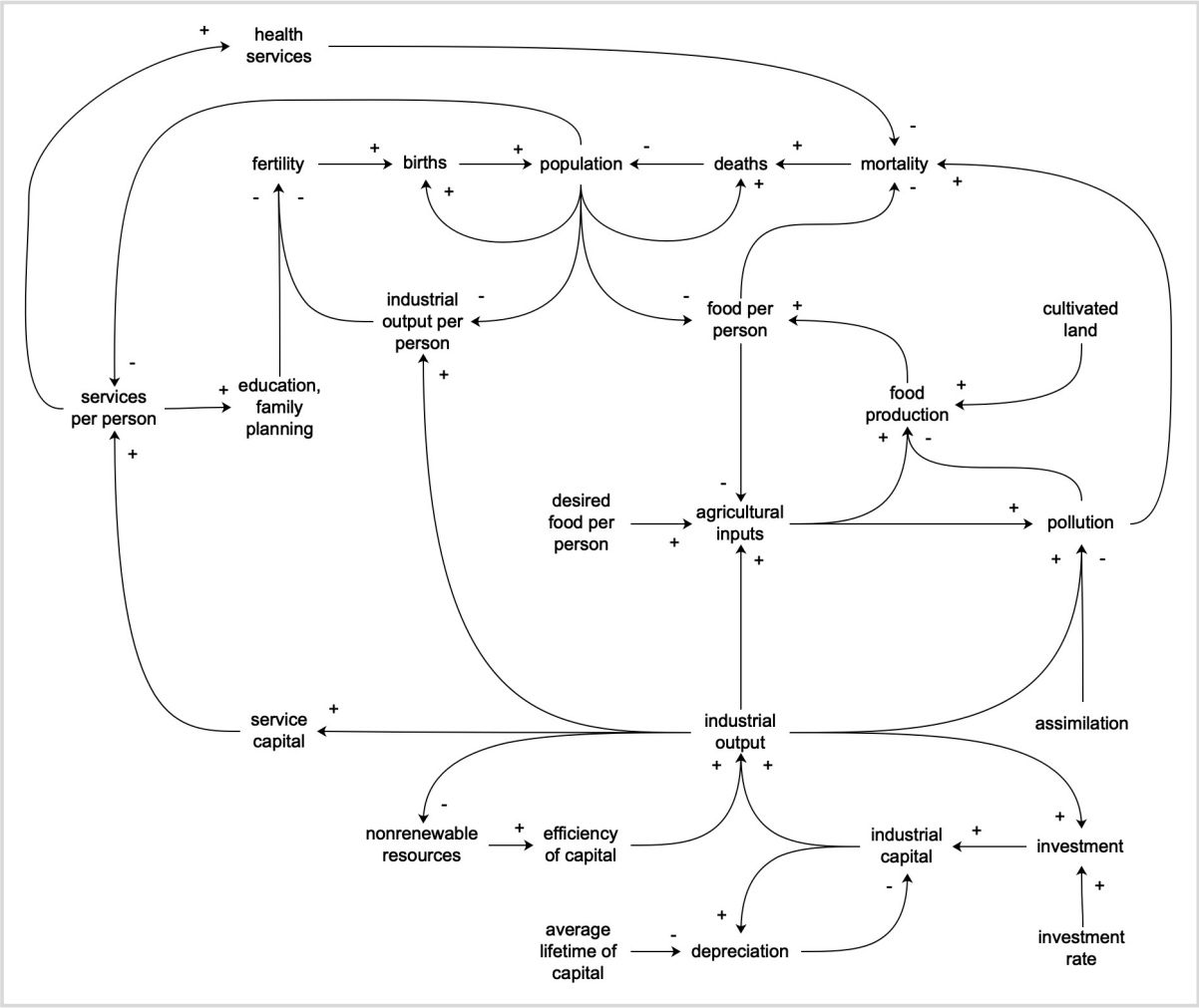


Figure 2.3: The global scale and granularity real world system simulated by World3. Based on: Meadows et al. (2004).

Others have focused on altering World3 'structure'. Brinton et al. (1974) replicate World3 content to create a national scale and granularity model of China. Meadows (2001) create an interactive game based on a simplified version of World3 as a regional scale and national granularity model of Central America. Kimura and Binder (2016) create a national scale and granularity model of Hawaii linked to an otherwise global scale and granularity 'rest of world' model based on World3, to explore the effect of external tourism and investment on technology and food production. Richards et al. (2021) identified the value in exploring future societal collapse risk landscapes using global scale and national granularity versions of World3, such as by leveraging the global system dynamics of World3 in combination with an agent-based model of countries. However, such studies remain underdeveloped due limited data availability and computational challenges as described by Monasterolo et al. (2014).

World3 and derivative models provide insights into the future risk landscape under different scenarios. There are two important insights to note. Firstly, World3 is one of few models that has explored an

'extreme climate change' scenario (BAU-CC), reflective of global warming above 8°C by 2100. Secondly, World3 and derivative models do not currently provide for exploration of the international risk landscape, which requires global scale and national granularity.

2.3. Scenarios for exploring decision factors in the present

This section examines the literature on climate policy and socioeconomic development scenarios, and the extent to which such scenarios have been used to explore the influence of decision factors in the present. To refine the research objective for RQ3, this review is bounded to literature on the Representative Concentration Pathways - Shared Socioeconomic Pathways - Shared Climate Policy Assumptions (RCP-SSP-SPA) framework, which represents the latest set of scenarios developed by the climate change research community. Three types of studies are considered in turn, namely: those addressing development of the SSP-RCP-SPA framework (Section 2.3.1); those on isolated components of the framework (Section 2.3.2); and, those extending from the framework as a whole (Section 2.3.3).

2.3.1 Development of the RCP-SSP-SPA framework

The climate change research community may be considered in three groups that focus on earth system modelling (ESM), socioeconomic and environmental integrated assessment modelling (IAM) and impact, adaptation and vulnerability modelling (IAV), with the latter remaining a grand challenge, particularly in considering climate change impact feedbacks on human societies (Steffen et al. 2020). This community has for several decades used scenarios to explore different aspects of the relationship between socioeconomic development and climate change outcomes as documented by Moss et al. (2010). Scenarios underpinning the IPCC's Assessment Reports include the 'SA90' in AR1 (IPCC 1995), 'IS92' in AR2 (IPCC 2000) and AR3 (IPCC 2001), 'SRES' in AR4 (IPCC 2007) and RCPs in AR5 (IPCC 2014). These all define future emissions based on various socioeconomic assumptions and an absence of climate policy and climate change impact feedbacks.

The latest development underpinning AR6 (IPCC 2021) is the RCP-SSP-SPA framework, established by Kriegler et al. (2012) and Van Vuuren et al. (2012). It is distinct in its integration of climate forcing, socioeconomic development and climate policy assumptions in a three-dimensional matrix architecture that yields 15 plausible scenarios, as shown in Figure 2.4. Each aspect is described in turn below.

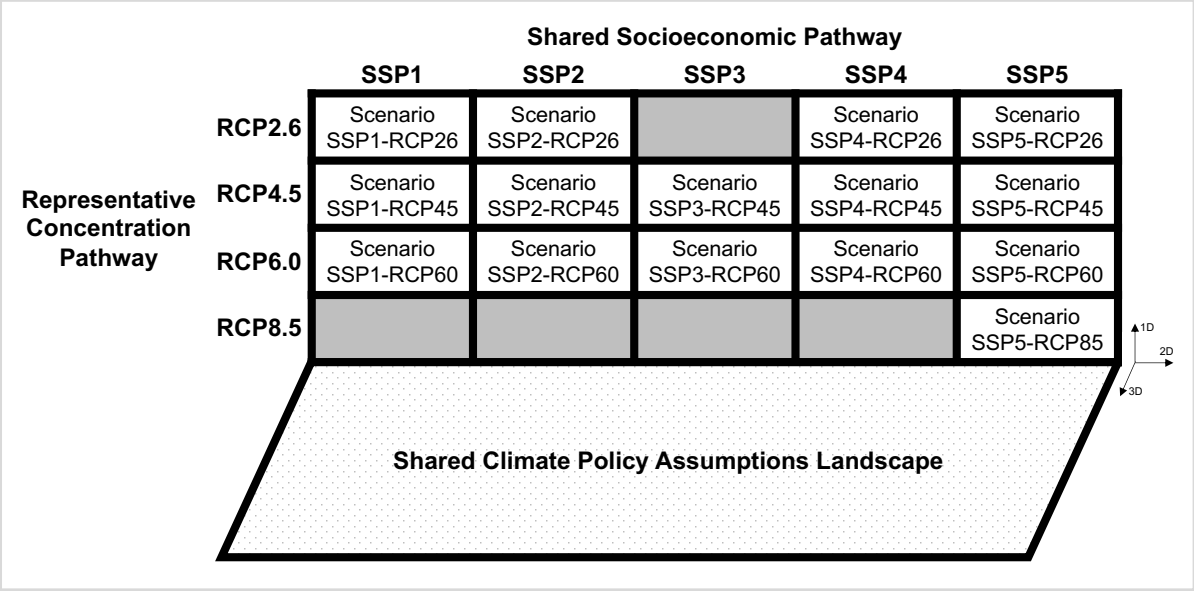


Figure 2.4: The scenario matrix architecture of the RCP-SSP-SPA framework. Based on: van Vuuren et al. (2014)

The first dimension is climate forcing in the form of four core RCPs, established by van Vuuren et al. (2011a) and summarised in Figure 2.5. The RCPs define quantitative trajectories of global average radiative forcing to 2100 based on expert judgement of likely emission concentration pathways. Specifically, RCP2.6 is detailed by van Vuuren et al. (2011b), RCP4.5 by Thomson et al. (2011), RCP6.0 by Masui et al. (2011) and RCP8.5 by Riahi et al. (2011). A higher RCP generally corresponds to a higher intensity of climate change. However, a range of outcomes, such as temperature and precipitation, exist for each RCP due to modelling uncertainties in climate response, as described by Tebaldi and Arblaster (2014).

	Radiative forcing (rate of change in radiative forcing) at 2100	Global mean (likely range) temperature increase from 2000 to 2100
RCP8.5	8.5 W/m^2 (rising)	+3.7 (~2.6-4.8) ºC
RCP6.0	6.0 W/m^2 (stabilising)	+2.2 (~1.4-3.1) ºC
RCP4.5	4.5 W/m^2 (stabilising)	+1.8 (~1.1-2.6) ºC
RCP2.6	2.6 W/m^2 (declining)	+1.0 (~0.3-1.7) ºC

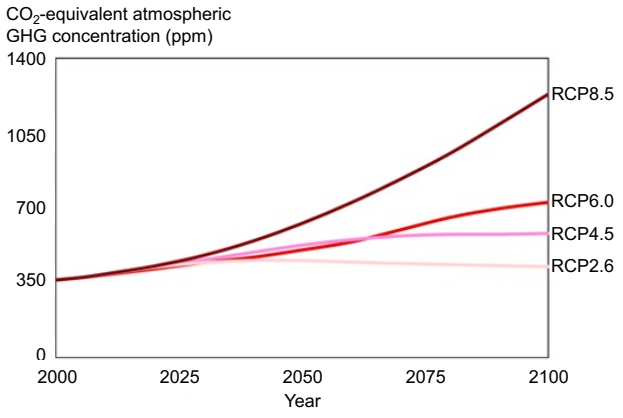
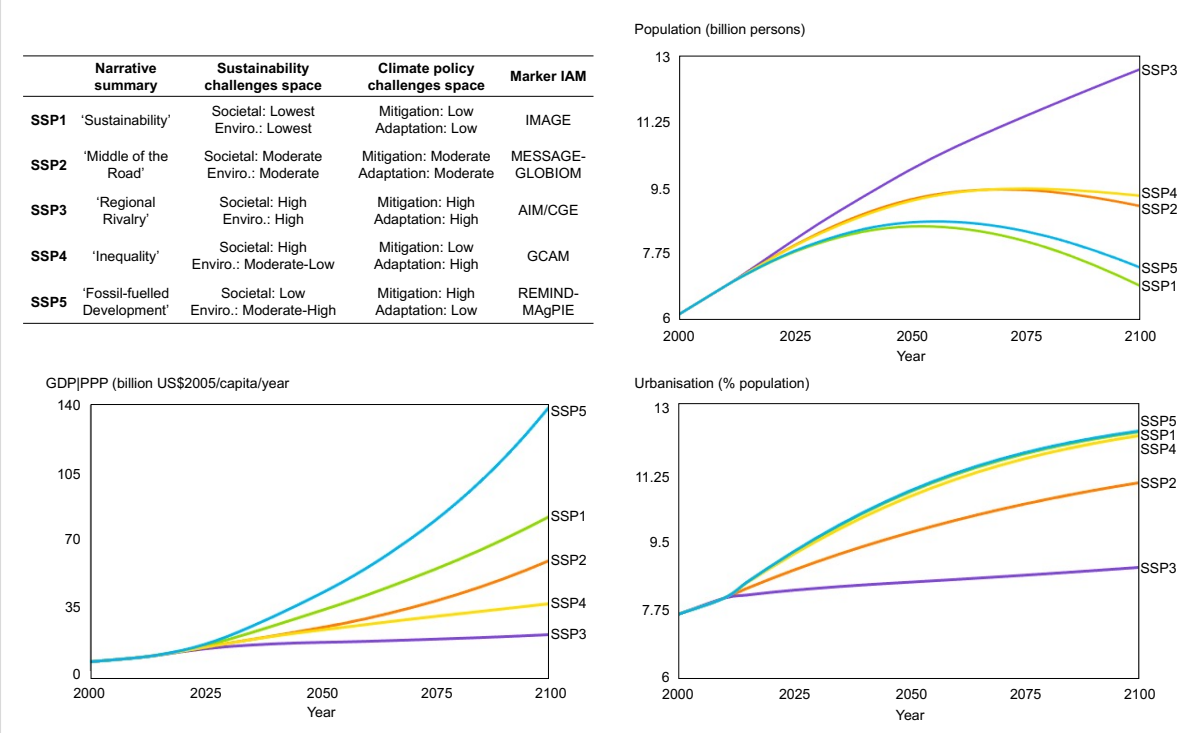


Figure 2.5: The RCP dimension of the RCP-SSP-SPA framework. Data basis: CO_2-eq. concentration from IIASA (2009); temperature from IPCC (2014); radiative forcing from van Vuuren et al. (2014).

The second dimension is socioeconomic development in the form of five SSPs established by O'Neill et al. (2017) and summarised in Figure 2.6. The SSPs define qualitative and quantitative elements of expert-informed narratives that describe how society may develop in the future. Qualitative elements span characteristics of demographics, economics, welfare, the environment, resources, institutions and governance, technology, culture and lifestyle and non-climate policy. Quantitative elements include three characteristics: population growth and education, defined by KC and Lutz (2017); economic growth, defined by Crespo Cuaresma (2017), Dellink et al. (2017) and Leimbach et al. (2017) under different assumptions; and, urbanization, defined by Jiang and O'Neill (2017). The narratives exhibit characteristic barriers to mitigation and adaptation, with each SSP occupying a distinct 'challenges space' domain, defined by O'Neill et al. (2014). Challenges to mitigation relate to factors such as the capacity of policy-making institutions, availability of financial and social capital, and technological development. Challenges to adaptation are a function of exposure in terms of population, infrastructure and services, sensitivity in terms of socioeconomic responsiveness and vulnerability, and adaptative capacity in terms of the same factors effecting challenges to mitigation.



	Narrative summary	Sustainability challenges space	Climate policy challenges space	Marker IAM
SSP1	'Sustainability'	Societal: Lowest Enviro.: Lowest	Mitigation: Low Adaptation: Low	IMAGE
SSP2	'Middle of the Road'	Societal: Moderate Enviro.: Moderate	Mitigation: Moderate Adaptation: Moderate	MESSAGE-GLOBIOM
SSP3	'Regional Rivalry'	Societal: High Enviro.: High	Mitigation: High Adaptation: High	AIM/CGE
SSP4	'Inequality'	Societal: High Enviro.: Moderate-Low	Mitigation: Low Adaptation: High	GCAM
SSP5	'Fossil-fuelled Development'	Societal: Low Enviro.: Moderate-High	Mitigation: High Adaptation: Low	REMIND-MAgPIE

Figure 2.6: The SSP dimension of the RCP-SSP-SPA framework. Data basis: population, GDP and urbanization from IIASA (2018); challenges space from O'Neill et al. (2014); narrative and marker IAMs from Riahi et al. (2017).

The RCPs and SSPs provide reference pathways of climate forcing and socioeconomic development in isolation, assuming no climate policy. It is the SPAs, the third dimension, that connect the RCP and SSP pathways to form scenarios, as described by Kriegler et al. (2014). SPAs provide a qualitative narrative

and quantitative information that capture three climate policy attributes, namely: goals, such as emissions reduction targets; regimes and measures, such as carbon taxes or policy subsidy instruments; and, implementation limits and obstacles, such as regional barriers or behavioural biases. SPAs of varying stringency applied to a given SSP yield varying levels of climate forcing, which gives rise to the scenario combinations. By nature, some SSP and RCP combinations are incompatible—e.g., SSP1 is defined such that the underpinning energy system cannot produce a climate forcing reaching 8.5 W/m^2 regardless of SPA—which yields 15 plausible scenarios.

These 15 scenarios result from iterative elaborations of the framework using five IAMs, as described by Riahi et al. (2017). The IAMs simulate socioeconomic development in the human system based on a given SSP and how this alongside SPA variations translates across the natural-human system interface to influence the natural system toward the climate forcing of the target RCP scenario combination. Each IAM, designed by different modelling teams to be unique, can provide alternate elaborations of any given SSP. However, each SSP has a designated marker IAM (see Figure 2.6) that provides the best representation of its narrative. The implementation of the marker IAM for SSP1 is described by van Vuuren et al. (2017), SSP2 by Fricko et al. (2017), SSP3 by Fujimori et al. (2017), SSP4 by Calvin et al. (2017) and SSP5 by Kriegler et al. (2017). Popp et al. (2017), Bauer et al. (2017) and Rao et al. (2017) respectively detail the land use, energy mix and emissions data for all five SSP elaborations.

The RCP-SSP-SPA framework scenarios describe 'ideal' socioeconomic development—that is, in absence of dynamic climate change impact and societal adaptation feedbacks—that in combination with static climate policy assumptions results in a particular climate forcing by 2100. Thus, as described by O'Neill et al. (2014), although the IAMs have capacity to account for climate change feedbacks, these are 'switched off' for the purpose of framework elaboration to provide a set of reference scenarios to support subsequent IAV research, such as this study.

These first type of studies document the RCP-SSP-SPA framework, which provides 15 scenarios characterising different climate policy and socioeconomic development factors over the century. However, these reference scenarios of 'ideal' socioeconomic development do not incorporate the impact on society of climate change feedbacks.

2.3.2 Studies on isolated components of the framework

The second type of study elaborates isolated components of the framework. Numerous aspects have been studied, including methodological expositions of modelling limitations, such as simulation sensitivity to baseline period (Liersch et al. 2020), model selection bias (Gohar et al. 2017), SSP assumption variations (Marangoni et al. 2017) and grid cell downscaling methods (Wootten et al. 2020). This review focuses on a subset that examine aspects of food security as most relevant, in three themes: RCP influence on crop-based agriculture; RCP influence on animal-based agriculture; and, SSP influence on food security.

A dearth of literature examines climate change impacts on crop yields using quantitative projections of temperature and precipitation under the RCPs in isolation. To be concise, select studies are detailed while others with similar methodologies and findings are summarised in Table 2.1. Across four independent simulations of the RCPs, Zhao et al. (2017) find that each 1°C increase in global mean temperature will decrease global yields of maize by 7.4%, rice by 3.2%, soybean by 3.1% and wheat by 6.0%. Rosenzweig et al. (2014) demonstrate that higher latitudes may experience yield gains up to 50% while lower latitudes may experience losses of up to 50%. The influence of temperature and precipitation on these four major crops has received significant attention, with most studies citing net losses globally but with varying absolute percentage changes in yield depending on climate forcing, methodology and assumptions such as CO_2 fertilization, soil fertility and irrigation technology.

On maize, Ahmad et al. (2020) show declines in global average yields of 29% by mid-century under RCP8.5. Anapalli et al. (2021) indicate yield declines of 10–62% for irrigated and 9–60% for rainfed crops under RCP2.6 to RCP8.5 by 2100 in the Lower Mississippi Delta, USA. For rice, Guo et al. (2021) estimate global average yield losses of 13% due to drought, while Chun et al. (2016) suggest losses up to 45% in Cambodia, under RCP8.5 by 2100. On soybean, Coleman et al. (2021) show that yields in the UK under RCP8.5 may increase 9–30% by 2050 due to CO_2 fertilization but will then decline by 2100 as heat and water stress offset this effect. For wheat under RCP8.5 to 2100, Liu et al. (2021) show global yield reductions across 44% of currently harvested areas due to temperature increase, Miroslav et al. (2021) find 15–60% increase in crops facing water scarcity and Gul et al. (2020) indicate yield variation of 14% increase to 11% decrease across Pakistan. Beyond temperature and precipitation, scholars find similar declines in yields with increasing prevalence of crop disease, such as wheat stem rust pathogen (Prank et al. 2019), mould and mycotoxins (Van de Perre et al. 2015).

Table 2.1: Summary of other studies that, similarly to those detailed in text, find declines in crop yields associated with climate change across various geographies over the century. Yields from each study are not included to avoid oversimplifying their variance in methodology, results and uncertainty.

Crop group	Crop item	Geographic area	Studies
Cereals	Buckwheat	Nepal	Luitel et al. (2021)
	Maize	Benin	Amouzou et al. (2019)
		China	Lin et al. (2017)
		Ethiopia	Kassie et al. (2015)
			Degife et al. (2021)
		Kenya	Mumo et al. (2021)
		Malawi	Warnatzsch and Reay (2020)
		Tanzania	Lana et al. (2018)
			Luhunga (2017)
	Pearl millet	Pakistan	Ullah et al. (2019)
	Quinoa	West Africa	Alvar-Beltrán et al. (2021)
	Rice	Bangladesh	Acharjee et al. (2019)
		Bhutan	Chhogyel et al. (2020)
		China	Wang et al. (2021)
		India	Raji et al. (2021)
		Indonesia	Kinose et al. (2020)
		Mediterranean	Bregaglio et al. (2017)
		Pakistan	Shabbir et al. (2020)
		Senegal	Gérardeaux et al. (2021)
		South Korea	Yoon and Choi (2020)
		Thailand	Arunrat et al. (2018)
		Vietnam	Kang et al. (2021)
	Sorghum	Ethiopia	Eggen et al. (2019)
	Wheat	Brazil	Nóia Júnior et al. (2021)
		China	Yue et al. (2018)
		Egypt	Ali et al. (2020)
		Iran	Paymard et al. (2019)
		Mexico	Guarin et al. (2019)
		Russia	Di Paola et al. (2018)
		Turkey	Vanli et al. (2019)
		USA	Pequeno et al. (2021)
Fruits	Bananas	Global	Varma and Bebber (2019)
	Breadfruit	Hawaii	Mausio et al. (2020)
	Plantain	Andean-Amazon	Beltrán-Tolosa et al. (2020)
	Wine grapes	Canada	Hewer and Gough (2021)
	Various deciduous fruit and nuts	Argentina	del Barrio et al. (2021)
		Chile	Fernandez et al. (2020)
		Spain	Rodríguez et al. (2021)
Oil crops	Rapeseed	China	Tian et al. (2018)
	Soybean	Brazil	Figueiredo Moura da Silva et al. (2021)
		China	Zhang et al. (2019)
		Iran	Satari Yuzbashkandi and Khalilian (2020)
		USA	Liu and Desai (2021)
Pulses	Common beans	Brazil	Heinemann et al. (2017)
	Peanuts	USA	Ruane et al. (2014)
Roots and tubers	Cassava	India	Raji et al. (2021)

			Shiny et al. (2019)
	Potatoes	Global	Raymundo et al. (2018)
		India	Raji et al. (2021)
	Sweet potatoes	India	Raji et al. (2021)
Sugar crops	Sugar beets	England	Okom et al. (2017)
	Sugarcane	China	Mi et al. (2017)

Animal-based agriculture has received less treatment. Rahimi et al. (2021) find that 4–19% of livestock in East Africa will be at risk of heat stress, and Holsman et al. (2020) estimate collapse to 70% for pollock and 35% for Pacific cod fisheries in the USA, under RCP8.5. Others find similar declines for mixed crop-livestock systems in Burkina Faso (Rigolot et al. 2017), key aquaculture species in Canada (Marushka et al. 2019) and Europe (Cubillo et al. 2021), and 180 finfish and shellfish species globally (Froehlich et al. 2018, Thomas et al. 2018).

Studies elaborating the SSPs in isolation are relatively limited. While the above RCP studies highlight disparities of climate change impacts across different regions (Deryng et al. 2014), especially the poleward shift of the breadbasket climate niche (Franke et al. 2021), SSP studies highlight complementary matters in relation to global justice. For instance, the influence of socioeconomic factors on climate resilient development and risk of starvation across the five SSPs is demonstrated in terms of population and economic growth by Hasegawa et al. (2015), gender inequality by Andrijevic et al. (2020), income inequality and food waste by Bijl et al. (2017) and lifestyle food demand by Gouel and Guimbard (2019).

These second type of studies highlight the importance of accounting for the impact on agriculture of climate change feedbacks. However, they provide only isolated insights under single dimensions, rather than considering influence of climate policy and socioeconomic development decision factors in combination under the integrated RCP-SSP-SPA framework.

2.3.3 Studies extending from the framework as a whole

The third type of study extends from the RCP-SSP-SPA framework scenarios to explore the impact of climate change feedbacks. Some studies address impacts on the natural system, such as bumblebee biodiversity loss by Prestele et al. (2021), on the human system, such as prevalence of mosquito borne viruses by Rohat et al. (2020), and at the interface of these systems, such as air, water, land and energy security under the SDGs by Liu et al. (2020). To be concise, this review focuses on the subset examining

the food system interface as most relevant, with focus on the scenario combinations, time frames, scale and granularity examined, rather than absolute estimates of risk of starvation, in three themes: regional risk of starvation; global risk of starvation; and, societal adaptation response to starvation.

In regional studies, Sallaba et al. (2017) examine Sahel agriculture under all 15 scenarios, concluding that food demand will outpace supply as early as 2050. Chen et al. (2021) find that China will experience widespread food scarcity by 2100 under combinations of the five SSPs with RCP2.6 and RCP6.0. Palazzo et al. (2017) tailor the five SSPs to West Africa and implement these in combination with RCP8.5 in a participatory multi-stakeholder futures assessment that finds significant increases in food insecurity post-2050.

In global studies, Wiebe et al. (2015) explore climate change impacts on agriculture under scenario combinations of SSP1–3 with RCP4.5, RCP6.0 and RCP8.5 through to 2050. Hasegawa et al. (2014) analyse risk of hunger under combinations of SSP1–3 with the four RCPs through to 2050. Van Meijl et al. (2018) compare the impact of climate change on agriculture to the impact of mitigation measures under combinations of SSP1–3 with RCP2.6 and RCP6.0 through to 2050. Van Meijl et al. (2020) examine food availability, access and utilisation under all five SSPs through to 2100, with a sensitivity analysis under RCP2.6 and RCP6.0 applied only to SSP2 results. Molotoks et al. (2021) find that global undernourishment may increase from 13% to 60%, with both climate change and socioeconomic factors acting as dominant drivers, under combinations of SSP1–3 with RCP2.6 and RCP6.0 through to 2050. Jägermeyr et al. (2021) leverage a new generation of models to show that negative climate impacts on global crop yields emerge as early as 2040 under SSP1-RCP26 and SSP5-RCP85.

Other scholars have explored societal adaptation in specific sectors and/or regions. Dueri et al. (2016) examine global skipjack tuna fisheries under SSP3-RCP85 in 2010, 2050 and 2095 to inform management planning. Duku et al. (2018a) analyse rainfed and irrigated crop systems under scenario combinations of SSP1 and SSP3 with RCP2.6 and RCP8.5 for 2041–2050 and 2091–2100 to inform cropping pattern adaptation, and Duku et al. (2018b) explore trade-offs between cropland expansion and forestland/woodland conservation, in Benin. Wessels et al. (2021) quantify climate risk for 1190 wild-harvested food plant species in Africa under combinations of SSP2 with the four RCPs in 2060–2080 to inform crop diversity adaptation. Ramasamy et al. (2021) detail global distribution of crop pest fall armyworm under SSP1-RCP26 and SSP5-RCP85 in 2050 and 2070 to inform outbreak control strategies. Smolenaars et al. (2021) evaluate the food-energy-water nexus in the Indus basin under SSP1-RCP4.5, SSP2-RCP6.0 and SSP3-RCP8.5 to 2080, while Byers et al. (2018) evaluate the nexus globally

under combinations of SSP1-3 with RCP4.5, RCP6.0 and RCP8.5 through to 2050, to inform adaptive sustainable development strategies.

These third type of studies indicate that both climate policy and socioeconomic development decisions in the present will influence the risk of starvation in the future. However, there is yet to exist a comparative investigation of decision factors across all 15 SSP-RCP-SPA framework scenarios through to 2100 at global scale and national granularity.

2.4. Chapter summary: research objectives

This chapter reviewed bodies of literature relevant to each of the three research questions (RQ1,2,3). The existing literature establishes partial answers to these questions and reveals remaining gaps in knowledge. This thesis addresses these gaps through the refined research objectives defined below, which direct the methodological basis for the three original research chapters (Chapter 3,4,5).

RQ1: "How can systematically documenting historical evidence improve our understanding of the complex risk landscape of climate change, food insecurity and societal collapse?"

The first body of literature establishes precedence of natural climate change as a mechanism of societal collapse, meta-theories of the process of societal collapse and narratives of hypothetical futures of societal collapse through systematic synthesis of historical sources. However, the empirical evidence examined dates to ancient ("Antiquity", ~3000 BCE – 500 CE) and post-classical ("Middle Ages", ~500–1500 CE) history when societies were relatively disconnected, and there currently exists no empirical evidence base of societal collapse in today's highly interconnected society. Nor have causal loop diagrams been used to visually structure the empirical evidence that does exist.

To address these gaps, the refined research objective for the first investigation is to identify an empirical evidence base of climate change, food insecurity and societal collapse in contemporary society using the societal collapse determinants (see Figure 2.2) as proxies and structure this evidence base using a causal loop diagram defined at global scale and national granularity.

RQ2: "What insights into the future international risk landscape can be gained by illustrating climate change, food insecurity and societal collapse under 'extreme global warming'?"

The second body of literature establishes insights into societal evolution and collapse dynamics based on theoretical exposition of artificial societies and historical case studies pre-dating contemporary society. World3 is the only quantitative computational model that simulates the contemporary real world to illustrate risk of societal collapse under an 'extreme climate change' scenario (BAU-CC). However, World3 does not illustrate the international risk landscape, due to its global scale and granularity.

To address this gap, the two aspects of World3's 'extreme climate change' scenario and granularity are first put into context of the mainstream RCP-SSP-SPA framework (detailed in Section 2.3). On the first, none of the RCPs embody 'extreme global warming' above 8°C as explored by World3. RCP8.5 engenders the worst rate of global warming, reaching 4.3°C by 2100. RCP8.5 is only 'plausible' in combination with SSP5, which embodies a narrative of 'fossil-fuelled development' that matches best with World3's BAU-CC narrative. On the second, the framework provides reference data at finer resolutions than World3's global granularity, including at regional, country and grid cell level, which provides for exploration of the international risk landscape. Ergo, the refined research objective for the second investigation is to develop a quantitative computational model to illustrate the international risk landscape of climate change, food insecurity and societal collapse through to 2100, using World3's BAU-CC scenario as a basis for defining an original 'extreme global warming' scenario alongside up-to-date historical and SSP5-RCP85 projection data to define national granularity characteristics.

RQ3: "How might decisions in the present regarding climate policy and socioeconomic development influence climate change, food insecurity and societal collapse?"

The third body of literature establishes the 15 RCP-SSP-SPA framework scenarios as a basis for conducting climate change impact analyses for comparative exploration of climate policy and socioeconomic development in the present. However, existing explorations of decision factors on the risk of starvation, as it pertains to human suffering and societal collapse, have provided insights limited to global and regional trends under select scenarios with limited coverage of the century.

To address this gap, the refined research objective for the third investigation is to explore the influence of climate policy and socioeconomic development decision factors on the risk of starvation and manifestation of global climate injustice under the 15 RCP-SSP-SPA framework scenarios, accounting for climate change impacts on agriculture at global scale and national granularity, through to 2100.

[blank page]

Chapter 3

The past: documenting complex evidence of climate change, food insecurity and societal collapse in contemporary society

The complexity of contemporary society is unprecedented. Fragile interdependencies may see localised climate change events trigger system wide catastrophes, but these causal pathways remain clouded. This chapter contains the first investigation of the three-part research framework (see Chapter 1), prompted by RQ1: *How can systematically documenting historical evidence improve our understanding of the complex risk landscape of climate change, food insecurity and societal collapse?* Addressing the refined research objective (see Chapter 2) of this investigation, Section 3.1 documents the methodology implemented to identify an empirical evidence base of climate change, food insecurity and societal collapse in contemporary society using the societal collapse determinants as proxies and structure this evidence base using a causal loop diagram (CLD) defined at global scale and national granularity. Section 3.2 presents the results from implementing this methodology. Section 3.3 provides a discussion of the results. Section 3.4 summarises key findings of this investigation in reflection of RQ1.

3.1 Methodology

An overview of the investigation concept is provided (Section 3.1.1). The process for establishing an empirical evidence base (Section 3.1.2) and constructing a novel format CLD (Section 3.1.3) of climate change, food insecurity and societal collapse in contemporary society is documented. Aspects of

validation, verification and interpretation are recorded (Section 3.1.4). Key assumptions, and implicit limitations, are noted throughout for consideration alongside relevant methodological information.

3.1.1 Investigation concept

This investigation involved a two-stage methodology, consisting of five steps. The first stage establishes an empirical evidence base of climate change, food insecurity and societal collapse in contemporary society based on a literature search leveraging the societal collapse determinants derived in Chapter 2 as proxies. The second stage involves structuring this evidence base using a novel format CLD, which visually documents the relationships between variables in a complex system using a simple approach of nodes to represent variables, arrowed lines to represent links between variables and positive or negative notation to denote the direction of relationship between two linked variables (Randers 2000). An overview of the methodology is presented graphically in Figure 3.1 for context. For each stage of the methodology described below, each step is first outlined generically and then specifically described in terms of its application to this investigation of climate change, food insecurity and societal collapse.

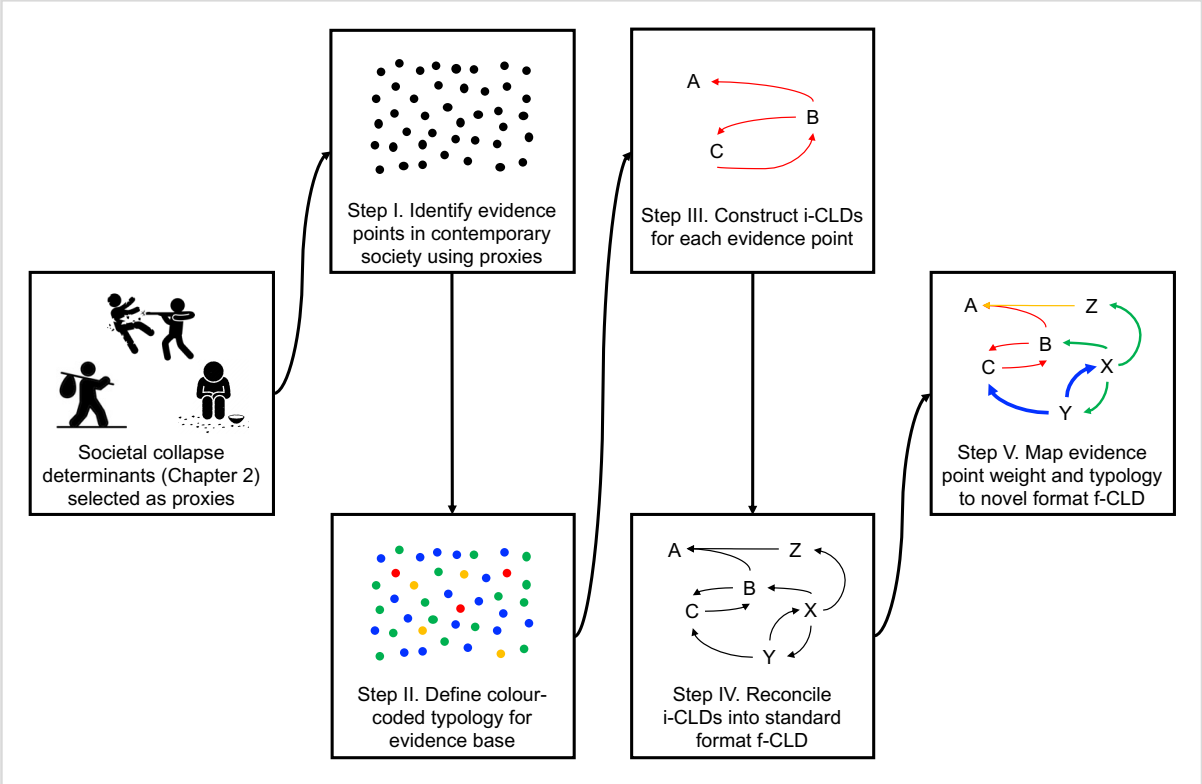


Figure 3.1: Methodology overview for the first investigation (RQ1) of the three-part research framework.

3.1.2 Establishing an empirical evidence base in contemporary society

Step-I deploys the societal proxies via a key word search to identify 'evidence points' of societal collapse danger signs in contemporary society, in lieu of actual events of societal collapse in recent history. In this instance, 'evidence points' may be considered data points, in the form of publications that empirically examine the causal pathway of interest in contemporary society.

The primary and secondary determinants of societal collapse defined in Chapter 2—namely, *population loss* via natural *mortality, conflict mortality* and *emigration*, and *institutional breakdown* via *sociocultural unrest, economic loss* and *political dysfunction*—provide these proxies. The *population loss* set are straightforward to isolate, consistent to measure across nations and describe tangible consequences, while the *institutional breakdown* set are relatively less so. Therefore, this investigation adopted only the population loss set of determinants, namely: *natural mortality* (i.e., starvation, with respect to food insecurity), *conflict mortality* and *emigration*. Key words were selected based on typical terminology of climate change, food insecurity and the societal collapse proxies. Peer-reviewed journal articles from a single academic database, rather than books and reports, were assumed to provide a good representation of the current state of research and thus chosen as the single form of evidence point.

The keyword search was performed in Scopus. A record of the search is contained in Appendix A. Over 3,000 publications were reviewed by reading the title, abstract and main body as needed. Evidence points were selected based on satisfaction of the following criteria: the publication (a) is a peer-reviewed, English-language, journal article; (b) uses empirical, data driven methods; (c) examines the period from 1990 to present (2019), assumed representative of contemporary society; and (d) primarily examines the causal pathway of interest. An exception to (a) was made to include the most recent *Limits to Growth* book (Meadows et al. 2004), which was not itself a search result but documents the World3 model that was identified in the search results. It should be noted that (b) precluded selection of review or essay-style publications; however, these were found to be often discussed in the literature review of selected evidence points, so were, nonetheless, accounted for indirectly.

This step resulted in a new empirical evidence base consisting of 41 evidence points, which are presented in Section 3.2.1.

Step-II defines a custom colour-coded typology for the new empirical evidence base. This typology is used in Section 3.1.3, to construct a novel format CLD showing the spread of the evidence base across the system.

The methodological spread is of interest as this provides information on research methods and data that may be useful for future studies. Four methodological categories were identified in the new empirical evidence base. Each evidence point was classified into one of these categories and assigned a colour coding, namely: quantitative complex systems model - red; statistical analysis of quantitative dataset - blue; collection / analysis of qualitative interview / survey data - green; quantitative data-led case study / scenario - yellow.

The typology of the new empirical evidence base resulting from this step is presented in Section 3.2.1.

3.1.3 Constructing a novel format causal loop diagram

Step-III involves creating an individual CLD (i-CLD) for each evidence point to give visual structure to the complex causal relationships examined. These i-CLDs provide the building blocks from which to construct the final CLD (f-CLD) in *Step-IV*.

The process to create an i-CLD is as follows. The corresponding evidence point was examined in its entirety to identify and record key information in the form of variables (nodes), links (arrowed lines) and relationship notation (positive or negative). Key information derived from the original data-driven content, i.e., the main analysis, of the evidence point was colour coded (red, blue, green, yellow) in the i-CLD according to the typology established in *Step II*. Any relationships hypothesised but not supported by the main analysis were coloured grey. Key information derived from other content, i.e., the literature review, of the evidence point was coloured black. The scale and granularity of the i-CLD was recorded as detailed in the evidence point. This process was repeated for each evidence point in isolation until a complete set of i-CLDs was produced for the new empirical evidence base.

All 41 i-CLDs created in this investigation are contained in Appendix A. One of the i-CLDs is shown in Figure 3.2 as an example.

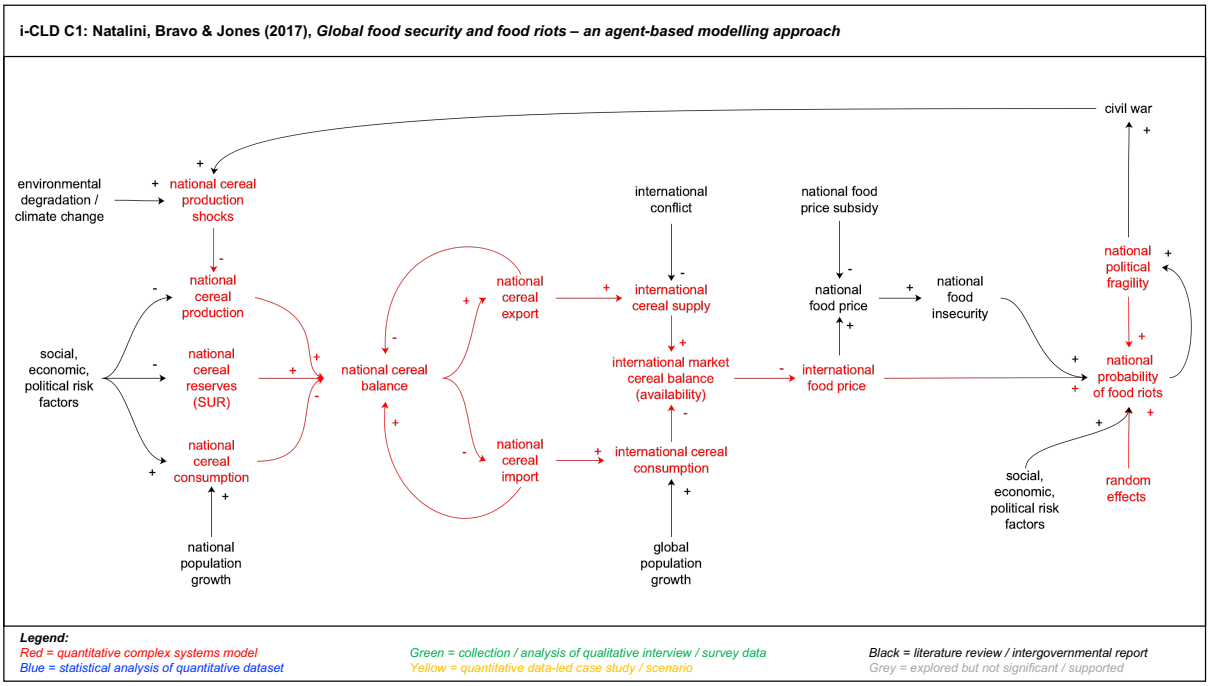


Figure 3.2: One of the i-CLDs created for each of the 41 evidence points in the new empirical evidence base of climate change, food insecurity and societal collapse in contemporary society. The 'node' text describes the variable, the arrowed lines represent a directional 'link' between variables, and the positive (+) and negative (-) notation defines the 'relationship' between two linked variables by indicating that they change in the same direction or opposite direction respectively. The information derived from each evidence point is colour-coded based on a custom-typology; in this example, the evidence point described a quantitative complex systems model (red), with supporting literature review (black) noting additional variables of relevance not explicitly defined in the model.

Step-IV reconciles the set of i-CLDs into a standardised format to construct the f-CLD of the system of interest at the desired scale and granularity.

The standardisation process has two aspects. One aspect is related to component (variables and links) definition, necessary to maximise clarity of the f-CLD while covering all information contained in the evidence base. This addresses the typical challenge of CLDs becoming dense and overcomplicated, which decreases their utility. The other aspect is related to level of aggregation, necessary to ensure the f-CLD conveys information at the intended scale and granularity. The standardisation is an iterative process, as follows.

The ~950 variables from the set of 41 i-CLDs were recorded on a blank worksheet (using edraw (2020) software) for the f-CLD, without links between them. A clustering approach was used to reconcile these variables into like groups. For each group, an overarching major node was isolated and the i-CLD variables in the group were virtually deposited into a matrix for that major node. For example, *drought, sea level rise* and *crop disease* were some of the i-CLD variables clustered into an 'environmental risk factors' f-CLD major node matrix. The f-CLD major nodes were defined at a level of aggregation representative of a nation in line with the objective of this investigation. Doing so effectively scaled

down any global or regional aggregation, and scaled up any sub-national or local aggregation, in the i-CLD variables. For example, *household food imports* was an i-CLD variable of local aggregation scaled up to *national food imports (trade)* in the f-CLD.

The ~1150 links from the set of 41 i-CLDs were reconciled into arrowed lines between the major nodes in the f-CLD. This sometimes-required interpretation of implied causality in the i-CLD relationships to route them across the major nodes in the f-CLD. For example, where an i-CLD showed a direct link from *international food price* to *conflict* variables, this was routed using arrowed lines from *international food price* to *national food price* to *food accessibility* to *food insecurity* and finally to *conflict* major nodes defined in the f-CLD. Where there was a discrepancy between relationship descriptions, the relationship with the majority of supporting i-CLDs was adopted.

The interim f-CLD produced at the end of each standardisation iteration was examined to determine whether the major node definition could be refined to maximise clarity. For example, in one iteration *water* and *land* were defined as separate major nodes, but examination determined that each had the same arrowed lines to other major nodes; therefore, another iteration was undertaken with *water* and *land* now clustered under a single *natural resources* major node to minimize redundant arrowed lines. This process was iterated several times until an f-CLD had been constructed at an appropriate level of detail for the objective of this investigation.

The standard-format f-CLD, consisting of un-coloured and un-weighted components, resulting at the end of this step is contained in Appendix A.

Step-V maps each i-CLD to the f-CLD using a custom weighted (line thickness) typology (line colour). This visually documents the spread of the evidence base across the system described by the f-CLD.

The process to map an i-CLD to the f-CLD is as follows. Each variable (node) of the i-CLD was assigned to its corresponding major node(s) in the f-CLD. Each link (arrowed line) of the i-CLD was assigned to its corresponding route along the arrowed lines in the f-CLD. Each time an arrowed line in the f-CLD had an i-CLD link assigned to it, an incremental weighting of one-unit line thickness in the corresponding typology colour-coding of the i-CLD link was added to the f-CLD arrowed line. This process was repeated for each of the 41 i-CLDs until all had been mapped to the f-CLD. A record of this process for each of the 41 i-CLDs is contained in Appendix A.

The novel format f-CLD, consisting of colour-coded and weighted components, resulting at the end of this final step is presented in Section 3.2.2.

3.1.4 Validation, verification and interpretation

The activity of validating, verifying and interpreting a model, including qualitative models such as CLDs, varies depending on its purpose (Edmonds et al. 2019). The f-CLD produced in this investigation is illustrative in purpose, meaning that care in interpretation, more so than validation and verification, is most important. Each aspect is addressed in turn below.

The f-CLD was produced by systematically documenting the information contained in empirical studies of climate change, food insecurity and societal collapse. To this end, the f-CLD is internally validated to the extent that it was produced based on empirical evidence, rather than, say, a thought experiment. It is important to recognise that the f-CLD may show negligible empirical evidence point density for important links or even be missing important variables and/or links for three reasons. Firstly, because those links and/or variables have not yet been studied. Secondly, because the empirical evidence points on those links and/or variables were excluded by the scope of this investigation on the climate change, food insecurity and societal collapse process mechanism. Thirdly, because the empirical evidence points on those links and/or variables were excluded by the scope of this investigation on the *population loss* set of societal collapse proxies rather than the *institutional breakdown* set. This methodology attempted to maximise rigour and transparency by documenting the spread of empirical evidence base to help make the reader aware of how much and what type of evidence was supporting the f-CLD.

The logic of the information contained in the f-CLD was verified through iterative methodological cross-checks by the author as well as peer-review. It is important to appreciate that CLDs are only as good as their information inputs (Cernev and Fenner 2020), which leads to several verification related issues. CLDs may mask variability of relationships in different contexts and locations because they can only depict a single scale and granularity. The portrayal of explicit causality between variables in a CLD is a challenge as this can often work in both directions rather than one. CLDs can often become either too complicated or too simplified, which undermines their usefulness. In considering each of these issues, the methodology attempted to maximise the rigour and transparency of this investigation by first documenting the information in each evidence point with an i-CLD and then consistently applying, and recording, the iterative process of reconciling the variables and links from each i-CLD to construct the f-CLD at the selected global scale and national granularity. This methodology sought to make the reader

aware of the nuances of the different scales and granularity of information underpinning the f-CLD, as well as the process of carefully reconciling over 950 variables to 39 variables and 1150 links to 105 links to maximize the information conveyed while balancing readability.

In interpreting the information contained in the f-CLD, the reader should be mindful of the fact that the f-CLD is based on the author's interpretation and original quality of the information contained in the empirical evidence base, as well as the methodological scope of this investigation. It is important to note that, as expected given the objective of this investigation, the f-CLD shows no empirical evidence linking the proxies of *starvation, conflict* and *emigration* to *societal collapse*. This does not mean that such a relationship does not exist but, rather, is due to the fact that there are no contemporary events of societal collapse, under the same definition as those in the historical studies pre-dating contemporary society, that enable these links to be empirically studied (Beard et al. 2020).The reader should also be mindful of the fact that, due to its qualitative and static nature, the f-CLD does not facilitate comprehension of the dynamics of the system, including nonlinear and emergent behaviour, non-intuitive quantitative results and time delays (Sterman 2011).

3.2 Results

This section presents the results from implementation of the methodology. The new empirical evidence base (Section 3.2.1) and novel format CLD (Section 3.2.2) of climate change, food insecurity and societal collapse in contemporary society are presented. The results are described below, before moving into a contextualised discussion in Section 3.3.

3.2.1 New empirical evidence base

The new empirical evidence base (*Step I*), along with its colour-coded typology (*Step II*), is presented in Figure 3.3. It consists of 41 evidence points, of which 9 examine the *natural mortality* (i.e., *starvation*, with respect to food insecurity), 20 the *conflict mortality* and 12 the *emigration* societal collapse proxy, alongside other human and natural world system factors. Figure 3.3 summarises characteristics of each evidence point, including its label, the data-drive method typology classification, study reference and temporal and spatial scale and granularity of the study. Three aspects of the evidence base, namely temporal distribution, spatial distribution and data-driven method distribution are described below.

#	Proxy Examined	Typology Classification	Evidence Point Reference	Spatial Scale	Spatial Granularity	Temporal Period	Temporal Granularity
N1	Natural mortality	Model (SDM)	Meadows et al, 2004	Global	Global	1900-2100	Yearly
N2		Statistical analysis	Agboola, 2017	Global (114 countries)	National	1995-2009	Yearly
N3			Lee et al, 2016	Global (95 countries)	National	2001-2011	Yearly
N4		Interview/survey	Campbell et al, 2009	Indonesia	Sub-national	2000-2003	Period
N5			Fledderjohann et al, 2016	India	Sub-national	2002-2008	Period
N6			Gundersen et al, 2018	Canada	Sub-national	2005, 2007-2010	Period
N7			Nandy et al, 2016	Nigeria, Ethiopia	Sub-national	2000-2013	Yearly
N8			Sati & Vangchhia, 2016	India	Sub-national	2014	Period
N9			Walker et al, 2019	USA	National	2003-10	Period
C1	Conflict mortality	Model (ABM)	Natalini et al, 2017	Global (213 countries)	National	2005-2017	Monthly, yearly
C2		Statistical analysis	Arezki & Brueckner, 2014	Global (60 countries)	National	1970-2007	Yearly
C3			Bellemare, 2014	Global	Global	1990-2011	Monthly
C4			Berazneva & Lee, 2013	Africa (14 countries)	National	2007-2008	Period
C5			Caruso et al, 2016	Indonesia	Sub-national	1993-2003	Yearly
C6			Hendrix & Haggard, 2015	Africa, Asia (49 countries, 55 cities)	Sub-national	1961-2010	Yearly
C7			Jones et al, 2017	Africa	National	1991-2011	Monthly
C8			Koren & Bagozzi, 2016	Global	0.5×0.5 deg.	1991-2008	Yearly
C9			Maystadt et al, 2014	Global (arab world vs rest of world)	National	1960-2010	Yearly
C10			Natalini et al, 2015	Africa, Asia, MiddleEast (25 countries)	National	2005-2011	Monthly, yearly
C11			Newman, 2018	Global (79 countries)	National	2005-2015	Yearly
C12			Pinstrup-Andersen & Shimokawa, 2008	Global (146 countries)	National	1980-2005	Yearly
C13			Raleigh et al, 2015	Africa (24 countries, 113 markets)	Sub-national	1997-2010	Monthly
C14			Smith, 2014b	Africa (40 countries)	National	1990-2012	Monthly
C15			van Weezel, 2016	Africa (45 countries)	National	1990-2011	Monthly
C16			Weinberg & Bakker, 2015	Global (71 countries)	National	1972-2007	Yearly
C17			Wischnath & Buhaug, 2014	India	Sub-national	1980-2011	Yearly
C18		Interview/survey	Legwegoh et al, 2015	Cameroon	Sub-national	2008	Period
C19		Data-led/scenario	Lunt et al, 2016	Global	National	2016	Period
C20			Sternberg, 2012	Global (Egypt, China)	National	2010-2011	Period
E1	Emigration	Model (ABM)	Smith, 2014a	Tanzania	Sub-national	2012-2050	Period, yearly
E2		Interview/survey	Afifi et al, 2014	Tanzania	Sub-national	2012	Period
E3			Etzold et al, 2014	Bangladesh	Sub-national	2011	Period
E4			Jacobson et al, 2019	Cambodia	Sub-national	2016	Period
E5			Milan & Ho 2014	Peru	Sub-national	2011	Period
E6			Milan & Ruano, 2014	Guatemala	Sub-national	2011	Period
E7			Murali & Afifi, 2014	India	Sub-national	2011	Period
E8			Panter-Brick & Eggerman, 1997	Nepal	Sub-national	1996	Period
E9			Rademacher-Schulz et al, 2014	Northern Ghana	Sub-national	2011	Period
E10			Warner & Afifi, 2014	Global (S/SEAsia, SSAfrica, LatAm)	Sub-national	2011-2012	Period
E11		Data-led/scenario	Doos, 1994	Global	Global, national	1990-2025	Yearly
E12			Puma et al, 2018	Global	National	2011-2018	Yearly

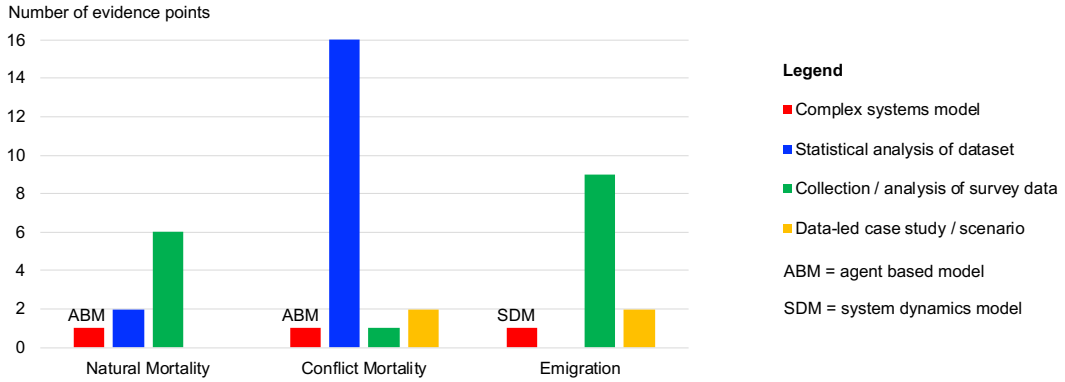


Figure 3.3: Summary and custom colour-coded typology of the new empirical evidence base of climate change, food insecurity and societal collapse in contemporary society.

The temporal scale and granularity of study varies across the evidence base. It should be noted that the methodology limited the possible scale of study to the period from 1990 to present, representative of contemporary society. Within this period, approximately half of the evidence points cover a scale of less than one decade and the other half a scale of greater than one decade. Approximately half of the evidence points conduct analyses at yearly granularity and the other half conduct analyses at granularity greater than one year, with only a few studies conducting analyses at monthly granularity.

The spatial scale and granularity of study varies across the evidence base. Approximately one third of the evidence points investigate the system at a global scale, with the remaining two thirds focusing on regional or national scales, primarily in Africa as well as the Middle East and Asia. Approximately half of the evidence points analyse the causal pathway at sub-national granularity, with the other half primarily focusing on national-level granularity.

The distribution of data-driven methods in the evidence base is different for each societal collapse proxy. Evidence points for *natural mortality* mostly use collection/analysis of interview/survey data. This is because the minimum daily food intake for human survival is well established (FAO 2004). As such, statistical analysis of food and mortality data sets would not yield significantly new insights into thresholds whereas interviews/surveys provide insight into an individual's circumstances influencing this relationship. Evidence points for *conflict mortality* mostly use statistical analysis of existing datasets. This reflects interest in rigorously curated conflict datasets, such as by UCDP & PRIO (2019), across the conflict and peace fields. Evidence points for *emigration* mostly use collection/analysis of interview/survey data. This is because such data provides nuanced insight into an individual's decision to migrate. It also reflects data availability and quality challenges that limit quantitative statistical analyses, which are being addressed by groups such as IOM GMDAC (2019). These data challenges crease issues in reconciling different types of voluntary and forced migration with causal drivers, given the complex social, economic and political factors at play. These challenges may similarly apply to the other societal collapse proxies but are particularly noted in the migration studies. Within the evidence base, a food insecurity threshold for *natural mortality* is well established but thresholds for *conflict mortality* and *emigration* are not. Indeed, distinguishing causal drivers within datasets and defining quantitative thresholds for these determinants remains a 'grand challenge' (Kintigh et al. 2014).

The temporal, spatial and data-driven method variation across the new empirical evidence base provided different coverage of the complex relationships within the climate change, food insecurity and societal collapse system documented, which was informative for constructing the CLD.

3.2.2 Novel format causal loop diagram

The main result of this investigation is the CLD (the f-CLD from *Step V*), presented in Figure 3.4. It systematically documents information from the new empirical evidence base to clearly structure the complex relationships of climate change, food insecurity and societal collapse in contemporary society

at global scale and national granularity. Two aspects of the CLD, namely, the standard format conventions and the novel format conventions, are described below.

In standard format convention, the CLD depicts variables, links and notation. Variables are represented as nodes in five different shapes. Hexagons represent natural sub-system variables. Rectangles represent food sub-system variables at the natural-human system interface. Circles represent human population sub-system variables. Diamonds represent human institutional and infrastructure/service variables. Triangles represent primary societal collapse determinants. Links between variables are represented with arrowed lines, indicating the direction of the relationship. Each link has positive (+) or negative (−) notation, indicating that the two variables change in the same direction or opposite direction, respectively. For example, the relationship between *births* and *population* is positive, meaning that an increase in *births* results in an increase in *population*.

In novel format convention—originally created in this investigation—the CLD depicts the type and relative density of data-driven methods of the empirical evidence, from which the CLD was constructed. Where a link between two variables has been examined by an empirical evidence point, the type of data-driven method employed is depicted by line colour. Red lines represent quantitative complex systems models. Blue lines represent statistical analyses of quantitative datasets. Green lines represent collection / analyses of qualitative interview / survey data. Yellow lines represent quantitative data-led case studies / scenarios. The relative density of the number of empirical evidence points examining a link between two variables, is depicted by line thickness. For example, the link between *food insecurity* and *conflict* has mainly been examined using statistical analysis of quantitative datasets, while the link between *food insecurity* and *natural mortality* has been examined to a lesser extent and mainly using collection / analysis of qualitative interview / survey data.

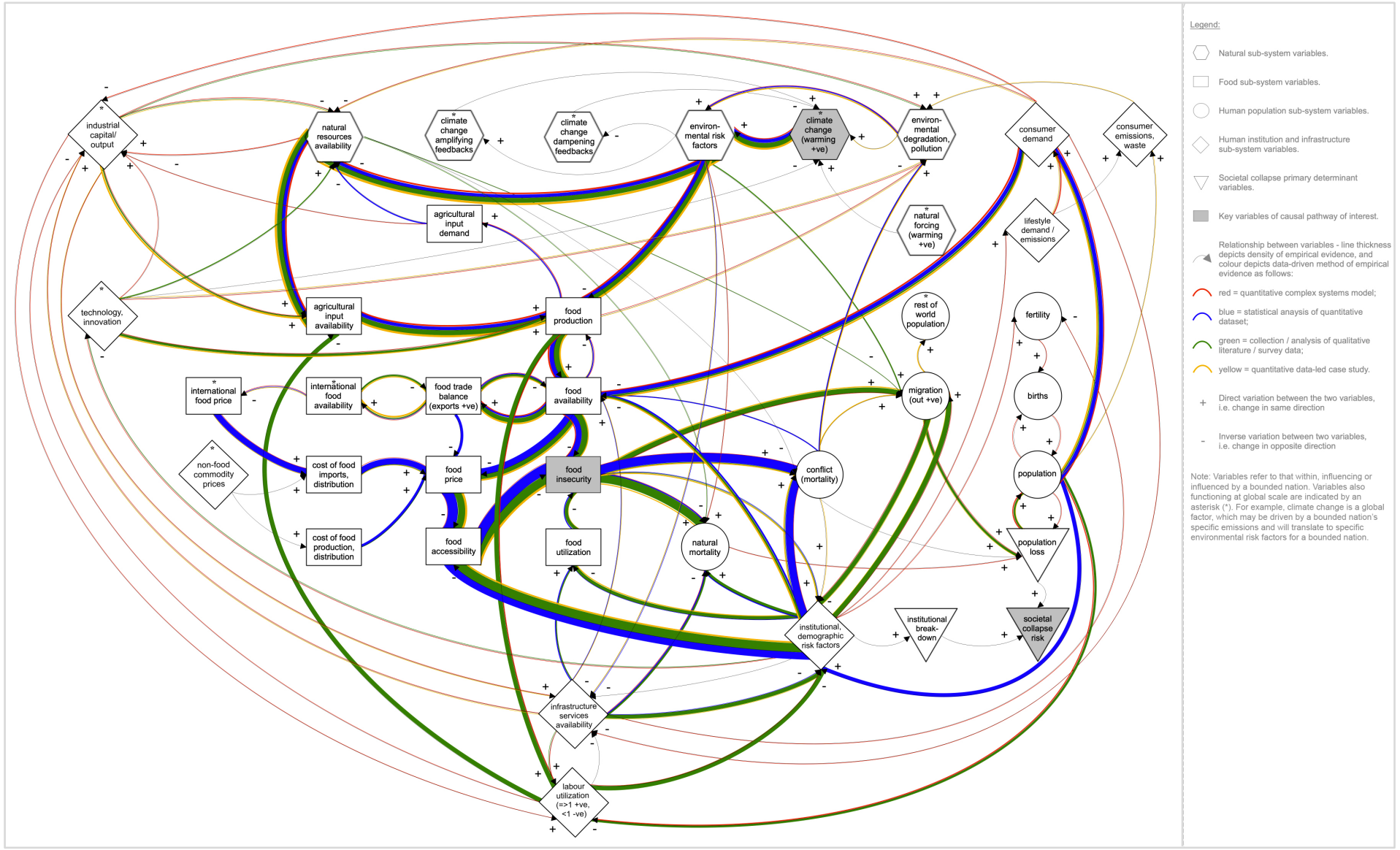


Figure 3.4: Novel format causal loop diagram of climate change, food insecurity and societal collapse in contemporary society at global scale and national granularity. Variables are depicted as nodes in five different shapes, indicating different sub-systems. Links between variables are depicted as arrowed lines, indicating the direction of the relationship. Each link has positive (+) or negative (−) notation, indicating that the two variables change in the same or opposite direction, respectively. The density and type of data-driven method of the empirical evidence base, from which the causal loop diagram was constructed, are depicted by line thickness and colour, respectively.

3.3 Discussion

This section explains the results in two themes. Insights into the complex risk landscape of climate change, food insecurity and societal collapse depicted by the CLD are discussed (Section 3.3.1). Insights into the spread of empirical evidence detailing the CLD are then considered (Section 3.3.2).

3.3.1 Understanding the complex risk landscape depicted

CLDs present a myriad of information in a simple diagram, enabling efficient consideration and communication of the structure and behaviour of complex systems (Sterman 2011). In doing so, they provide an effective tool for better stakeholder engagement, including interdisciplinary collaboration and cooperation in considering the problem and designing solutions (Coletta et al. 2021). In particular, the CLD constructed in this investigation offers utility in combining multidisciplinary data to highlight far-reaching interdependencies, feedbacks and intervention points, addressed in turn below.

The CLD presented in Figure 3.4 covers 39 variables, 105 links and 32,000 feedback loops (calculated using Ventana Systems Inc. (2019) software). It integrates information from different fields, including climate science, food security, conflict, migration and health research, to succinctly depict the complex risk landscape of climate change, food insecurity and societal collapse in contemporary society at global scale and national granularity, which would otherwise require tomes of text.

Walking through the CLD presented in Figure 3.4, it is evident that *population* growth and *lifestyle emissions*, influenced by *institutional/demographic factors* (e.g., emission reduction incentives), combine to directly drive *climate change*. Similarly, they indirectly drive *climate change* via *consumer demand* on *food production*, which produces emissions directly (e.g., ruminant livestock) and indirectly via *industrial capital/output* (e.g., processing factories). The *environmental risk factors* (e.g., extreme weather events) of *climate change* may cause losses of *food production* either directly (e.g., plant disease) or indirectly via *agricultural input availability* (e.g., loss of water source for irrigation). A country's *food availability* is influenced by domestic *food production* and international *food trade*. *Food accessibility* is influenced by *food price*, which responds to domestic (e.g., *cost of food production and distribution)* and international (e.g., *international food price)* markets, and *institutional/demographic factors* (e.g., food subsidies). *Food utilization* is influenced by *infrastructure/services* (e.g., education) and *institutional/demographic factors* (e.g., cultural traditions). *Food insecurity* is underpinned by these three pillars of *food availability, food accessibility* and

food utilization. For a given country, *food insecurity* can drive *natural mortality* (i.e., starvation), *conflict* and *migration*, contributing to *population loss,* as well as economic shocks and socio-political instability, contributing to *institutional breakdown,* which exacerbates the risk of *societal collapse*.

This synthesis of multidisciplinary data highlights how the fragile interdependencies of today's highly interconnected society may see localised events trigger system wide catastrophes (Vespignani 2010). For instance, a localised climate change event in isolation may cascade across a nation by damaging critical food, water, energy and transportation infrastructure (Buldyrev et al. 2010). Such damage may further cascades to impact individuals, utility companies, the banking and insurance sectors and government, as evidenced with increasing extreme weather events in New Zealand (Lawrence et al. 2020). A climate change event may also cascade as a threat multiplier (Below 2019), as evidenced by drought induced crop failures in China cascading through increased international food prices to exacerbate sociocultural unrest in countries during the Arab Spring (Sternberg 2012). Additionally, synchronous failures may arise where an isolated climate change event simultaneously impacts multiple 'breadbaskets', leading to a global food system collapse (Gaupp et al. 2020), triggering institutional breakdown, starvation, migration and conflict, ultimately leading to societal collapse (Mehrabi 2020).

Further to illuminating the climate change, food insecurity and societal collapse mechanism, including the direct and indirect relationships at play, the CLD also succinctly unfurls critical balancing and reinforcing feedbacks. For example, it highlights the stark contrast between the relatively certain balancing loops of self-regulating supply-demand response within the human system, such as in the international food market, and the relatively uncertain reinforcing loops bridging the natural and human systems, such as the amplifying feedback of forest dieback on climate change, that may dangerously exacerbate this mechanism. Delving into these feedbacks highlights potential for the occurrence of systemic lock-in as well as intervention points.

For instance, beyond a given country suffering increased *natural mortality*, famines (i.e., *food insecurity*) can place pressure on international humanitarian efforts (i.e., *institutional risk factors*). *Conflict* may occur domestically or internationally and can feedback to exacerbate *food insecurity* and institutional fragility (i.e., *institutional risk factors*). Potential mass *emigration* can increase pressure on *food availability*, *natural resources* and *infrastructure/services* in the destination nation, which can lead to socio-cultural tensions (i.e., *institutional risk factors*) that further fuel *conflict*. *Food insecurity* can also directly contribute to *institutional risk factors* such as social unrest, political instability and economic inequality, which increase the risk of *societal collapse*. This systemic lock-in mode of *institutional breakdown* can feedback to undermine capacity

of socio-politico-economic governance structures to respond to the threat of *climate change* and intervene *food insecurity*. Evidently, it is shown that, once triggered, the climate change, food insecurity and societal collapse mechanism may enter a reinforcing 'global systems death spiral' (Beard et al. 2021).

The 'switching' nature of some feedback loops, with respect to increasing complexity both increasing and decreasing contemporary society's resilience and vulnerability to climate change (McMichael 2012), along with the concepts of interventions 'backfiring' and having 'unintended consequences' is also clearly illustrated. For example, improvements in technology can increase resilience of food production through novel enclosed agriculture systems (Tzachor et al. 2021). However, technology may also increase vulnerability through "termination shocks" where failure of the technology, such as geoengineering, exposes society to sudden temperature increases that otherwise would have been gradual (Morton 2016). Similarly, globalisation can increase resilience of societies to local agricultural production shocks via recovery through access to global markets (Davis et al. 2021). However, globalisation can also increase vulnerability through exposure to sudden reversal in connectivity, such as food trade restrictions (Tu et al. 2019). This illustration provides insights into the nature of intervention points in a complex socio-technical system where there is rarely a single 'silver bullet' solution. Robust governance of both technological and socio-politico-economic mitigative and adaptive measures to build resilience and decrease vulnerability will likely be necessary to intervene the climate change, food insecurity and societal collapse mechanism toward humanity's 'existential security' (Sears 2020).

3.3.2 Understanding the spread of empirical evidence depicted

The novel format of the CLD in Figure 3.4 provides unique insights into the spread of the empirical evidence base detailing the complex risk landscape of climate change, food insecurity and societal collapse in contemporary society. This discussion addresses aspects of identifying gaps in existing empirical analyses and improving existing complex models in turn below.

Depicting the spread of empirical evidence across the complex risk landscape documented allows comprehension of where existing work has been focused. It also facilitates identification of gaps in existing analyses. For example, it is evident that the link between *food insecurity* and *conflict* has been investigated mostly by evidence points using statistical analyses (blue), whereas the links between *food insecurity* and *migration,* and *food insecurity* and *natural mortality*, have been investigated mostly by evidence points using interviews/surveys (green). This hints that it may be useful to investigate the former using

quantitative statistics, and the latter using qualitative interviews/surveys, to gain additional insights offered by the different data-driven methods.

Each data-driven method embodied in the new empirical evidence base offers different advantages. The complex systems models each describe 'chunks' of the system at different scale and granularity. The models provide mathematical definition, are calibrated to real-world data and enable quantitative simulation of key relationships in the system. The statistical analyses quantitatively examine relationships between a dependent variable and one or more independent variables within the system, which can be used as a mathematical basis for extending modelling capabilities. The collection/analysis of interview/survey data provides insight into qualitative aspects of human perspective and decision-making that quantitative data sets cannot provide directly. The data-led case study/scenarios combine quantitative data with qualitative expert interpretation to better understand global trends and forecasts. These latter two methods can also be used to inform the development of modelling capabilities, the scenarios analysed by such models and their application in decision-making processes. Collectively, these different data-driven methods can yield useful insights into the nuances of the complex risk landscape of climate change, food insecurity and societal collapse.

Turning to complex systems models specifically, it is evident from the CLD that their application is relatively limited. While CLDs provide succinct qualitative depictions, complex systems models provide an opportunity to extend beyond this by quantitatively analysing the dynamics of the system depicted to gain insights into the potentially far-reaching impacts of our decisions (Sterman 2000).

Data from the empirical evidence base, and information contained in the CLD, may be useful for improving existing complex systems modelling capabilities to examine the complex risk landscape of climate change, food insecurity and societal collapse in contemporary society. Reflecting on the World3 evidence point N1, for example. The CLD highlights important factors at global scale and national granularity that World3 does not incorporate because it is defined at global scale and granularity. World3 does not distinguish heterogenous characteristics of nations, such as distribution of *population* or geographic endowment of *natural resources*. It also does not account for international interactions, such as *food trade*, *conflict* and *migration*. Relatedly, World3 evaluates *societal collapse* only by *natural mortality* (defined by *food availability*, age and pollution) and does not include the other two *population loss* secondary determinants of *conflict* and *migration*, nor the three *institutional breakdown* secondary determinants. While the empirical evidence base may provide useful direction to datasets, quantitative definition of these relationships, particularly in terms of thresholds of food insecurity triggering

institutional breakdown, conflict and *migration*, remains a key challenge of developing complex systems models (Sterman 2002). Nonetheless given that individuals associate with national identity, business governance and policymaking are concentrated at national level, and international interactions underpin the functioning of contemporary society, it would be valuable to model societal collapse risk profiles of different nations to inform the prioritisation and development of intervention strategies.

3.4 Chapter summary: key findings

This investigation established a new empirical evidence base of climate change, food insecurity and societal collapse in contemporary society and structured the evidence base using a novel format CLD defined at global scale and national granularity to satisfy the refined research objective of RQ1.

The new empirical evidence base varies in temporal and spatial distribution of study and in the type of data-driven methods used, including quantitative complex systems models, statistical analyses of quantitative datasets, qualitative analyses of interview/survey data and data-led case study narratives. The CLD provides a succinct visual description of the complex risk landscape of climate change, food insecurity and societal collapse in contemporary society at global scale and national granularity, and of the spread of empirical evidence from which it was constructed. In standard format, it unfurls thousands of feedbacks providing a basis for interdisciplinary collaboration and cooperation. The CLD facilitates understanding of fragile interdependencies, cascading effects and synchronous failures that may see climate change, in isolation or as a risk multiplier, trigger an avalanche of catastrophes. Specifically, it shows how both direct and indirect, and abrupt and gradual, effects of climate change may undermine agricultural systems and disrupt food supply chains, leading to institutional breakdown through economic loss, political dysfunction and sociocultural unrest as well as population loss through starvation, migration and conflict, which may enter a reinforcing 'global systems death spiral'. In illuminating the switching nature of balance and reinforcing feedback loops, the CLD also provides clarity in identifying technological and socio-politico-economic intervention points, including their potential to 'backfire' or have 'unintended consequences', needed to build resilience and decrease vulnerability amongst the unprecedented complexity of contemporary society. In novel format, the CLD facilitates understanding of where empirical studies have focused and identification of gaps in knowledge as well as providing a systematic basis for improving existing complex modelling capabilities, leading into the second investigation in Chapter 5.

Good risk management requires learning from the past. While some of these findings may appear obvious, it is the act of bringing this information, which otherwise would be siloed, together in one place to tell the 'full story' that is of value (Hinkel et al. 2020). The CLD enables consideration of the worst-case impacts of climate change that we want to avoid, communication of transformative narratives of "where we want to go" and identification of interventions toward this desired future. This first investigation of the three-part research framework provides an incremental contribution to knowledge with respect to RQ1, which has broader implications for society discussed in Chapter 6.

Chapter 4

The future: illustrating the international risk landscape of climate change, food insecurity and societal collapse under extreme global warming

Anthropogenic climate change is unprecedented, and the magnitude of its ramifications is uncertain. As greenhouse gas emissions continue to rise, we propel toward tipping points that may see global warming increase from 3°C to over 8°C by 2100, but high-end global warming scenarios have received minimal attention. This chapter contains the second investigation of the three-part research framework (see Chapter 1), prompted by RQ2: *What insights into the future international risk landscape can be gained by illustrating climate change, food insecurity and societal collapse under 'extreme global warming'?* Addressing the refined research objective of this investigation (see Chapter 2), Section 4.1 documents the methodology implemented to develop a quantitative computational model to illustrate the international risk landscape of climate change, food insecurity and societal collapse through to 2100, using World3's BAU-CC scenario as a basis for defining an original 'extreme global warming' scenario alongside up-to-date historical and SSP5-RCP85 projection data to define national granularity characteristics. Section 4.2 presents the results from implementing this methodology. Section 4.3 provides a discussion of the results. Section 4.4 summarises key findings of this investigation in reflection of RQ2.

4.1 Methodology

An overview of the investigation concept, including definition of an 'extreme global warming' scenario, is provided in Section 4.1.1. The process for input data preparation is documented in Section 4.1.2. The model simulation workflow is documented in Section 4.1.3. Aspects of validation, verification and interpretation are documented in Section 4.1.4. Key assumptions, and implicit limitations, are noted throughout to consider them alongside relevant methodological information.

4.1.1 Investigation concept

This investigation involved defining an 'extreme global warming' scenario, preparing input datasets and developing a quantitative model implemented in Python to perform simulations. The model takes a simple approach to exploring climate change, food insecurity and societal collapse at global scale and national granularity under 'extreme global warming'. A graphical overview is presented in Figure 4.1 to show how key components, which are introduced below with italicised text to indicate elaboration on data preparation in Section 4.1.2, and simulation workflow, which is described in 4.1.3, fit together.

To summarise, in each year of simulation, countries produce food based on climate change impacted crop yields. Countries then internationally trade food based on trading power, in attempt to meet the lifestyle food demand of their population. Starvation deaths occur where the resulting food balance does not satisfy the minimum food required for nourishment, which leads to population loss and socioeconomic growth shock feedbacks in subsequent years.

An international trade network consisting of 242 countries (*country list*) was modelled. Each country pair was assigned a constant trade distance *(trade_distance)* from an input dataset. Each country was characterised by four key variables: population; gross domestic product (GDP); lifestyle food demand; and, food production. The model was initialised in 2020 by calculating four key variables for each country based on input datasets: population (*population_historical*), GDP per capita (*gdp_pc_historical*), lifestyle food demand per capita (*food_demand_pc_historical*), food production (*food_production_historical*). Each country was assigned a future growth profile based on SSP5-RCP85, used to calculate the four key variables in subsequent years, defined by respective datasets: population growth (*population_growth*); GDP per capita growth (*gdp_pc_growth*); crop land growth (*food_production_growth_cropland*); crop yield growth under climate change and technological development (*food_production_growth_cropyield*); and, lifestyle food demand per capita growth (*food_demand_pc_growth*).

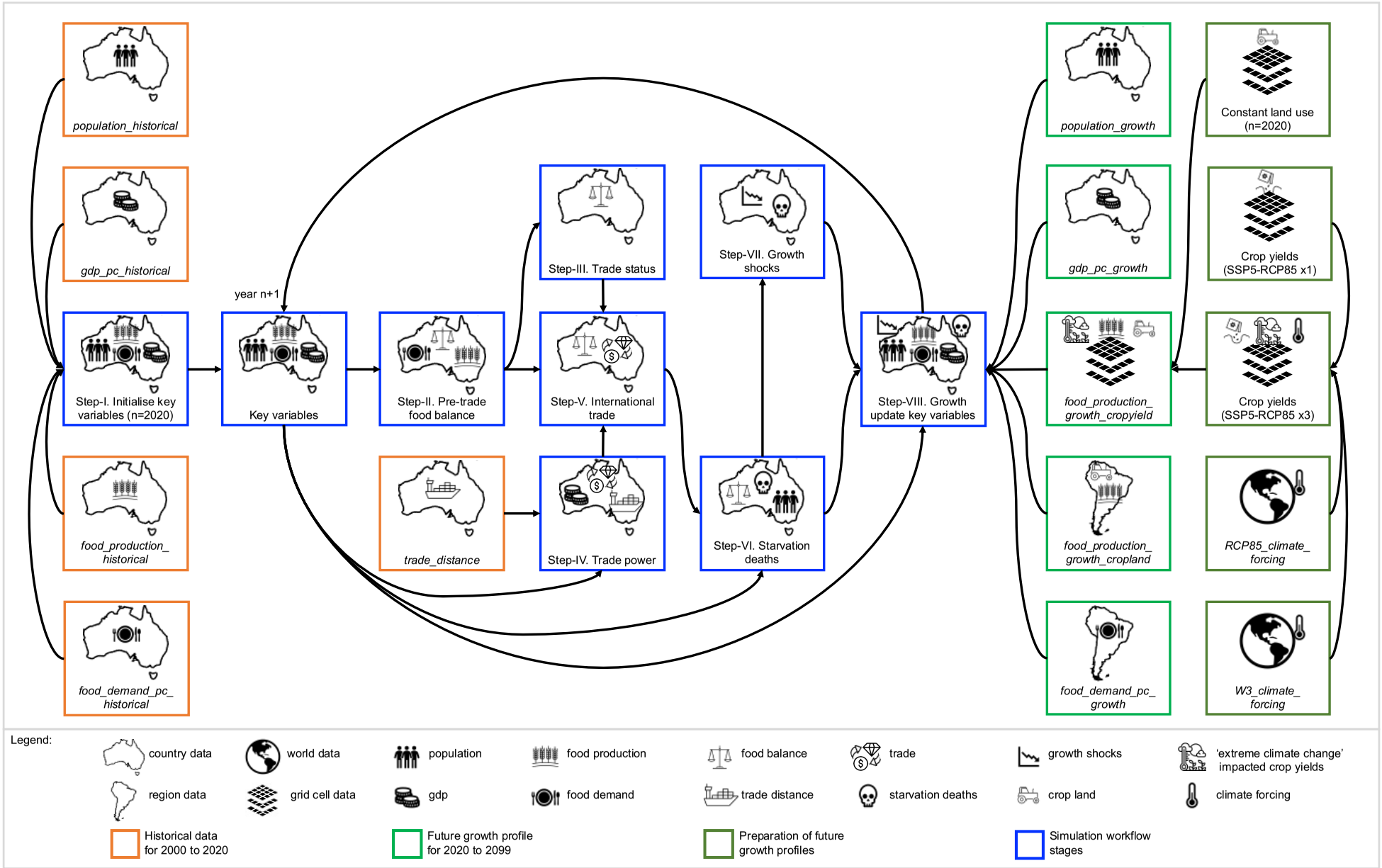


Figure 4.1: Methodology overview for the second investigation (RQ2) of the three-part framework. This shows how input datasets (described in Section 4.1.2) and the simulation workflow (described in Section 4.1.3) fit together. The simulation workflow represents a year 'n' unless otherwise noted.

The results presented in Section 4.2 include the simulation output for 2020 to 2100 and historical data for 2000 to 2020 to provide coverage of the 21st century, alongside World3 BAU-CC outputs (*W3_population, W3_gdp, W3_food_production, W3_food_demand*) for 2000 to 2100 for comparison. The international risk landscape is considered at global, regional and country level, the latter in context of development classification and vulnerability and resilience rankings and scores (*country list)*.

'Extreme' climate change definition

Climate change is considered in the form of temperature effect on crop yields, which is one of many potential impacts. This approach intends to isolate a single impact for transparent physical quantification, with temperature evidenced as the most robust measure of climate change (Hausfather et al. 2020) and its influence on crop yields well studied (Iizumi et al. 2017)

An 'artificial' scenario of 'extreme global warming' was approximated using World3's BAU-CC as a basis for accelerating available crop yield data under the 'natural' SSP5-RCP85 scenario. This involved estimating 'speeding up' and 'extrapolating' factors for *food_production_growth_cropyield* data preparation, which is documented in Appendix B and summarised as follows.

In 'speeding up', the absolute *RCP85_climate_forcing* and *W3_climate_forcing* values were referenced to 2020 as the initial year of the simulation to obtain unitless 'multiplier' values. A 'speeding' up factor of three was then used to 'match' the *RCP85_climate_forcing* 'multiplier' values to the *W3_climate_forcing* 'multiplier' values, which effectively 'compressed' the 'natural' values for 2020–2099 to 2020–2046. In doing this, it was assumed that climate change impacts have been negligible until 2020 in comparison to what may be experienced under 'runaway' global warming through to the end of the century (Goldblatt and Watson 2012). In 'extrapolating', the 2050–2099 'natural' values (i.e. 2037 to ~2046 referencing 'compressed' values) were linearly extrapolated to populate the remainder of the 'artificial' century from 2047 to 2099 (i.e. 2100 to ~2265 referencing extrapolated 'natural' values). In doing this, the last 50 years of 'natural' data, rather than say the whole century or last decade, was used to strike a balance in capturing the increasing rate of climate change influence on crop yields in the latter half of the century. A simple linear approach was taken with the intent of providing a transparent approximation of 'extreme global warming', given the lack of available data and uncertainties surrounding such climate forcing, temperature and crop yield response. Despite the simplicity of this approach, the resulting level of global warming nonetheless falls within comparative likely ranges from detailed climate model simulations of RCP8.5 to 2300 by Tokarska et al. (2016).

This 'artificial' scenario of 'extreme global warming' essentially results in a ~3175 ppm CO_2-equivalent concentration in 2100 (2.6x that of RCP8.5) corresponding to a ~22 W/m^2 climate forcing (R^2=0.9465) and ~10°C global warming (R^2=0.9779), as shown with the results in Section 4.2.

Food insecurity definition

Food insecurity is measured based on food availability, which is one of four pillars of food security defined by FAO (2009), although food accessibility is proxied somewhat in the form of wealth-based trading power. This approach intends to provide a single transparent physical quantification of physical food insecurity, without introducing non-physical factors associated with pillars of accessibility, utilization and stability.

Societal collapse definition

Societal collapse is measured based on starvation related population loss, which is one of two primary determinants of societal collapse defined by Richards et al. (2021). This approach intends to provide a single transparent physical quantification of societal collapse, without introducing non-physical factors associated with the determinant of institutional identity.

4.1.2 Data preparation

The country list and preparation of 16 input datasets introduced in Section 4.1.1 are summarised below. Accompanying details of all data preparation, including calculations and assumptions made for individual countries missing raw data, are provided in Appendix B.

Country list

The model explicitly represents 242 of the 249 countries defined in ISO (2021) standard 3166. Only countries that contain a permanent civilian population were included, given this investigation of societal collapse based on population loss. Each country belongs to one of 17 regions and 22 sub-regions within one of five continents defined by UNSD (2021), and was spatially defined using shape files from (Natural Earth 2021). Each country was classified a 'landlocked developing country' (LLDG), 'small island developing country' (SIDG), 'other developing country' (ODG) or 'developed country' (DVD) as defined by UNSD (2021). Each country was assigned a vulnerability and resilience rank and score based

on the Fragile States Index (The Fund for Peace 2021) and Resilience Index (FM Global 2021). Where raw data underpinning the following input datasets was not readily available for a given country, the characteristic of the country was estimated using region-based averages, rather than excluding the country, with the intent of providing a comprehensive illustration of the international risk landscape.

population_historical

The *population_historical* dataset contains the historical total population, in units of persons, for each country in yearly increments from 2000 to 2020.

Preparation involved processing raw data on population at country-level in yearly increments from UNDESA (2019), including unit conversion as well as research into census data and calculations to estimate missing values for 11 countries.

gdp_pc_historical

The *gdp_pc_historical* dataset contains the historical GDP per capita at purchasing power parity (PPP), in units of constant 2017 international dollars, for each country in yearly increments from 2000 to 2020.

Preparation involved processing raw data on GDP|PPP per capita at country-level in yearly increments from The World Bank (2021a), including unit conversion as well as research into alternate databases and calculations to estimate missing values for 70 countries.

food_production_historical

The *food_production_historical* dataset contains the historical food production, in custom units of energy-equivalent-grain-weight-at-harvest in tonnes, for each country in yearly increments from 2000 to 2020.

Preparation involved processing raw data on primary agricultural production of 128 food crops across eight food crop groups (cereals, fruit, oilcrops, pulses, roots and tubers, sugarcrops, treenuts, vegetables), in at-harvest form, at country-level in yearly increments from FAO (2021). This included derivation of energy-equivalent-grain-weight conversion factors, based on nutritional profile data for each food crop obtained from USDA (2021), to convert the production values for the 128 food crops into a total food production value defined in custom units. Research into significant staple crops for 123

countries missing data for some, but not all, of the eight food crop groups was conducted to inform the total food production values. Region-based averages, scaled by land area, were used to estimate values for 40 countries missing data for all eight food crop groups.

All countries missing data for all food crop groups, even those with negligible traditional agriculture, were assigned a land-scaled quantity of food production. This approach intends to account for countries with small-scale farming, such as Palau and Curaçao, as well as countries that have 100% urban land or a landmass not suited to traditional farming so have recently adopted forms of urban farming, such as Monaco (Morrow 2020), Vatican City (Best 2014) and Gibraltar (Shay and Shay 2017).

Food production is considered only in the form of primary agricultural food crops as defined by FAO (2021). This approach assumes that food crop production provides a reasonable representation of total food production given that crops are staple foods constituting ~90% of the world's food energy intake (Su et al. 2017). Relatedly, food production (and food demand) are referred to in custom units of energy-equivalent-grain-weight-at-harvest for simplicity and consistency, where grains (cereals, oilcrops, pulses) are staple foods providing over 66% of the world's food energy intake (FAO 1995), and "at-harvest" is a particular stage in the global food system (Alexander et al. 2017).

food_demand_pc_historical

The *food_demand_pc_historical* dataset contains the historical lifestyle food demand per capita, in custom units of energy-equivalent-grain-weight-at-harvest in tonnes, for each country in yearly increments from 2000 to 2020.

Preparation involved processing raw data on food supply at-consumption at country-level in yearly increments from FAO (2021), including calculating region-based averages to estimate missing values for 68 countries. These values were converted from units of kilocalories per capita per day to energy-equivalent-grain-weight per capita per day based on a conversion factor derived from nutritional profile data for each grain crop (15 cereals, 21 oilcrops, 11 pulses) obtained from USDA (2021), and converted from units of at-consumption to at-harvest using a conversion factor derived from an analysis of losses (44% from at-harvest to at-consumption) throughout the food supply system by Alexander et al. (2017). Finally, a 'minimum lifestyle food demand' (MLFD) was set, which was derived by calculating a constant global 'average dietary energy requirement' (ADER) from FAO (2021) data and converting to units of energy-equivalent-grain-weight-at-harvest in tonnes, that adjusted values for 83 countries.

It is important to note that values greater than the MLFD reflect an 'excess lifestyle', while values less than MLFD reflect a supply deficit in meeting a 'healthy lifestyle'. This is in contrast to 'minimum dietary energy requirements' (MDER) that defines the caloric intake below which a human is 'undernourished' used in calculating starvation (see *simulation workflow)*. This MLFD approach assumes a globally constant ADER throughout the simulation for simplicity and equality in considering food demand in terms of an 'average human'. In reality, ADER (and MDER) values vary by country and over time depending on the demographics of a given population.

trade_distance

The *trade_distance* dataset contains trade distance, in units of kilometres, between each pair of countries.

Preparation involved processing raw data on trade distance at country-level from Mayer and Zignano (2011), including manual distance measurements in Google Earth (2021) to estimate missing values for 20 countries. Geodesic distances measured between the coordinates of the most populous cities, rather than shipping route distances, were used for simplicity.

population_growth

The *population_growth* dataset contains the SSP5 growth profile for total population, in units of annual average percentage, for each country in yearly increments from 2020 to 2099.

Preparation involved processing raw data on population at country-level in five-yearly increments from IIASA (2018), including calculating growth rates and region-based averages to estimate missing values for 49 countries, and converting values to yearly increments.

gdp_pc_growth

The *gdp_pc_growth* dataset contains the SSP5 growth profile for GDP|PPP per capita, in units of annual average percentage, for each country in yearly increments from 2020 to 2099.

Preparation involved processing raw data on GDP|PPP per capita at country-level in five-yearly increments from IIASA (2018), including calculating growth rates and region-based averages to estimate missing values for 58 countries and converting values to yearly increments.

food_production_growth_cropland

The *food_production_growth_cropland* dataset contains the SSP5-RCP85 growth profile for the land related component of food production growth (i.e. land allocated to food/feed crop agriculture), in units of annual average percentage, for each country in yearly increments from 2020 to 2099.

Preparation involved processing raw data on total crop land and energy crop land at regional-level in ten-yearly increments from the SSP5 marker IAM (REMIND-MagPIE) simulations stored at IAMC and IIASA (2018). The energy crop land values were subtracted from the total crop land values to obtain food crop land absolute values. Food crop land annual growth values were then calculated, and these regional values were converted to yearly increments and assigned to each of the 242 countries.

food_production_growth_cropyield

The *food_production_growth_cropyield* dataset contains a SSP5-RCP85 based growth profile for the crop yield (i.e. climate and technology) related component of food production growth, in units of annual average percentage, for each country in yearly increments from 2020 to 2099.

Preparation involved processing GIS-based raw data on climate impacted crop yields at 0.5°x0.5° grid resolution in yearly increments from Iizumi et al. (2017, 2020) and land use at 0.05°x0.05° grid resolution for a constant base year from Chen et al. (2020). Iizumi et al. (2017, 2020) provided average yield projections for four major crops—namely, maize, rice, soybean and wheat—for both irrigated and non-irrigated conditions under the SSP5-RCP85 scenario. Chen et al. (2020) provided 32 land use categories of which we used the twelve specifying food crop land—namely, maize, rice, soybean and wheat as well as sugarcrops and 'other' food crops, which were assumed to encompass the remaining crops from the eight groups described in *food_production_historical*—under both irrigated and non-irrigated conditions. Crop yield related food production values were calculated for each year in each grid cell as the product of crop yield and land use, using the h3 geospatial indexing system (Uber Technologies 2021) to remedy the influence of distortion inherent in longitude-latitude grid form data. Maize, rice, soybean and wheat crop yields under irrigated and non-irrigated conditions were matched to the corresponding land use category. An average of maize, rice, soybean and wheat crop yields was assigned to the sugarcrop and other crop land use categories, under both irrigated and non-irrigated conditions, in lieu of sugarcrop and other crop yield data. These grid cell values were mapped to the country shape files, and their sum calculated, to obtain country-level values. The 'extreme global

warming' acceleration (see Section 4.1.1) was applied to 'speed up' these 'natural' country-level crop yield related food production values by the factor of three. This effectively compressed the 'natural' values for 2020–2099 to give 'artificial' values spanning 2020–2046. The 2050–2099 'natural' values were linearly 'extrapolated' to populate the remainder of the 'artificial' century from 2047 to 2099. Finally, crop yield related food production annual growth values for each country were calculated from this 'artificial' dataset. Region-based averages were used to estimate missing values for 66 countries.

It is important to note that crop yields from Iizumi et al. (2017, 2020) include climate change impacts on crop yields under RCP8.5 as well as the influence of technology on crop yields based on SSP5. Firstly, due to the nature of the data, it was not possible to separate the climate change and technology impacts, preventing application of socioeconomic growth shocks to technological development in the simulation workflow and meaning that technological development is also 'sped up', which effectively offsets or enhances negative or positive climate change impact. Secondly, the SSP5 marker IAM (Kriegler et al. 2017) calculates cropland development (used in *food_production_growth_cropland)* in response to its internal crop yield calculation, which does not include climate change but does include technology impacts. While both calculate technological development based on SSP5, there exists some discrepancy between the SSP5 marker IAM and Iizumi et al.'s (2017, 2020) technological influence on crop yields, carried through to the *food_production_growth_cropland* and *food_production_growth_cropyield*.

The crop yields from Iizumi et al. (2017, 2020) are projected under the no-CO_2 fertilization condition, similarly to Wiebe et al. (2015). This approach intends to consider the worst-case by isolating the temperature effect on crop yields, without the additional effect of CO_2 fertilization offsetting or enhancing temperature-induced decrease or increase in crop yields.

While considering maize, rice, soybean and wheat explicitly, their average yield is used as a proxy for all other crops accounted for in this investigation (see *food_production_historical*). This approach is driven by data availability, and it was assumed that the variance of current yields as well as both positive and negative impacts of climate on yield projections of maize, rice, soybean and wheat provide a reasonable representation of other crops. Relatedly, these four crops provide over two-thirds of human food energy intake, being staples for more than 80% of world population (FAO 1995).

food_demand_pc_growth

The *food_demand_pc_growth* dataset contains SSP5-RCP85 growth profile for lifestyle food demand per capita, in units of annual average percentage, for each country in yearly increments from 2020 to 2099.

Preparation involved processing raw data on food demand per capita at regional-level in ten-yearly increments from the SSP5 marker IAM simulations stored at IAMC and IIASA (2018). Food demand per capita annual growth values were then calculated, and these regional values were converted to yearly increments and assigned to each of the 242 countries.

RCP85_climate_forcing

The *RCP85_climate_forcing* dataset contains RCP8.5 global climate forcing, in units of CO_2-equivalent emissions concentration in parts per million (ppm), in yearly increments from 2020 to 2099.

Preparation involved processing raw data on CO_2 equivalent concentration of all forcing agents at global-level in five yearly increments from the RCP projections stored at IIASA (2009).

W3_climate_forcing, W3_population, W3_gdp, W3_food_production, W3_food_demand

The World3 datasets contain the BAU-CC scenario projections of population, GDP|PPP, food production, lifestyle food demand and persistent pollution for the world in yearly increments from 2000 to 2100. Units are irrelevant as this data is only used in relative, not absolute, terms.

Preparation involved processing raw data for several variables at global-level derived from offline simulations using World3-03 with Scenario 2 settings as detailed by Meadows et al. (2004).

4.1.3 Simulation workflow

The simulation workflow consists of eight steps as follows.

Step-I. The model is initialised in year 2020 (n=2020), with the four key variables defined for each country (i=1 to 242) based on values in the historical datasets:

$$population[i,n] = population_historical[i,n]$$
$$gdp_pc[i,n] = gdp_pc_historical[i,n]$$
$$gdp[i,n] = gdp_pc[i,n] \times population[i,n]$$
$$food_production[i,n] = food_production_historical[i,n]$$
$$food_demand_pc[i,n] = food_demand_pc_historical[i,n]$$
$$food_demand[i,n] = food_demand_pc[i,n] \times population[i,n]$$

The simulation then loops through *Step-II* to *Step-VIII* from year 2020 (n=2020) to 2099 (n=2099).

Step-II. Several variables are calculated to set-up the international trade simulation. First, a pre-trade food balance is calculated for each country:

$$food_balance_pretrade[i,n] = food_production[i,n] - food_demand[i,n]$$

Step-III. Each country is allocated a *trade_status*. A country is an 'importer' if its pre-trade food balance is in deficit, i.e., national lifestyle demand exceeds national production. A country is an 'exporter' if its pre-trade food balance is in surplus, i.e., national production exceeds national lifestyle demand. A country is a 'non-trader' if its food balance is equal to zero, i.e., national production meets national lifestyle demand.

Step-IV. A trade power is calculated for each potential trading pair, i.e., if all countries are either an 'importer' or an 'exporter' then there are 242 x 242 = 58,564 potential trading pairs:

$$trade_power\ [importer, exporter] = \frac{gdp_pc[importer,n] \times gdp_pc[exporter,n]}{trade_distance[importer, exporter]}$$

International trade is considered in 'free form' based on a non-preferential hierarchy of trade power between trade partners, meaning that the model purposefully does not account for trade agreements. This approach intends to explore the future international risk landscape without introducing bias in the results by attempting to unreliably predict future geopolitics, particularly given the current state of shifting world order (Dalio 2021).

The calculation of trade is based on the gravity model of trade (Isard 1954), which predicts bilateral trade flows by multiplying GDP of, and dividing by distance between, two trading units. In this model, GDP per capita rather than GDP is used as this investigation is interested in relative purchasing power rather than absolute quantities purchased, and the effect of distance on trade relations is maintained (Carrère et al. 2020).

Step-V. International food trade is simulated. Each 'importer' and 'exporter' pair trade based on the trade power hierarchy until all have traded, except for a given pair when one partner has a food balance equal to zero (i.e. an 'importer' has imported sufficient food to satisfy their pre-trade deficit, or an 'exporter' has exported all of its pre-trade surplus). Each trading country's food balance is updated iteratively after each trade, with a final post-trade food balance being calculated:

$$food_balance_posttrade[i,n] = food_production[i,n] - food_demand[i,n] + imports[i,n] - exports[i,n]$$

Each year is treated as a single trade period, rather than dividing it into quarterly, monthly or weekly trade periods that would provide more equally distributed trade of commodities. This approach intends to examine the 'worst case' inequalities of a highly competitive world, reflecting the human nature of stockpiling most recently demonstrated during the coronavirus pandemic (Preston 2020).

Step-VI. The consequence of population loss for each country, in the form of starvation deaths, is determined based on the post-trade food balance and a food insecurity threshold representing the minimum food required for nourishment (FIT = 0.230 tonnes per capita per year, energy-equivalent-grain-weight-at-harvest), as follows:

$$population_loss[i,n] = MAX[0, population - \frac{food_demand[i,n] - food_balance_posttrade[i,n]}{FIT}]$$

The FIT is equal to the food related population loss threshold used in World3 (Meadows et al. 2004) for consistency in comparison. This value is less than the 'minimum dietary energy requirements' (MDER) of ~0.346 in the same units, and therefore results in a lower estimate of population loss than if using the FAO's threshold of 'undernourishment' equivalent to the MDER.

Step-VII. A socioeconomic growth shock is detected for a given country in a given year (GSY = initialised to 0, then updated to store the year) if the ratio of population loss to total population exceeds a growth shock threshold (GST = 3%). The occurrence of a given growth shock initiates a five-year period (GSP = 5 years) of zero-growth, counted from the last year (GSY) in which a growth shock is detected, following which growth resumes at the growth rate prior to the last period of zero growth based on a persistent discount counter (GSD = initialised to 0, then updated to store the number of years' discount to be applied in *Step-VIII* growth calculation). This is expressed mathematically as follows:

$$IF: \frac{population_loss[i,n]}{population[i,n]} \leq GST$$
$$THEN: GSY = GSY \;\&\; GSD = GSD$$
$$ELSE\ IF: \left[\frac{population_loss[i,n]}{population[i,n]} \geq GST\right] AND\ [n \geq (GSY + GSP)],$$
$$THEN: GSD = GSD + GSP,$$
$$GSY = n$$
$$ELSE\ IF: \left[\frac{population_loss[i,n]}{population[i,n]} \geq GST\right] AND\ [n \leq (GSY + GSP)],$$
$$THEN: GSD = GSD - (GSY + GSP - n) + GSP,$$
$$GSY = n$$

The GST and GSP values were estimated based on recent estimates of socioeconomic 'disruption' in terms of the number of cases associated with the ongoing coronavirus pandemic. The GST is based on approximately ~250 million cases having been recorded, equating to ~3.2% of the ~7.8 billion global population impacted (JHU CSSE 2021). The GSP and persistent growth discount (Estrada et al. 2015) is based on recent estimates that it may take five years to return to the projected socioeconomic growth path post-pandemic (IMF 2021).

Step-VIII. The four key variables for each country in the next time step are then calculated based on their respective growth profiles and growth shock status from *Step-VII*. Countries within a GSP experience no growth, countries that have yet to experience any GSP continue along their original growth path and countries emerging from a GSP resume their original growth path at the rate before the GSP. This is expressed mathematically as follows (where α is *food_production_growth_cropyield* and β is *food_production_growth_cropland*):

$$IF: n \leq (GSY + GSP), THEN:$$
$$population[i,n+1] = population[i,n] - population_loss[i,n]$$
$$gdp_pc[i,n+1] = gdp_pc[i,n]$$
$$gdp[i,n+1] = gdp_pc[i,n+1] \times population[i,n+1]$$
$$food_production[i,n+1] = food_production[i,n] \times (1 + \alpha[i,n]) \times (1 + \beta[i,n])$$
$$food_demand_pc[i,n+1] = food_demand_pc[i,n]$$
$$food_demand[i,n+1] = food_demand_pc[i,n+1] \times population[i,n+1]$$
$$ELSE\ IF: n \geq (GSY + GSP), THEN:$$
$$population[i,n+1] = (population_[i,n] - population_loss[i,n]) \times (1 + population_growth[i,n - GSD])$$
$$gdp_pc[i,n+1] = gdp_pc[i,n] \times (1 + gdp_pc_growth[i,n - GSD])$$
$$gdp[i,n+1] = gdp_pc[i,n+1] \times population[i,n+1]$$
$$food_production[i,n+1] = food_production[i,n] \times (1 + \alpha[i,n]) \times (1 + \beta[i,n])$$
$$food_demand_pc[i,n+1] = food_demand_pc[i,n] \times (1 + food_demand_pc_growth[i,n - GSD])$$
$$food_demand[i,n+1] = food_demand_pc[i,n+1] \times population[i,n+1]$$

The short-term growth shock is applied to population, GDP and lifestyle food demand but not food production. This approach intends to maintain the climate change impact on food production as this would not be impacted by short-term growth shocks. Given data limitations (see *food_production_growth_cropyield),* this approach assumes that technological development and urbanization, as pervasive long-term socioeconomic development aspects, are relatively unresponsive to short term growth shocks. A minimum lifestyle food demand equal to the MLFD is set in assuming that food demand will not fall below that of a 'healthy lifestyle' (see *food_demand_pc_historical*).

Following the final loop (n=2099) through *Step-I* to *Step-VIII* the simulation concludes.

4.1.4 Validation, verification and interpretation

The activity of validating, verifying and interpreting a model varies depending on its purpose (Edmonds et al. 2019). This model—much like World3—is illustrative in purpose, meaning that care in interpretation, more so than validation and verification, is most important. Each aspect is addressed in turn below, and readers are referred to Meadows et al. (2004) for details of World3 and Kriegler et al. (2017) for details of the SSP5-RCP85 marker IAM.

The historical values for 2000 to 2020 presented in the results, and used to initialise the model in 2020, are based on real-world empirical data. The model simulations run from year 2020 to 2100, a period in the future for which real world data does not exist, using growth profiles based on SSP5-RCP85 under the 'extreme global warming' scenario based on World3 BAU-CC. To this end, the model is internally validated to the extent that real world input data is available to initialise the simulation of a hypothetical future based on expert-informed projections. In the same vein that World3 has only been validated in growth mode, the model cannot be validated in terms of societal collapse because the contemporary world is yet to experience a reference event (Herrington 2021). While the analysis of 'free form' trade makes explicit calibration to historical data effected by evolving trade agreements redundant, the logic of the results is verified in terms of food insecurity below.

The input data and simulation workflow preparation throughout model development was verified through iterative methodological cross-checks by the author as well as peer-review. Verification that the simulation produced logical results was also undertaken. This was done by comparing the countries experiencing starvation deaths in earlier years of the simulation with a ranking of current 'percentage of population undernourished' from the FAO (2021) Food Security Indicators, which is presented in

Appendix B. The population loss due to starvation deaths simulated may be assumed as an incremental count of starvation deaths above any currently experienced due to food insecurity. As the basis for the 'extreme global warming' scenario, the World-3 BAU-CC scenario results also provide for general verification of the results from this model, as presented in Section 4.2.

By nature, it is difficult to simulate the behaviour of a complex system. This model is not predictive, nor does it provide a strict forecast. Rather, it illustrates one of many possible international risk landscapes, under one of many possible socioeconomic development and climate change scenarios. Readers should bear in mind that countless future scenarios could unfold, and the results presented here are sensitive to changes in underlying assumptions. This investigation emphasises focus on relative rather than absolute values in interpretation of results, insofar as exploring the consequences of 'extreme global warming' for our society in the future.

4.2 Results

This section presents the results from implementation of the methodology. The global and continental societal collapse dynamics are compared with World3 BAU-CC outputs over the century in Section 4.2.1. The continental and regional distribution of population loss, in terms of starvation deaths over the century, is presented in Section 4.2.2. The national cumulative starvation deaths in 2100, compared with current development, resilience and vulnerability, is documented in Section 4.2.3. The results are briefly described below, before moving into a contextualised discussion to explain them in Section 4.3.

4.2.1 Global and continental societal collapse dynamics

The five main aspects of the global and continental dynamics from this investigation from 2000 to 2100 are presented in Figure 4.2(a)-(e). Real-world historical values are shown for 2000 to 2020, and simulated values are shown for 2020 to 2100. The World3 BAU-CC simulation output for 2000 to 2100 is also shown for comparison. The values for each aspect are all referenced to 2020, as the first year of simulation in this investigation, for ease of comparing the dynamics in relative rather than absolute terms over time. Different line colours are used to differentiate the global and continental values. Red depicts the world simulation in this investigation. Black depicts World3 BAU-CC outputs. Yellow depicts the African continent. Orange depicts the Americas. Green depicts the Asian continent. Purple depicts Europe. Blue depicts Oceania.

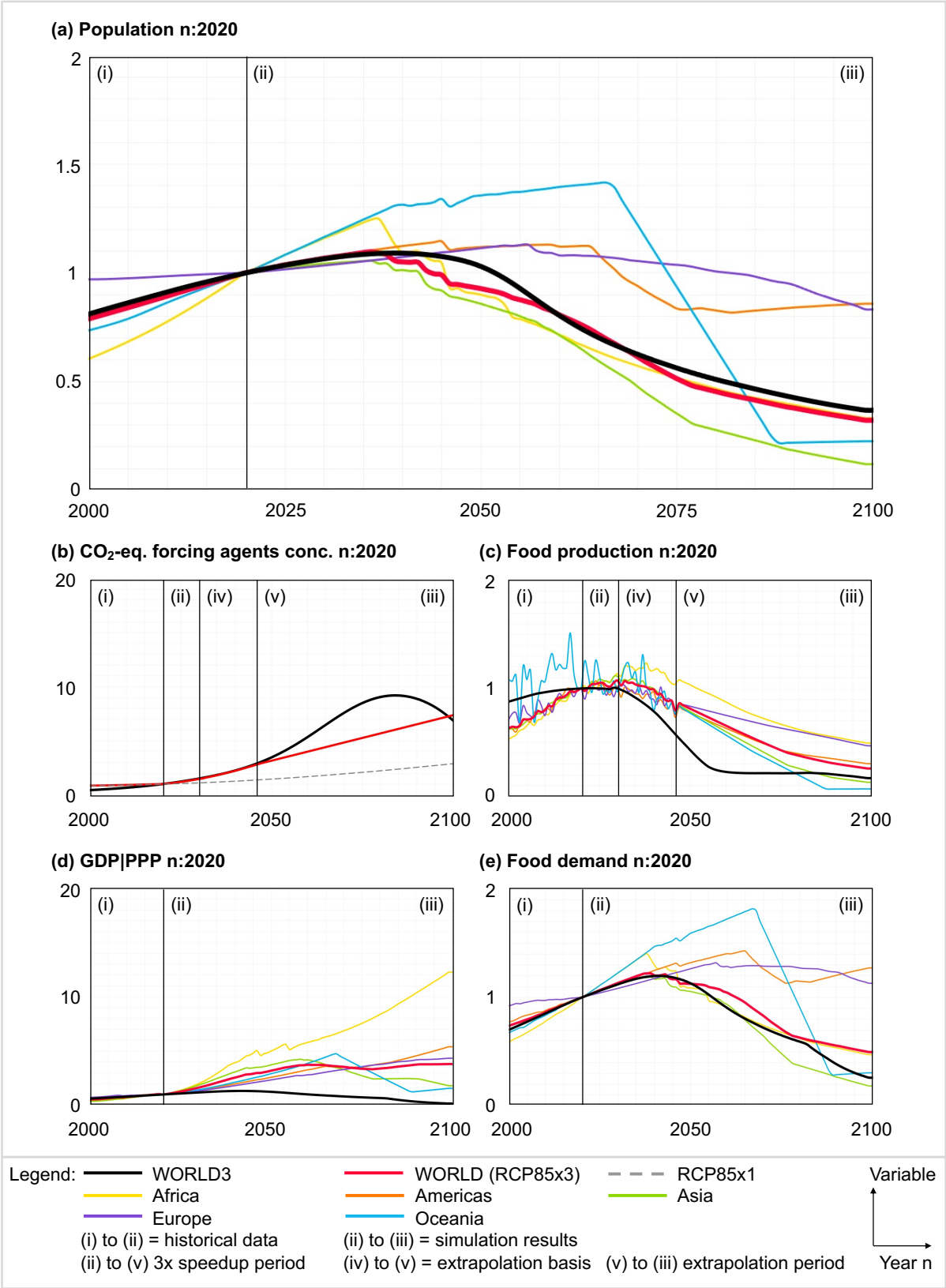


Figure 4.2: Global and continental climate change, food insecurity and societal collapse dynamics from 2000 to 2100 under 'extreme global warming'. All yearly values from 2000 to 2100 referenced to year 2020.

Figure 4.2(b) presents the global atmospheric CO_2-equivalent concentration associated with the 'extreme global warming' scenario. Figure 4.2(a), (c), (d) and (e) present global and continental

dynamics for the four key variables of population, GDP, food production and lifestyle food demand, respectively. The results show that world GDP will peak and plateau in 2060, food production will peak and collapse by 2040 and food demand concomitant with population will peak and collapse by 2050.

At global level, it is striking how closely the results from this investigation match the World3 BAU-CC output, particularly in terms of population and food demand. Although more complex models are often expected to yield more nuanced insights, this similarity highlights the utility of simple models for exploring underdeveloped concepts (Bardi 2013), such as 'extreme global warming'. Nonetheless, some differences between these results and those of World3 were expected given this model's less complex but less aggregated approach compared to World3's more complex but more aggregared approach. For instance, the relative lag in food production collapse is associated with the linear approximation of the climate forcing trend compared to World3's exponential concave down function. Similarly, the discrepancy in GDP is related to simple population and GDP per capita dynamics, compared to World3's multiplex dynamics of industrial capital.

4.2.2 Continental and regional population loss

The simulated continental and regional population loss, in terms of starvation deaths, from 2000 to 2100 are presented in Figure 4.3(a)-(e). As noted in Section 4.1.4, these may be assumed as an additional count of starvation deaths above those historically experienced due to existing food insecurity over 2000 to 2020. Different column colours are used to differentiate the continental and regional values. Yellow represents the African continent. Different shades of yellow differentiate the sub-regions of Eastern, Middle, Northern, Southern and Western Africa. Orange represents the Americas. Different shades of orange differentiate the sub-regions of the Caribbean and Central, North and South America and the Caribbean. Green represents the Asian continent. Different shades of green differentiate the sub-regions of Eastern, Central, Southern, South-Eastern and Western Asia. Purple represents Europe. Different shades of purple differentiate the sub-regions of Eastern, Northern, Southern and Western Europe. Blue represents Oceania. Different shades of blue differentiate the Oceania continent sub-regions of Australia & New Zealand, Melanesia, Micronesia and Polynesia.

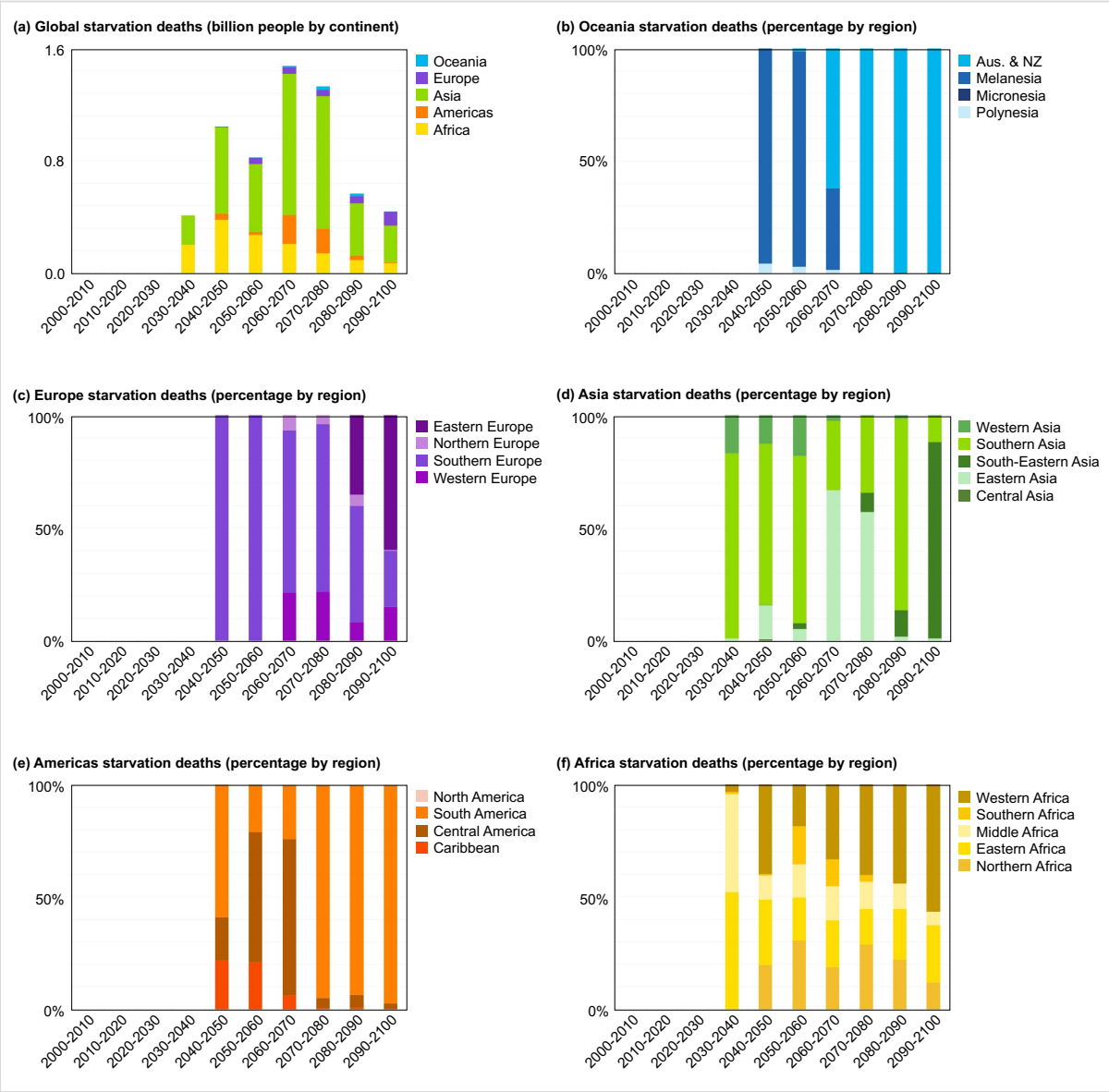


Figure 4.3: Continental and regional starvation deaths by decade under 'extreme global warming'.

Figure 4.3(a) presents the global count of starvation deaths broken up by continent. The values are expressed as absolute count summed by decade. Figure 4.3(c), (c), (d) and (e) respectively present the continental count of starvation deaths broken up by region. The values are expressed as a relative percentage of the absolute count summed by decade. The results show that starvation deaths will generally increase from 2030-40, peaking at some 1.5 billion over 2060-70 and then decreasing to 2090-2100 corresponding to the related decline in global population and food demand, with variation in terms of the population loss experienced by different continents and regions.

4.2.3 National starvation, development, vulnerability and resilience

The simulated national starvation deaths, expressed as a cumulative absolute count at 2100, are presented in Figure 4.4(a). As noted in Section 4.1.4, these may be assumed as an additional count of starvation deaths above those historically experienced due to existing food insecurity over 2000 to 2020. The cumulative starvation deaths at 2100 are compared with current (2020) development status and resilience (Resilience Index (RI)) and vulnerability (Fragile States Index (FSI)) scores of each country in Figure 4.4(b)-(d).

Figure 4.4(a) uses red shading to represent the density of cumulative starvation deaths, from a minimum value of zero in lightest red to a maximum value of ~1.6 billion in darkest red. The resilience (RI) and vulnerability (FSI) scores are noted for select countries (high, medium and low scores) to facilitate discussion about preparedness in Section 4.3.

Figure 4.4(bi) shows the absolute count of cumulative starvation deaths at 2100 by current (2020) country development status. Figure 4.4(bii) shows the count of cumulative starvation deaths at 2100 relative to the current population (2020) by country development status as a percentage distribution. Black shading is used to differentiate the development classifications of 'developed countries', 'landlocked developing countries', 'small island developing countries' and 'other developing countries'.

Figure 4.4(c) and (d) respectively present the cumulative starvation deaths at 2100 versus the current (2020) vulnerability (FSI) score and versus the current (2020) resilience score (RI) for each of the 242 countries simulated. Different data point colours are used to differentiate countries by continent. Yellow represents countries from the Africa. Orange represents countries from the Americas. Green represents countries from the Asia. Purple represents countries from Europe. Blue represents countries from Oceania. A linear trendline, shown in red, is fitted to all data points (242 countries). It should be noted that the relatively low coefficient of determination (R^2) is to be expected given the plethora of confounding factors influencing both resilience and vulnerability, and this does not de-strengthen the correlation depicted. Logically, the general trend indicates that the risk of starvation increases with increasing vulnerability and decreases with increasing resilience.

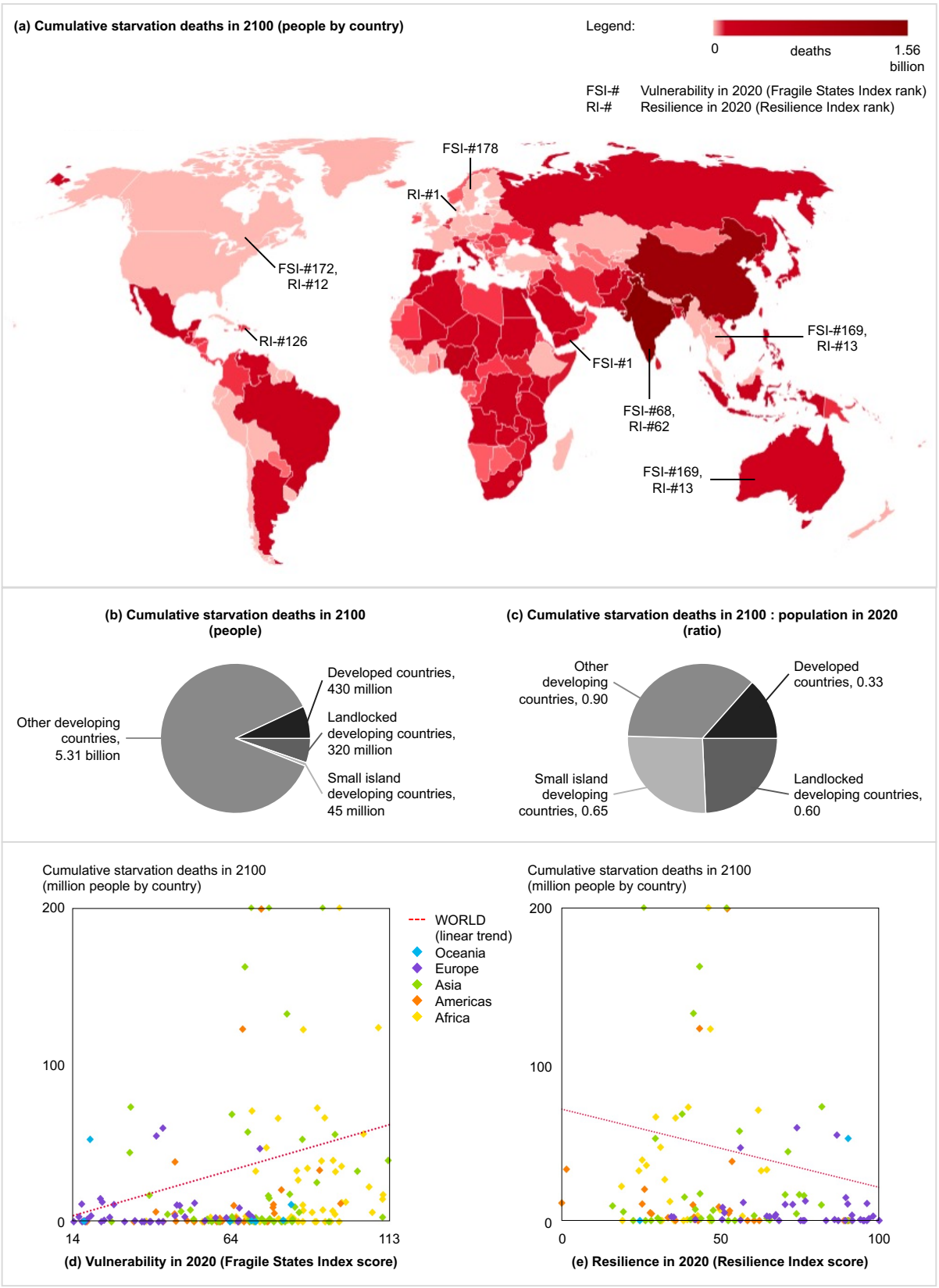


Figure 4.4: National cumulative starvation deaths in 2100 under 'extreme global warming' compared to development status, vulnerability and resilience in 2020. Data basis: Fragile States Index (FSI) from The Fund for Peace (2020), noting only 178 of the 242 countries are listed; Resilience Index (RI) from FM Global (2021), noting only 128 of the 242 countries are listed. In (d) and (e) four outliers have been compressed to the y-axis maximum for readability: India (FSI score = 75.3, RI score = 52.0, cumulative deaths = $15.6x10^8$), China (FSI score = 69.9, RI score = 46.1, cumulative deaths = $11.7x10^8$), Nigeria (FSI score = 97.2, RI score = 46.3, cumulative deaths = $3.3x10^8$) and Pakistan (FSI score = 92.1, RI score = 25.9, cumulative deaths = $2.6x10^8$).

4.3 Discussion

This investigation provides insights into the international risk landscape of climate change, food insecurity and societal collapse under 'extreme global warming' in three themes. The global threat of societal collapse under 'extreme global warming' is discussed in Section 4.3.1. The geographic distribution of human suffering is discussed in Section 4.3.2. The preparedness of populations at risk is discussed in Section 4.3.3.

4.3.1 Danger of societal collapse under 'extreme global warming'

The global and continental simulation dynamics presented in Figure 4.2 illustrate a concerning narrative about the risk of societal collapse. Should anthropogenic emissions continue to rise, humanity risks triggering tipping points that may see global warming increase to over 8°C by 2100 (Kemp et al. 2022). Under such 'extreme global warming' of ~RCP22, equating to ~10°C, by the end of the century (Figure 4.2(b)), food production (Figure 4.2(d)) will peak by 2040. Crop yields will decline through the second half of the century to approximately one quarter of current productivity, despite ongoing technological development. 'Fossil-fueled development' will similarly see population (Figure 4.2(a)), wealth (Figure 4.2(c)) and lifestyle food demand (Figure 4.2(d)) continue to grow through the first half of the century. However, the climate induced agricultural failures coupled with international food trade competition will lead to a cascade of global food insecurity. Ultimately, following an initial period of continued growth to 2050, society may experience a collapse to 32% of current population by 2100.

Although concerning, these results should not be surprising. Currently, over 10% of our global population are at risk of starvation and over 30% experience some form of food insecurity (FAO et al. 2021), with climate change expected to exacerbate these figures (Wheeler and von Braun 2013). Xu et al.'s (2020) analysis of the more conservative RCP8.5 scenario to 2070 indicates that ~3.5 billion people and significant portions of agricultural land will be left outside the stable climate niche in which humanity has evolved over the past 6,000 years. Accounting for 1-in-100-year climate related crop yield shocks under RCP8.5, Hasegawa et al. (2021) estimate an additional 20-36% of the population will face starvation by 2050. A recent comparative study by Lyon et al. (2021), which uses detailed climate models to examine more conservative climate forcing scenarios (RCP2.6, RCP4.5, RCP6.0 at 2100) extended to 2500, concludes that climate-forced agricultural failures may be expected by the end of the century, with areas of Earth becoming alien to humanity long-term. Using different methodological

approaches, this investigation, echoing Lyon et al.'s (2021) findings, reinforces the story of caution presented by Meadows et al. (2004) in *The Limits Growth* based on their World3 BAU-CC simulation: our globalised society may face the fate of societal collapse from 2050 onwards should we not act with haste to reduce anthropogenic emissions to intervene the risk of 'extreme global warming'.

Addressing the limitation of World3's global scale and granularity, this investigation illustrates that the dynamics of climate change, food insecurity and societal collapse will not occur consistently worldwide. Figure 4.2 shows that Africa tracks similarly to the overall world trend, experiencing an initial period of growth before collapsing to ~33% of its current population. Asia suffers more than the rest of the world, dwindling to ~12% of its current population by 2100. Oceania sustains significant growth through to the fourth quarter of the century, before a shock collapse to 23% its current population. Meanwhile, Europe and the Americas, with the former exhibiting a more stable trend than the latter, fare better than the rest of the world, maintaining a population roughly equivalent to the present. These results further emphasise the urgency of climate action given that some continents, such as Asia, may face impending doom as early as 2040, less than two decades from now.

Furthermore, it is important to note that this investigation examined societal collapse in the form of population loss via starvation deaths, one of six societal collapse determinants established in Chapter 2. As evidenced in the causal loop diagram in Chapter 3, climate change may simultaneously trigger or exacerbate sociocultural unrest, political dysfunction and economic losses. A population experiencing food insecurity may resign to starvation but equally may respond via conflict or migration. As such, the risk of societal collapse under 'extreme global warming' illustrated in the investigation would likely be much worse accounting for feedbacks of institutional breakdown, migration and conflict.

4.3.2 Geographic distribution of human suffering

Looking beyond these global and continental societal collapse dynamics, the continental and regional population loss presented in Figure 4.3 illustrates a concerning narrative about distribution of individual human suffering in terms of starvation deaths.

It is evident from Figure 4.3(a) that human suffering throughout the century will be concentrated in the continents of Asia and Africa, due to the relatively larger population and smaller purchasing power of countries within these continents, followed by the Americas, and to a lesser extent Europe and Oceania. For instance, in the peak 2030–40 decade, the world may experience some some 1.5 billion starvation

deaths, with 1 billion alone occuring in Asia, 200 million occuring in both Africa and the Americas, 50 million in Europe and 10 million in Oceania. In total over the century, Africa and Asia may experience some 3.9 billion and 1.4 billion starvation deaths compared to some 500 million in the Americas, 300 million in Europe and 70 million in Oceania.

Considering the percentage breakdown of starvation deaths in regions within continents, Figure 4.3(b) shows that in Oceania, the greatest suffering will be experienced by island states of Melanesia in the third quarter of the century, shifting to Australia & New Zealand in the fourth quarter of the century, relative to Micronesia and Polynesia. In Europe, the Southern region will initially endure the greatest count of starvation deaths, as shown in Figure 4.3(c), with the Eastern and Western regions experiencing a greater share toward the end of the century, and the Northern regions comparably faring better. Figure 4.3(d) shows that suffering will be concentrated in Southern Asia followed by Eastern and South-Eastern Asia, and to a much lesser extent in Western and Central Asia. While North America appears relatively unaffected in Figure 4.3(e), starvation deaths will be experienced by the island states of the Caribbean and Central America in the third quarter of the century, shifting predominantly to South America in the fourth quarter of the century. As shown in Figure 4.3(f), human suffering appears slightly more distributed across the African continent through to the end of the century, with the Western, Eastern and Northern regions experiencing the greatest percentage share, followed to a lesser extent by Eastern and Middle Africa.

Figure 4.4 highlights the unequal distribution of human suffering not only across continents and regions, but across countries globally. The choropleth in Figure 4.4(a), indicates that human suffering over the century, in terms of cumulative starvation deaths in 2100, will most intensely be felt by countries in the Global South, which are typically less developed and contribute less anthropogenic emissions than their counterparts in the Global North.

In terms of development classification, Figure 4.4(b) shows that only 7% of cumulative starvation deaths over the century will be sustained by developed countries concentrated in the Global North, while a majority 5.7 billion will be endured by developing countries in the Global South. Referencing this absolute cumulative starvation death count to the population in 2020, it appears that developed countries will experience human suffering equivalent to 33% of their current population. Landlocked, small island and other developing countries will respectively experience human suffering equivalent to 60%, 65% and 90% of their current population. Considering the relative global share of human

suffering, landlocked developing, small island and other developing countries will respectively face 1.8, 1.9 and 2.7 times more human suffering than encountered by developed countries.

These results speak to emerging literature on the need to understand how existing inequalities may manifest global climate injustice (Robinson and Shine 2018) and the moral obligation of high emitting countries to prevent harm to low emitters most exposed to climate change (Nielsen et al. 2021). Furthermore, these insights emphasises the need to tailor intervention strategies to local context, discussed further below, as well as the importance of international law to protect human rights (Viglione 2020), on which action is gravely lacking as evidenced by COP26 (Masood 2021).

4.3.3 Preparedness of populations at risk

Diving deeper into the international risk landscape, Figure 4.4's illustration of cumulative starvation deaths by 2100 at country-level facilitates contextual consideration of the human suffering over the century within a given country compared to its current development, vulnerability and resilience.

The cumulative starvation deaths over the century are compared to current Fragile States Index (FSI), proxying vulnerability, and Resilience Index (RI), proxying resilience, scores for each country in Figure 4.4(c) and (d) respectively. The overall trend exhibited in Figure 4.4(c) indicates that greater suffering will be experienced by the most vulnerable countries, that is those more exposed, more susceptible and less able to cope with the adverse effects of climate change. In a similar vein, the overall trend in Figure 4.4(d) shows that less suffering will be experienced by the most resilient countries, that is those more able to anticipate, prepare for and respond to systemic disturbances caused by climate change.

Developing countries in the Global South, where sociocultural, economic and political conditions increase the exposure and decrease the regenerative and adaptive capacity of populations to climate change, tend to exhibit higher fragility and lower resilience. Developed countries in the Global North, better prepared to tackle climate change, tend to exhibit a lower fragility and higher resilience. For instance, Figure 4.4(a) shows that Yemen, as the most fragile (FSI-1) country, is at risk of over 39 million starvation deaths while Finland, as the least fragile (FSI-178) country, has a potential cumulative starvation death count of zero. Haiti, as the least resilient (RI-126) country, is at risk of over 11 million starvation deaths while Denmark, as the most resilient (RI-1), has a potential cumulative starvation death count of zero. However, not all countries adhere to these overall trends. For example, despite both exhibiting medium vulnerability and resilience rankings, some 1.5 billion people may suffer from

starvation in India (FSI-68, RI-62) compared to none in Thailand (FSI-82, RI-69) over the century. Similarly, despite both exhibiting low vulnerability and high resilience rankings, Canada (FSI-172, RI-12) sustains no starvation deaths while Australia (FSI-169, RI-13) may endure over 850,000.

These results show that while the most vulnerable and least resilient populations will be hit the hardest, more developed countries are not entirely immune to the threat posed by climate change, food insecurity and societal collapse, revealing the complexity of the international risk landscape. This demonstrates the importance of assessing climate change impacts at multiple scales to optimise intervention strategies that are fit for purpose to the local context (Mpandeli et al. 2019). For instance, by targeting urgent mitigation in developed high emitting countries, including USA, Canada and Australia, and adaptation in low emitting countries, such as Rwanda, Puerto Rico and Vanuatu. It also highlights the unique position that emerging superpowers hold in the international risk landscape. For instance, commitments by China (Mallapaty 2021) and India (Vaidyanathan 2021) to mitigate emissions are essential to world efforts to tackle climate change, but also in the interests of both nations, each respectively at risk of some 1.2 billion and 1.6 billion people starving under 'extreme global warming' by 2100. Even if 'extreme global warming' does not eventuate this century, investment in climate change mitigation would not be wasted given the need to similarly prevent 'worst-case' outcomes under slow-burn conservative climate forcing, as demonstrated by Lyon et al. (2021), and synergies with sustainable development goals, as highlighted by Creutzig et al. (2021) and Soergel et al. (2021).

Such insights further emphasise the importance of urgent action to reduce vulnerabilities and build resilience, particularly in developing nations (Palmer 2020), and the need to understand how factors related to climate policy and socioeconomic development might influence the risk of societal collapse to inform climate financing decisions in the present as noted by Roberts et al. (2021).

4.4 Chapter summary: key findings

This investigation developed a quantitative model to illustrate the international risk landscape of climate change, food insecurity and societal collapse under 'extreme global warming' at global scale and national granularity through to 2100 to satisfy the refined research objective of component RQ2.

The computational simulation provides insights into the danger of societal collapse under 'extreme global warming', the geographic distribution of human suffering and the preparedness of populations at

risk. Should anthropogenic emissions continue to rise, humanity risks triggering tipping points that may see global warming increase to over 8°C by 2100. Against an initial backdrop of fossil-fuelled growth in population, wealth and lifestyle food demand, extreme temperatures will see crop yields plummet despite ongoing technological development. Coupled with competition for international food supply, agricultural failures will see food insecurity cascade to the point that our globalised society collapses to ~30% of its current population in the second half of the century. The distribution of individual human suffering will be unequal across continents, regions and countries. Africa and Asia may experience some 3.9 billion and 1.4 billion starvation deaths by the end of the century compared to 500 million in the Americas, 300 million in Europe and 70 million in Oceania. Some 5.7 billion people will suffer in the Global South by the end of the century, while only 7% of global starvation deaths will be sustained by developed countries in the Global North. Specifically, landlocked developing, small island and other developing countries will face two to three times more human suffering than developed countries. In terms of preparedness, while the most vulnerable and least resilient populations will be hit the hardest, more developed countries are not entirely immune to the threat posed by climate change, food insecurity and societal collapse. Emerging superpowers have a particularly unique role to play in mitigating climate change, not only in the best interests of the rest of the world but in their own best interests with China and India alone at risk of 1.2 billion and 1.6 billion people starving by 2100.

Good risk management requires surveying 'end-game' futures. Underexplored scenarios of 'extreme global warming' could prove catastrophic for society. These insights emphasise that humanity may face societal collapse under higher end warming by the end of the century should we not cooperatively act with haste to reduce anthropogenic emissions, build resilience and decrease vulnerability. The importance of tailoring intervention strategies to local context and need to understand how existing inequalities may manifest global climate injustice is also highlighted, leading into the third investigation in Chapter 5. This second investigation of the three-part research framework provides an incremental contribution to knowledge with respect to component RQ2, which has broader implications for society discussed in Chapter 6.

[blank page]

Chapter 5

The present: exploring the influence of climate policy and socioeconomic development decision factors on climate change, food insecurity and societal collapse

The global cooperation and coordination required to address the evolving challenge of anthropogenic climate change is unprecedented. Even low- to mid-range global warming (1.5–4.5°C by 2100) may prove devastating for our globalised contemporary society, but there remains a lack of agreement on climate policy and socioeconomic development strategies to tackle anthropogenic climate change. This chapter contains the third investigation of the three-part research framework (see Chapter 1), prompted by RQ3: *How might decisions in the present regarding climate policy and socioeconomic development influence climate change, food insecurity and societal collapse?* Addressing the refined research objective of this investigation (see Chapter 2), Section 5.1 documents the methodology implemented to explore the influence of climate policy and socioeconomic development decision factors on human suffering in terms of risk of starvation and manifestation of global climate injustice under the 15 RCP-SSP-SPA framework scenarios (see Chapter 2, Section 2.3.1), accounting for climate change impacts on agriculture at global scale and country-level granularity, through to 2100. Section 5.2 presents the results from implementing this methodology. Section 5.3 provides a discussion of the results. Section 5.4 summarises key findings of this investigation in reflection of RQ3.

5.1 Methodology

An overview of the investigation concept, including definition of the 15 scenarios and key decision factors, is provided in Section 5.1.1. The process for computing the risk of starvation is documented in Section 5.1.2. The process for comparing climate policy and socioeconomic development decision factors is documented in Section 5.1.3. Aspects of validation, verification and interpretation are documented in Section 5.1.4. Key assumptions, and implicit limitations, are noted throughout to consider them alongside relevant methodological information.

5.1.1 Investigation concept

This investigation involved a two-stage methodology. The first stage involved computing human suffering in terms of risk of starvation under the 15 RCP-SSP-SPA framework scenarios, including preparing input datasets and developing a quantitative model implemented in Python to perform simulations. The second stage involved comparing the risk of starvation results with underpinning climate policy and socioeconomic development decision factors, including future trends to 2100 and current inequalities in 2020. An overview of the methodology is presented graphically in Figure 5.1 to show how key components fit together.

5.1.2 Computing human suffering in terms of risk of starvation

The risk of starvation was computed each year from 2000 to 2100 for each of the 15 RCP-SSP-SPA framework scenarios. This was done using a quantitative model that takes a simple approach to exploring climate change, food insecurity and societal collapse at global scale and national granularity. The data preparation and simulation workflow for this computation leveraged a similar methodology to that applied in Chapter 4 to illustrate the 'extreme global warming' scenario. As such, for brevity and clarity, the methodology is not repeated in full here to avoid redundancy and instead a summary of each aspect noting dissimilarities in methodology is provided below. As in Chapter 4, supplementary documentation regarding data preparation is also contained in Appendix B. The results are presented in Figure 5.2 and further used in Section 5.1.3.

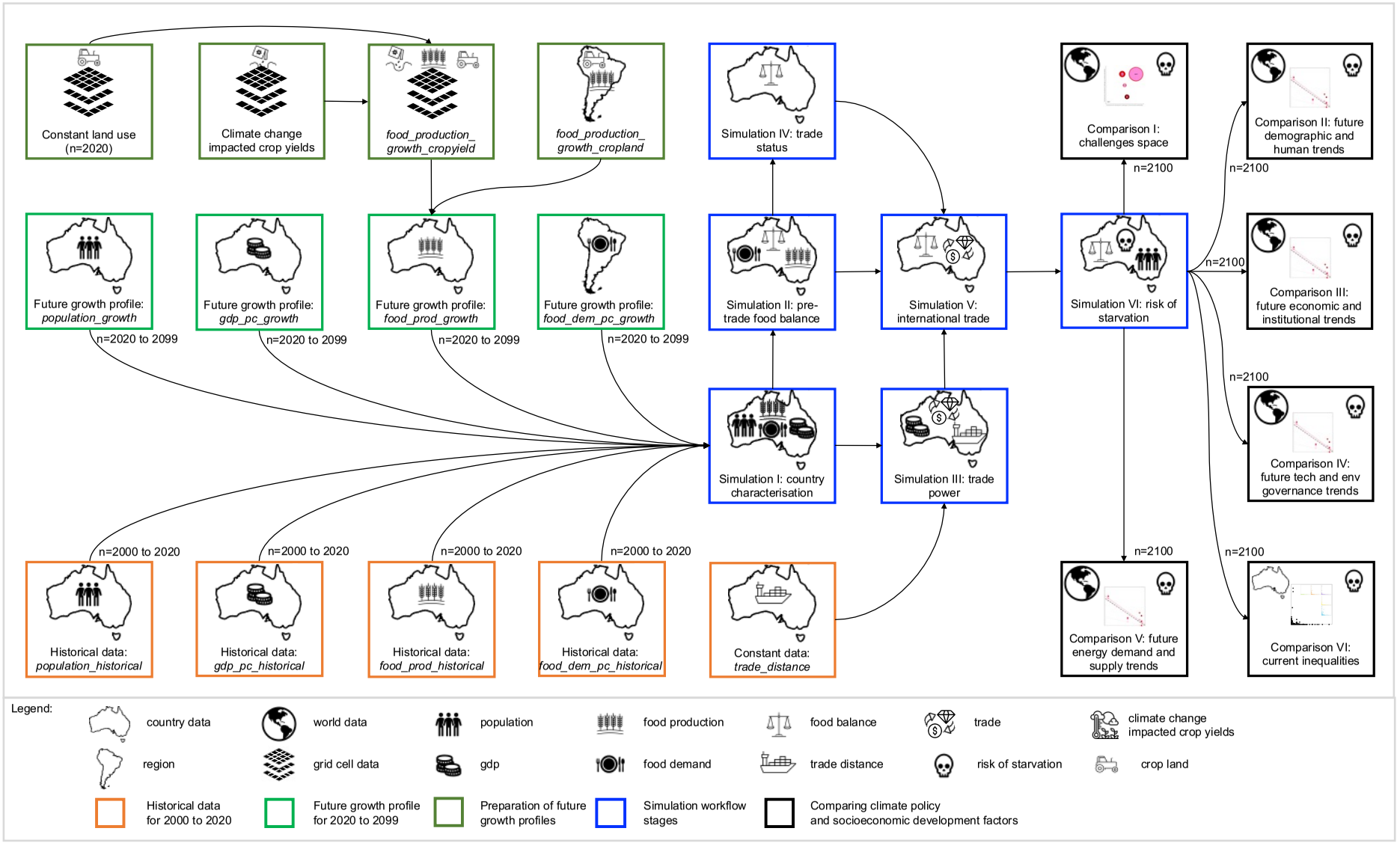


Figure 5.1: Methodology overview for the third investigation (RQ3) of the three-part framework. This shows how input datasets and simulation workflow for the computation of risk of starvation (described in Section 5.1.2) and comparison of underpinning climate policy and socioeconomic development decision factors (described in Section 5.1.3) fit together. The simulation workflow represents a year 'n' unless otherwise noted.

Constant country definition (2000–2100)

As in Chapter 4, the model characterises 242 countries that currently contain a permanent civilian population. Each country pair was assigned a constant *trade_distance* in units of kilometres.

Historical population, GDP, food production and food demand (2000–2020)

As in Chapter 4, historical data for population, GDP, food production and food demand was prepared. The *population_historical* dataset contains the historical total population in units of persons. The *gdp_pc_historical* dataset contains the historical GDP|PPP per capita in units of constant 2017 international dollars. The *food_production_historical* dataset contains the historical total food production in custom units of energy-equivalent-grain-weight-at-harvest in tonnes. The *food_demand_pc_historical* dataset contains the historical lifestyle food demand per capita in custom units of energy-equivalent-grain-weight-at-harvest in tonnes. Each dataset provides values for each country in yearly increments from 2000 to 2020.

Standard future growth profiles of population, GDP, food demand (2020–2100)

As in Chapter 4 except for one dissimilarity, 'standard' future growth profiles for population, GDP and food demand were prepared, where 'standard' refers to the 'standard' IAM elaborations of the RCP-SSP-SPA framework as opposed to the 'altered' future growth profile below. The dissimilarity is that instead of preparing the datasets for one scenario, as in Chapter 4, this investigation involved processing raw data from the marker IAM elaborations stored at IIASA (2018) and IAMC and IIASA (2018) for each of the 15 RCP-SSP-SPA framework scenarios. The *population_growth* datasets contain the total population future growth profiles. The *gdp_pc_growth* datasets contain the GDP|PPP per capita future growth profiles. The *food_demand_pc_growth* datasets contain the food demand per capita future growth profiles. Each dataset provides values for each country in yearly increments from 2020 to 2099 in units of percentage annual growth.

Altered future growth profile of climate impacted food production (2020-2100)

As in Chapter 4 except for two dissimilarities, 'altered' future growth profiles for food production were prepared, where 'altered' refers to this investigation accounting for the impact of climate change on crop yields not included in the 'standard' IAM elaborations of the RCP-SSP-SPA framework. The

first dissimilarity is that the 'extreme global warming' scenario acceleration and extrapolation used in Chapter 4 is not applied in this investigation, such that the processed data is left in 'natural' format. The second dissimilarity is that instead of preparing the datasets for one scenario, as in Chapter 4, this investigation involved processing raw data from the marker IAM elaborations stored at IIASA (2018) and IAMC and IIASA (2018) for each of the 15 RCP-SSP-SPA framework scenarios. The *food_production_growth* datasets contain the 'altered' total food production future growth profiles.

Simulation workflow

As in Chapter 4, except for three dissimilarities, in each year of simulation countries produce food based on crop land availability and crop yields influenced by technological development and climate change. Countries then internationally trade food based on trading power influenced by wealth and geographic distance between trading partners, to meet the lifestyle food demand of their population. Any post-trade deficit in food balance deficit, i.e., where food balance does not satisfy the minimum food demand for nourishment, leaves a country's population at risk of starvation, based on a food insecurity threshold (FIT) equivalent to the 'minimum dietary energy requirement' for nourishment (FIT MDER = 0.346 tonnes per capita per year, energy-equivalent-grain-weight-at-harvest):

$$population\ at\ risk\ of starvation\ = MAX\left[0, population - \frac{food\ demand - post\ trade\ food\ balance}{FIT}\right]$$

The first dissimilarity is that instead of using a FIT equal to World3's threshold of 0.230 per capita per year, this investigation uses the FAO (2021)'s threshold, which results in a higher estimate of population loss. The second dissimilarity is that in this investigation the risk of starvation is computed statically each year without incorporating the impact of starvation death and growth shock feedbacks on growth for the subsequent year as in Chapter 4 (*Step-VIII)*. This investigation is interested in isolating how the level human suffering evolves across the 15 RCP-SSP-SPA framework scenarios, which describe 'ideal' socioeconomic development pathways where food production equals food demand without climate change impacts, rather than societal collapse dynamics as in Chapter 4. The third dissimilarity is that instead of running the simulation for one scenario, as in Chapter 4, this investigation involved running the simulation for each of the 15 RCP-SSP-SPA framework scenarios.

5.1.3 Comparing climate policy and socioeconomic development factors

To explore the influence of climate policy and socioeconomic development decision factors on human suffering, the computed risk of starvation at the end of the century (2100) for each of the 15 RCP-SSP-SPA framework scenarios was compared with 22 underpinning factors in six comparison sets.

Comparison I, presented in Figure 5.3, involved mapping the computed risk of starvation at global granularity to the SSP climate policy challenges space and sustainability challenges space, which are qualitatively defined by O'Neill et al. (2014) and summarised in Chapter 2, Figure 2.6.

Comparisons II to V, presented in Figure 5.4 to Figure 5.8, involved plotting the computed risk of starvation at global granularity against the growth from 2020 to 2100 of quantitative and qualitative variables that characterise the SSPs. The quantitative variables are based on the input datasets from Section 5.1.2 or additionally sourced from the marker IAM elaborations of the RCP-SSP-SPA framework stored at IIASA (2018) and IAMC and IIASA (2018). The quantitative variables and respective growth percentages from 2020 to 2100, are presented in Table 5.1. The qualitative variables, some of which comprise multiple components, were sourced from the SSP narrative definitions provided by O'Neill et al. (2017a). For plotting purposes, each of the qualitative variables was given a quantitative growth score based on the narrative ranging from 0 (very low) to 7 (very high), where an average is taken of component elements scored individually. The qualitative variables and respective growth scores from 2020 to 2100, are presented in Table 5.2.

Comparison VI, presented in Figure 10, involved plotting the computed risk of starvation against the climate forcing (RCP) at global granularity, and five quantitative factors pertaining to climate policy and socioeconomic development inequality in the present (2020) at country granularity. The quantitative factors of GDP|PPP per capita, food production per capita and food demand per capita in 2020 are based on the input datasets from Section 5.1.2. CO_2 emissions per capita in 2020 was sourced from Ritchie and Roser (2020a), noting that data was only available for 216 countries. Energy demand per capita was sourced from Ritchie and Roser (2020b), noting that data was only available for 79 countries in 2019 as the closest year to 2020.

This comparative analysis purposefully focuses on general trends, rather than detailed statistical analysis toward determinant relationships amongst inherently confounding variables, to simply explore the relative influence across climate policy and socioeconomic development decision factors.

Table 5.1: Quantitative 2020 to 2100 growth for climate policy and socioeconomic development decision factors.

Quantitative variable (2100:2020)		SSP1	SSP2	SSP3	SSP4	SSP5
Population*		92%	118%	163%	121%	98%
Urban % population*		143%	128%	106%	141%	143%
Illiterate % population		10%	11%	136%	204%	9%
GDP|PPP		620%	579%	296%	367%	1081%
Inequality, GINI Index		24%	41%	73%	108%	20%
Agricultural land	RCP2.6	89%	86%	-	90%	93%
	RCP4.5	90%	100%	122%	97%	96%
	RCP6.0	91%	107%	132%	98%	108%
	RCP8.5	-	-	-	-	113%
Renewable % primary energy source	RCP2.6	443%	495%	-	584%	613%
	RCP4.5	362%	296%	344%	348%	359%
	RCP6.0	284%	198%	239%	268%	230%
	RCP8.5	-	-	-	-	101%

Table 5.2: Qualitative 2020 to 2100 growth score for climate policy and socioeconomic development decision factors.

Qualitative variable (score)		SSP1	SSP2	SSP3	SSP4	SSP5
Human development*	Health investments	5	3	1	2	5
	Access to health facilities, water, sanitation	5	3	1	2	5
	Gender equality	5	3	1	2	5
	Social cohesion	5	3	1	3	5
	Social participation	5	3	1	1	5
	AVERAGE	5	3	1	1.8	5
Institutional capacity and policy sustainability	Environmental policy	5	2	1	2	3
	Policy orientation	5	1	3	2	4
	Institutions	5	2	1	3	4
	AVERAGE	5	1.67	1.67	2.33	3.67
International cooperation and connectivity	International trade	3	3	1	3	5
	Globalization	4	3	1	2	5
	International Cooperation	5	2	1	3	4
	AVERAGE	4	2.67	1	2.67	4.67
Agricultural productivity	Agriculture	5	3	1	3	5
Natural resource governance	Fossil constraints	5	3	4	2	0
	Environment	5	1	0	3	5
	Land use	5	3	1	3	3
	AVERAGE	5	2.33	1.67	2.67	2.67
Technological capacity	Development	5	2	1	3	5
	Transfer	5	1	1	2	5
	AVERAGE	5	1.5	1	2.5	5
Consumption lifestyle	Consumption	1	5	5	3	6
	Diet	1	3	5	3	6
	AVERAGE	1	4	5	3	6
Sustainable energy technology	Energy tech change	5	2	1	4	0
	Carbon intensity	5	3	5	2	5
	AVERAGE	5	2.5	3	3	2.5
Energy demand	Energy intensity	1	3	5	2	5

* As population, urban % population and illiterate % population are quantified variables, the respective population demographic elements from O'Neill et al. (2017b) are not given a separate qualitative score.

5.1.4 Validation, verification and interpretation

The activity of validating, verifying and interpreting a model varies depending on its purpose (Edmonds et al. 2019). As in Chapter 4, this investigation leverages a model that is illustrative in purpose, meaning that care in interpretation, more so than validation and verification, is most important. Each aspect is addressed in turn below, and readers are referred to details provided for the marker IAM for SSP1 by van Vuuren et al. (2017), SSP2 by Fricko et al. (2017), SSP3 by Fujimori et al. (2017), SSP4 by Calvin et al. (2017) and SSP5 by Kriegler et al. (2017).

The historical values for 2000 to 2020 presented in the results, and used to initialise the model in 2020, are based on real-world empirical data. The model simulations run from year 2020 to 2100, a period in the future for which real world data does not exist, using growth profiles based on the 15 RCP-SSP-SPA framework scenarios. To this end, the model is internally validated to the extent that real world input data is available to initialise the simulation of a hypothetical future based on expert-informed projections. The simulation of only food availability and the condition of 'free form' trade makes explicit calibration to historical data influenced by food price, utilization and stability dynamics as well as trade agreements redundant, however, the logic of the computed risk of starvation is verified below.

The input data and simulation workflow preparation throughout model development was verified through iterative methodological cross-checks by the author as well as peer-review. Verification that the simulation produced logical results was also undertaken. This was done by quantitatively comparing the risk of starvation computed over 2000 to 2020 with historical data on undernourishment from FAO (2021) Food Security Indicators and qualitatively fact checking historical food crises within the countries recording a risk of starvation over 2000 to 2020. Full documentation is presented in Appendix B. The risk of starvation simulated may be assumed as an incremental population at risk of starvation above any currently experienced due to food insecurity.

By nature, it is difficult to simulate behaviour of a complex system. This model is not predictive, nor does it provide a forecast. Rather, it provides a hypothetical exploration of 15 future scenarios. Readers should bear in mind that countless future scenarios could unfold, and results presented here are sensitive to changes in underlying assumptions. This investigation emphasises focus on relative rather than absolute values in interpretation of the risk of starvation and general trends rather than precise statistical analysis of the comparisons, insofar as exploring the influence of climate policy and socioeconomic development decision factors on low- to mid-range climate change in the future.

5.2 Results

This section presents the results from implementation of the methodology. The risk of starvation under the 15 RCP-SSP-SPA framework scenarios and mapping of human suffering to the challenges space in Comparison I are presented in Section 5.2.1. Future climate policy and socioeconomic development trends in Comparison II to V are presented in Section 5.2.2. Current climate policy and socioeconomic development inequalities in Comparison VI are presented in Section 5.2.3. The results are briefly described below, before moving into a contextualised discussion to explain them in Section 5.3.

5.2.1 Risk of starvation under the 15 RCP-SSP-SPA framework scenarios

The risk of starvation over the century for each of the 15 RCP-SSP-SPA framework scenarios is presented in Figure 5.2 at global scale and continental granularity. Different plot colours are used to differentiate continents. Green depicts Oceania. Pink depicts Europe. Black depicts Asia. Yellow depicts the Americas. Blue depicts Africa.

Under SSP1, starvation remains negligible across all RCP combinations, reflecting the 'sustainability' narrative of 'clean-' and 'green-fuelled' technology and inclusive international relations. SSP3 exhibits greatest starvation, where the 'regional rivalry' narrative of weak institutional coordination and cooperation globally coupled with climate change sees 2.9 billion to 3.1 billion people at risk under RCP4.5 to RCP6.0. SSP5's rapid 'fossil fuelled' technological progress balanced by integrated participatory global economies sees 270 million to 1.01 billion people at risk under RCP2.6 to RCP8.5. Moderate risk of starvation is observed under SSP2, ranging from 400 million to 780 million under RCP2.6 to RCP6.0, and SSP4, ranging from negligible to 1.32 billion under RCP2.6 to RCP6.0.

Overall, starvation increases with increasing RCP across each SSP, except for the decline from 500 million to 410 million under SSP5-RCP45 to SSP5-RCP60 due to rapid agricultural innovations offsetting the negative impacts of climate change. Interestingly, risk of starvation under SSP5-RCP85, the only combination in which RCP8.5 is plausible, is less than that under the more conservative climate forcing of SSP3-RCP45, SSP3-RCP60 and SSP4-RCP60. These results highlight that both climate policy and socioeconomic development influence human suffering under low- to mid-range global warming, discussed further in Section 5.3.

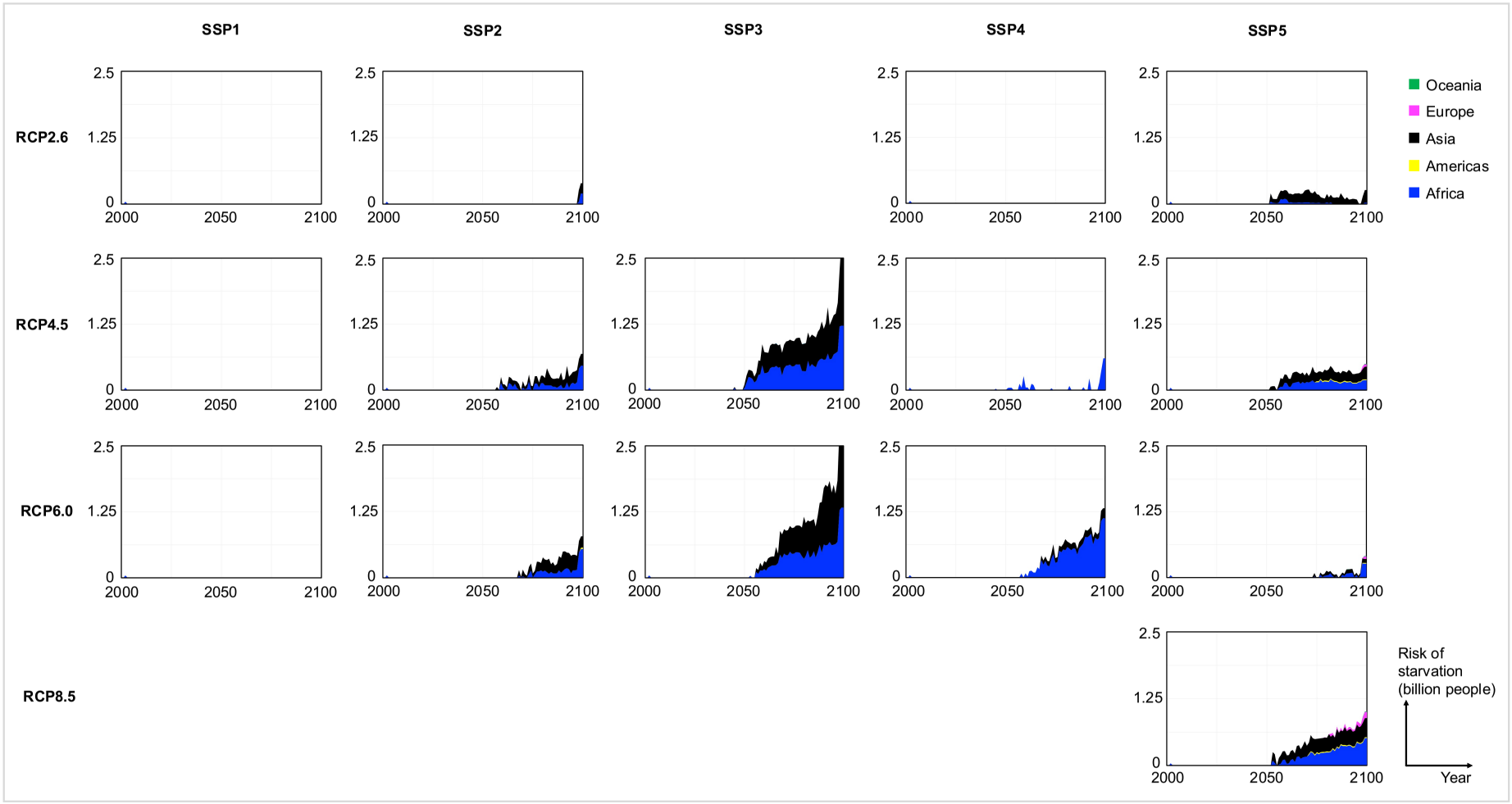


Figure 5.2: Risk of starvation at global scale and continental granularity under each of the 15 RCP-SSP-SPA framework scenarios. The population at risk is incremental above the current count.

In Figure 5.3, the global risk of starvation in 2100 under each of the 15 scenarios is mapped to the climate policy challenges space and sustainability challenges space (Comparison I). Each SSP occupies a given realm in each challenge space, shown in text. Bubble size depicts magnitude of risk of starvation for each SSP-RCP scenario and the red colour shade depicts the corresponding RCP combination.

The negligible risk of starvation under SSP1 correlates with socioeconomic development that yields both low challenges to climate change mitigation and adaptation as well as low challenges to societal and environmental sustainability. In contrast, the greatest increase in risk of starvation under SSP3 correlates both high challenges to climate change mitigation and adaptation as well as high challenges to societal and environmental sustainability. Exhibiting low challenges to climate change mitigation but high challenges to adaptation and high challenges to societal sustainability but moderate challenges to environmental sustainability under conditions of 'inequality', SSP4 populations experience higher risk of starvation than those under SSP5, which comparably exhibits high challenges to climate change mitigation but low challenges to adaptation and low challenges to societal sustainability but moderate challenges to environmental sustainability. Of the four SSPs experiencing significant risk of starvation, the 'middle of the road' narrative of SSP2, exhibiting moderate challenges across both the climate policy and sustainability spaces, appears the least exposed to detrimental RCP combinations.

These initial results highlight the nuanced influence of climate policy and socioeconomic development factors on the risk of starvation, explored further below.

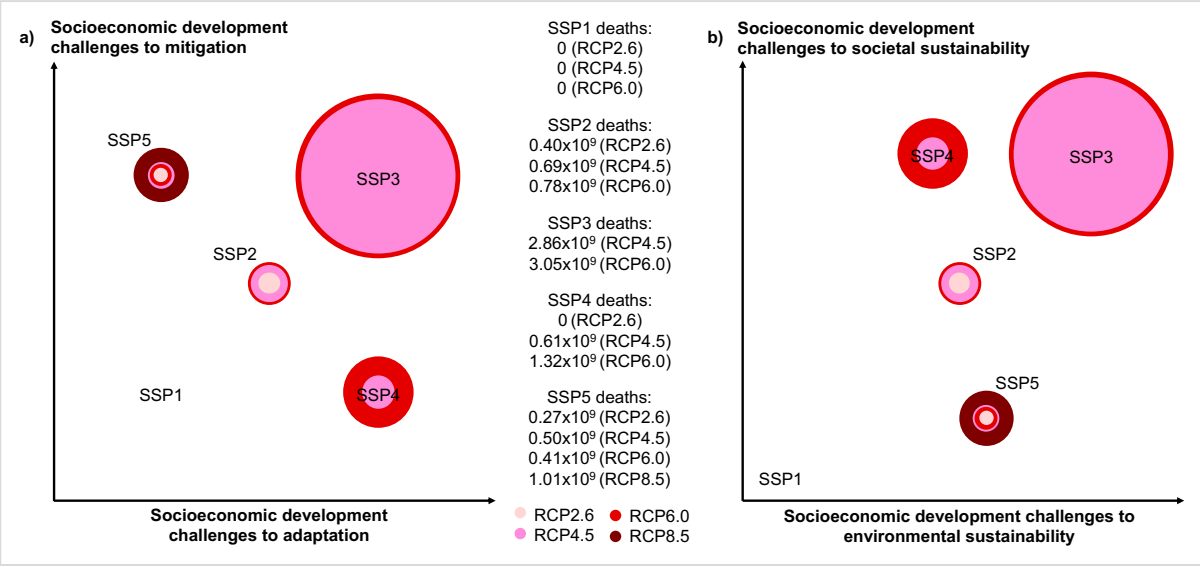


Figure 5.3: Comparison I – Global risk of starvation at 2100 under each of the 15 RCP-SSP-SPA framework scenarios mapped to the (a) climate policy challenges space and (b) sustainability challenges space. As introduced in Section 2, each SSP occupies a relative realm in each challenge space as part of the RCP-SSP-SPA framework definition. Bubble size depicts relative risk of starvation magnitude for each scenario.

5.2.2 Future climate policy and socioeconomic development trends

Delving into these nuances, the risk of starvation is compared with future climate policy and socioeconomic development trends in Figure 5.4 to Figure 5.7 (Comparison II to V). In each of these graphs, the global population at risk of starvation is shown on the y-axis. The quantitative variable growth percentage or qualitative variable growth score for each SSP over the 2020 to 2100 is shown on the x-axis. Each data point represents one of the 15 SSP-RCP scenario combinations, where the red colour shade depicts the corresponding RCP. Linear trendlines, in corresponding red colour shading, are plotted through each RCP collection of datapoints to highlight the influence of the SSP variable trend. A linear trendline, in black, is also plotted across all 15 datapoints to highlight the general trend.

Figure 5.4 compares SSP variables related to demographic and human development (Comparison II). On population, SSP1 is characterised by the greatest degrowth of -8%, while SSP3 is characterised by the highest growth at +63%, and the overall trend indicates that risk of starvation increases by a rate of 40 million people per 1% growth. As to urban share of population, SSP3 exhibits the lowest growth at +6%, while SSP1 and SSP5 exhibit the highest growth at +43%, and the overall trend indicates that risk of starvation decreases by 70 million people per 1% growth. Regarding education, SSP5 shows the greatest degrowth in illiteracy at -91%, while SSP4 shows the highest growth in illiterate people at +104%, and the overall trend indicates that risk of starvation increases by 5 million people per 1% growth in the illiterate share of population. For human development, SSP3 has the lowest growth score while SSP1 and SSP5 have the highest growth score, and the overall trend indicates that risk of starvation decreases by 400 million people per point increase in low-high growth narrative score.

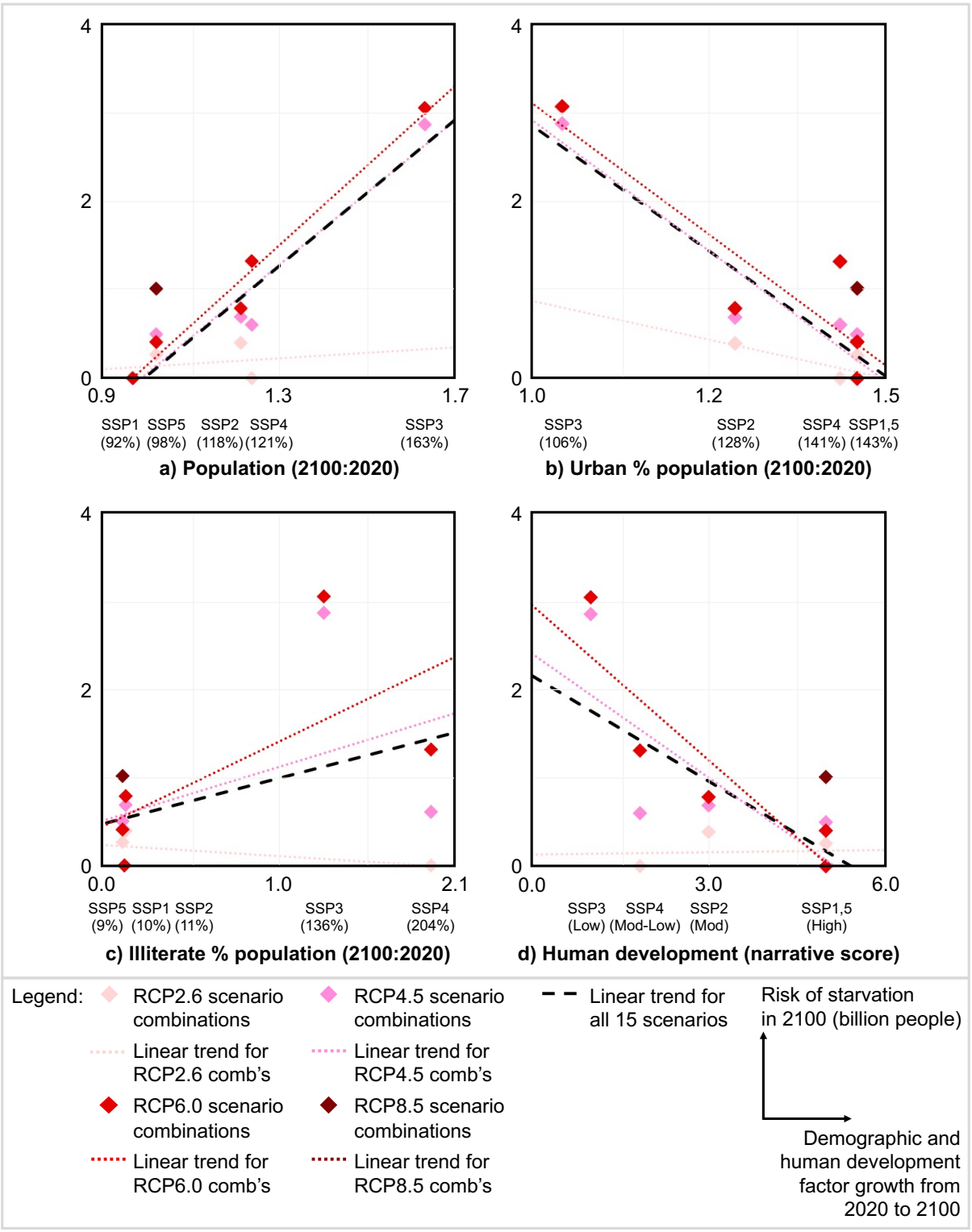


Figure 5.4: Comparison II – Global risk of starvation at 2100 compared to future demographic and human development growth trends under each of the 15 RCP-SSP-SPA framework scenarios.

Figure 5.5 compares SSP variables related to economic and institutional development (Comparison III). On GDP|PPP, SSP3 is characterised by the lowest growth at +196%, while SSP5 is characterised by the highest growth at +981%, and the overall trend indicates that risk of starvation decreases by a rate of 1 million people per 1% growth. As to economic inequality, SSP5 exhibits the greatest degrowth of -80%, while SSP4 exhibits the only growth across the SSPs of +8%, and the overall trend indicates that risk of starvation increases by 10 million people per 1% growth. Regarding institutional capacity and policy sustainability, SSP2 and SSP3 show the lowest growth score while SSP1 shows the highest growth score, and the overall trend indicates that risk of starvation decreases by 400 million people per score point increase. For international cooperation and connectivity, SSP3 has the lowest growth score while SSP5 has the highest growth score, and the overall trend indicates that risk of starvation decreases by 600 million people per score point increase.

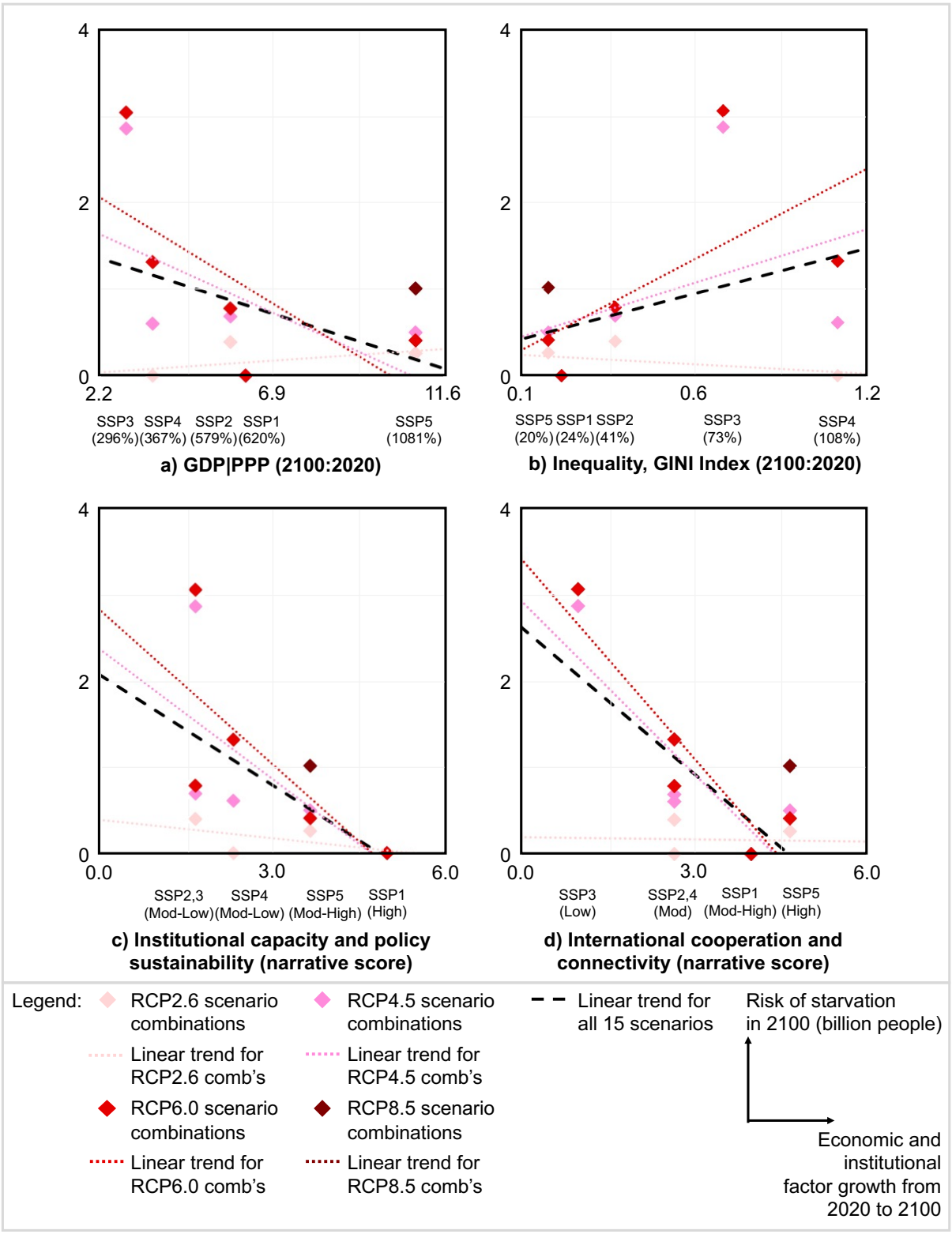


Figure 5.5: Comparison III – Global risk of starvation at 2100 compared to future economic and institutional growth trends under each of the 15 RCP-SSP-SPA framework scenarios.

Figure 5.6 compares SSP variables related to technology and environmental governance development (Comparison IV). On agricultural land development, SSP1 is characterised by the most degrowth on average, ranging from -9% to -11% depending on SPA, with SSP1-RCP26 the greatest at -11%, while SSP3 is characterised by the most growth on average, ranging from +22% to +32% depending on SPA, with SSP3-RCP60 the highest at +32%, and the overall trend indicates that risk of starvation increases by a rate of 60 million people per 1% growth in agricultural land to meet an increasing demand for food. As to agricultural productivity, SSP3 exhibits the lowest score while SSP1 and SSP5 exhibit the highest score, and the overall trend indicates that risk of starvation decreases by 500 million people per score point increase. Regarding natural resource governance, SSP2 and SSP3 show the lowest score while SSP1 shows the highest score, and the overall trend indicates that risk of starvation decreases by 600 million people per score point increase. For technological capacity, SSP3 has the lowest score while SSP1 and SSP5 have the highest score, and the overall trend indicates that risk of starvation decreases by 300 million people per score point increase.

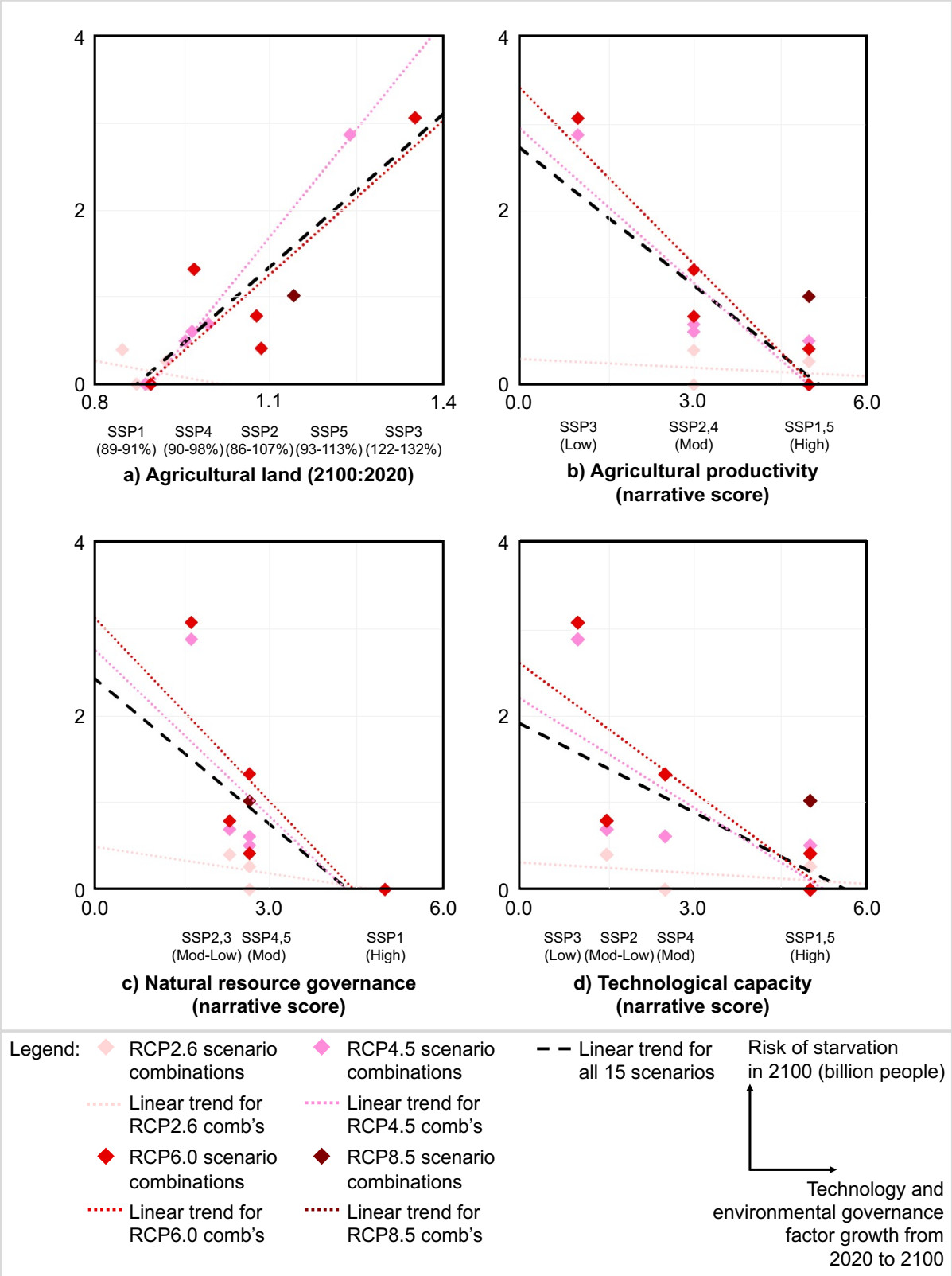


Figure 5.6: Comparison IV – Global risk of starvation at 2100 compared to future technology and environmental governance growth trends under each of the 15 RCP-SSP-SPA framework scenarios.

Figure 5.7 compares SSP variables related to energy demand and supply development (Comparison V). On renewable share of primary energy sources, SSP3 is characterised by the least growth on average, ranging from +139% to +244% depending on SPA, but with SSP5-RCP85 the lowest at +1%, while SSP4 is characterised by the most growth on average, ranging from +168% to 484% depending on SPA, with SSP4-RCP26 the highest at +484%, and the overall trend indicates that risk of starvation decreases by a rate of 3 million people per 1% growth. As to material consumption lifestyle, SSP1 exhibits the lowest score while SSP5 exhibits the highest score, and the overall trend indicates that risk of starvation increases by 200 million people per score point increase. Regarding sustainable energy technology, SSP2 and SSP5 show the lowest score while SSP1 shows the highest score, and the overall trend indicates that risk of starvation decreases by 300 million people per score point increase. For energy demand, SSP1 has the lowest score while SSP3 and SSP5 have the highest score, and the overall trend indicates that risk of starvation increases by 300 million people per score point increase.

These results demonstrate the influence of climate policy and socioeconomic development decision factors on human suffering, discussed further in Section 5.3.

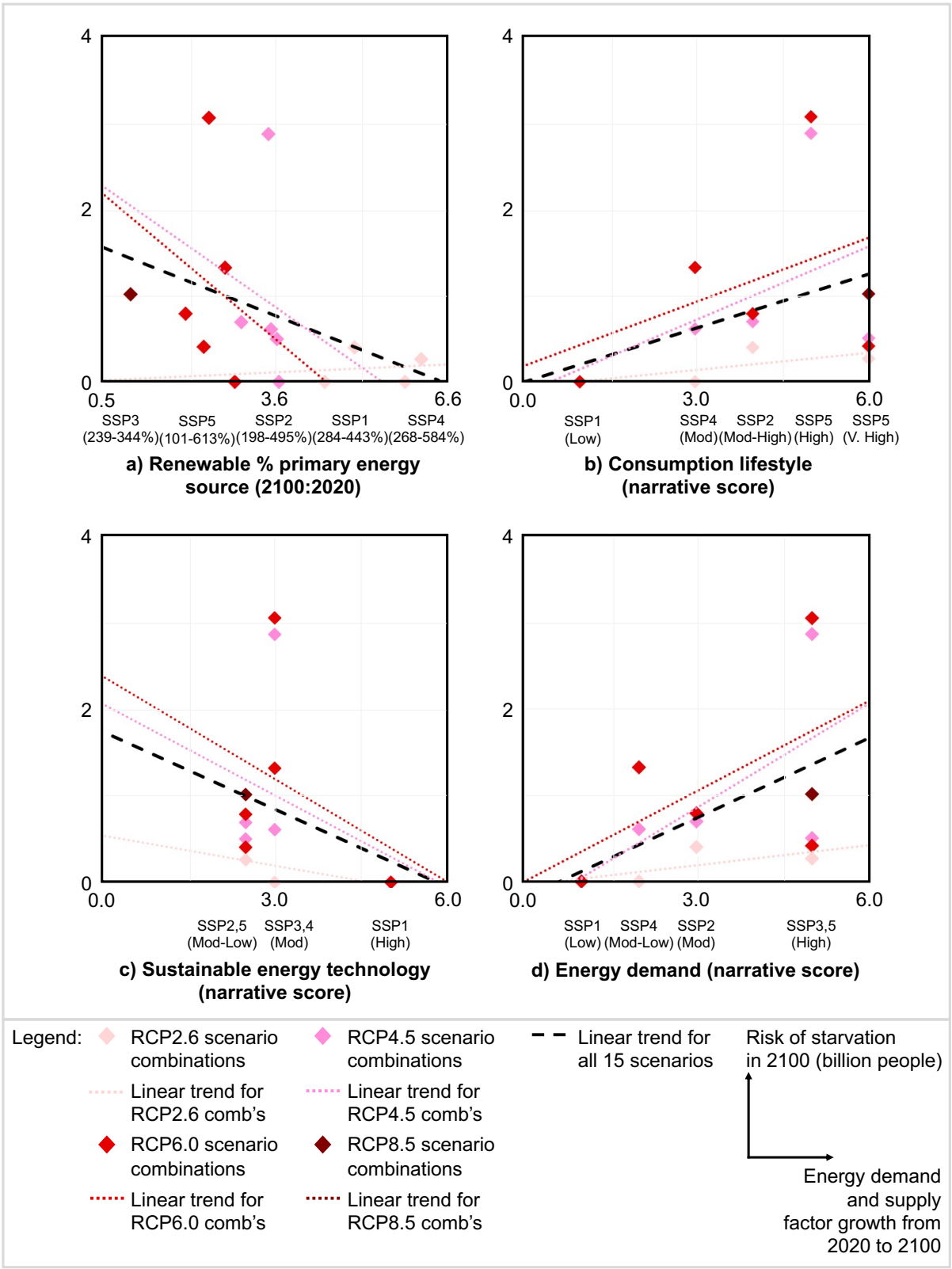


Figure 5.7: Comparison V – Global risk of starvation at 2100 compared to future energy demand and supply growth trends under each of the 15 RCP-SSP-SPA framework scenarios.

5.2.3 Current climate policy and socioeconomic development inequalities

Delving into these nuances from a different angle, Figure 5.8(a) presents the global risk of starvation versus RCP. Each data point represents one of the 15 SSP-RCP scenario combinations, where colouring depicts SSP. Specifically, green depicts SSP1, orange depicts SSP2, purple depicts SSP4, yellow depicts SSP4 and blue depicts SSP5. Linear trendlines, in corresponding colour, are plotted through each SSP collection of datapoints to highlight the influence of the RCP variable trend. A linear trendline is also plotted across all 15 datapoints, shown in black, to highlight the general trend. These results shows that climate change exacerbates human suffering regardless of SSP, with the overall trend indicating risk of starvation increasing by 200 million people per 1 W/m^2 increase in climate forcing by 2100.

Figure 5.8(b)-(e) further depicts the influence of current climate policy and socioeconomic development inequalities on the risk of starvation (Comparison VI). In each of these graphs, the national population at risk of starvation is shown on the y-axis. The current inequality factor in 2020 is shown on the x-axis. The black coloured data points represent all countries across all 15 SSP-RCP scenario combinations. The inset graphs distinguish the data points for all countries for each SSP group respectively, where green depicts SSP1, orange depicts SSP2, purple depicts SSP4, yellow depicts SSP4 and blue depicts SSP5.

In terms of current GDP|PPP per capita, proxying capacity to invest in climate change interventions, the results indicate that poorer countries will be exposed to greater risk of starvation than wealthier countries. As to current CO_2 emissions per capita, proxying supply side technology sustainability, higher emitters experience lower risk at the expense of lower emitters enduring the greatest risk of starvation. Regarding energy demand per capita, proxying demand side material lifestyle sustainability, countries with superfluous material lifestyles will face relatively low food insecurity, despite contributing most to climate change, at the expense of countries with conservative material lifestyles suffering the greatest risk of starvation. With reference to food production per capita, proxying supply side agricultural sustainability, countries without productive agriculture will be exposed to a greater risk of starvation than self-sustaining countries. Considering food demand per capita, proxying demand side dietary lifestyle sustainability, countries exhibiting excess lifestyles encounter relatively lower risk, despite driving international competition, at the expense of countries with conservative dietary lifestyles suffering the greatest risk of starvation.

These results demonstrate that existing inequalities in climate policy and socioeconomic development may manifest global climate injustice, discussed further in Section 5.3.

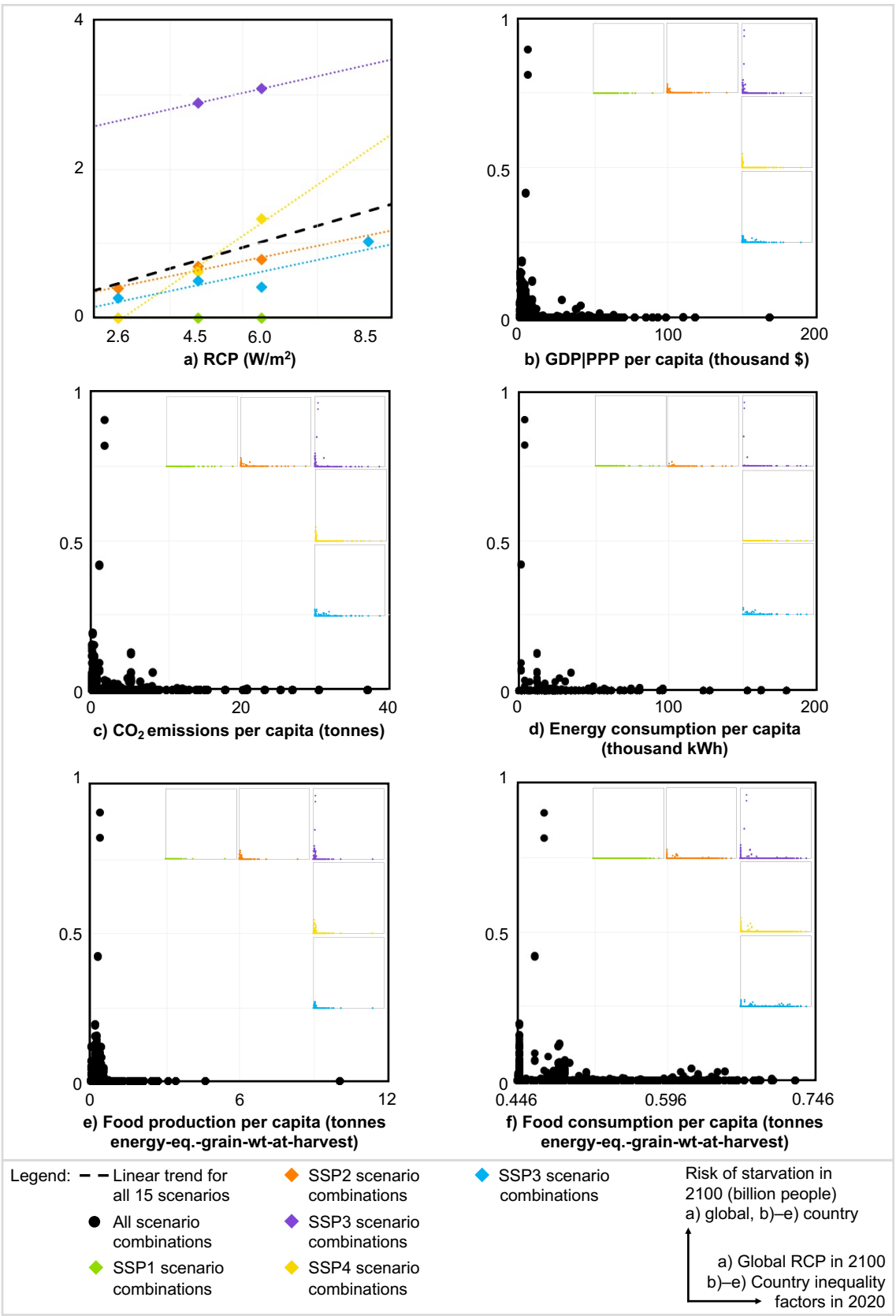


Figure 5.8: Comparison VI – (a) Global risk of starvation at 2100 compared to climate forcing for each of the 15 RCP-SSP-SPA framework scenarios. Each data point represents one of the 15 scenarios, where colouring depicts SSP. Linear trendlines are plotted through each SSP collection of data points to highlight the influence of the RCP. A black linear trendline is plotted across all 15 data points to highlight the general trend. (b)-(e) National risk of starvation at 2100 compared to current climate policy and socioeconomic development inequalities. Each black data point represents a country, with results for each country across all 15 scenarios plotted individually. The inset graphs distinguish the data points by SSP and maintain the x-axis and y-axis scale of the respective graph.

5.3 Discussion

This investigation provides insights into the influence of climate policy and socioeconomic development decision factors on the risk of starvation in four themes. The danger of human suffering under low- to mid-range global warming is discussed in Section 5.3.1. The influence of climate policy is discussed in Section 5.3.2. The influence of socioeconomic development is discussed in Section 5.3.3. The potential for inequalities to manifest global climate injustice is discussed in Section 5.3.4.

5.3.1 Danger of human suffering under low- to mid-range global warming

The investigation of 'extreme global warming' (8°C+ by 2100) in Chapter 4 illustrated a concerning narrative about the threat of societal collapse due to declining agricultural yields and cascading food supply chain disruption induced by climate change. Despite examining low- to mid-range global warming (1.5–4.5°C by 2100), this investigation demonstrates an equally concerning, albeit less extravagant, danger of up to 2.5 billion people suffering from starvation should we not act urgently to reduce emissions. Although concerning, these results should not be surprising. Figure 5.9 illustrates the simple narrative underpinning the results in Figure 5.2, using Pakistan as an example where some 91 million people, or 40% of the population, are at risk of starvation by 2100 under SSP5-RCP85.

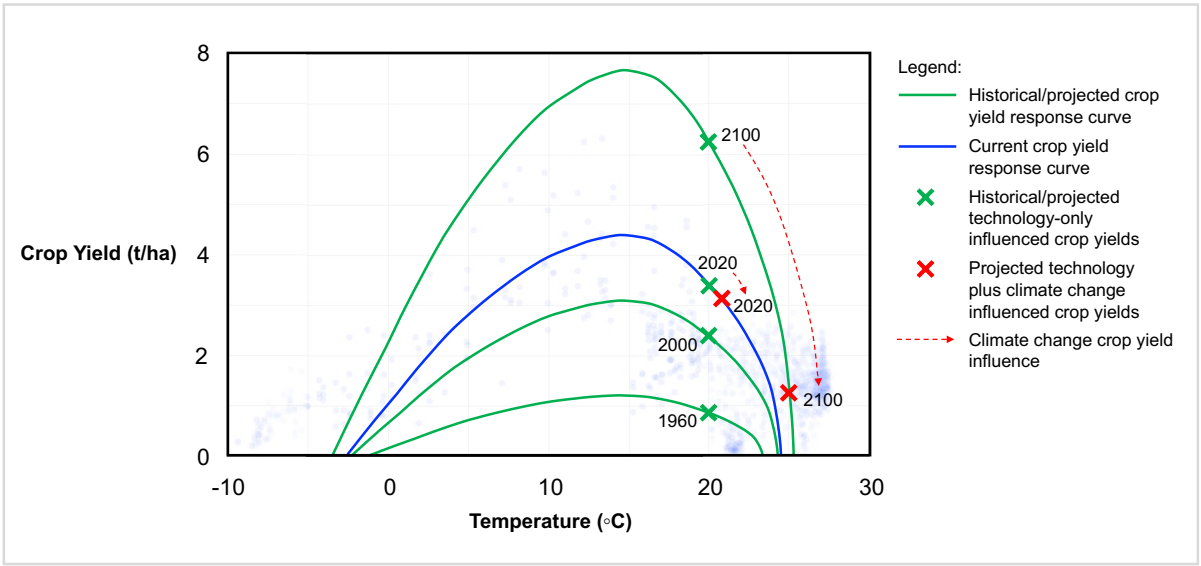


Figure 5.9: Simulation narrative of climate niche shift causing food insecurity and human suffering. Example depicted for staple cereals in Pakistan under SSP5-RCP85. Data basis: historical mean annual temperature from The World Bank (2021b); historical mean cereal yields and technology-based yield increases from Ritchie and Roser (2013); projected mean annual temperature and climate- plus technology-based cereal (proxied by wheat, rice, maize average) yield increases under SSP5-RCP85 from Section 3.1 (Iizumi et al. 2017, 2020).

Our complex contemporary society depends on open environment agriculture made possible by the stable climate niche of the Holocene. For Pakistan, this embodies a mean annual temperature of ~20°C, with associated mean cereal yield of ~1 t/ha (green X for 1960 in Figure 5.9). The explosion of agriculture since the Neolithic Revolution has seen technology increase crop productivity at a constant rate within this same climate niche through engineered crop varietals, irrigation systems and fertilizers. In Pakistan, technology has seen historical cereal yields increase ~0.385 t/ha per decade (green X for 2000, 2020 and 2100). Every crop has a unique productivity profile corresponding to a temperature range, shown for established staple cereals in Pakistan (blue and green lines). While technological innovation may continue to increase productivity, climate change is predicted to push most global agriculture outside its climate niche (Xu et al. 2020), resulting in an overall decline in crop yields. In Pakistan, the increase to ~21°C (red X for 2020) already induced by climate change has had negligible impact on cereal productivity, with yields at ~3 t/ha. However, an increase to ~25°C by 2100 under SSP5-RCP85 (red X at 2100) will leave the bulk of Pakistan's food production outside the stable climate niche on which it relies, with yields plummeting from a potential ~6 t/ha back to ~1t/ha.

Pakistan's buying power is predicted to improve with its GDP per capita increasing from 30% to 80% of the world average by 2100. However, gains in food security through international trade are offset by climate change induced production shocks across breadbaskets resulting in global food scarcity, as evidenced in the 2007–2008 world food crisis (Verschuur et al. 2021). Against this backdrop, with a 60% increase in Pakistanis compared to world population growth of only 24%, Pakistan looks to face societal collapse by the end of the century. Furthermore, people experiencing starvation may resign to natural mortality, but equally may exhibit a 'fight' or 'flight' response. As such, the human suffering indicated in this study would be worse when accounting for other aspects of institutional breakdown, migration and conflict that can cascade globally (Richards et al. 2021), as established in Chapter 3.

This investigation demonstrates that our choices today regarding both climate policy and socioeconomic development will determine whether zero or over 2.5 billion people will suffer from starvation by the end of the century. The influence of some of these decision factors is discussed below.

5.3.2 Influence of climate policy decision factors

Decision factor trends observed in the results are contextualised below by considering two hot topics in the climate action debate: mitigation versus adaptation and technology versus behaviour.

On mitigation versus adaptation, Figure 5.2 and Figure 5.8 indicate that risk of starvation increases under worsening climate change. Figure 5.3 shows that populations most exposed will face the greatest challenges to adaptation. This suggests that mitigation to prevent climate change, thereby avoiding the need to adapt to uncertain consequences under challenging circumstances, is the best pathway forward.

However, the nuances in these results demonstrate that the answer is not so straightforward, echoing Hasegawa et al. (2018) and Fujimori et al. (2019). In some cases (e.g. SSP5), stringent mitigation actions, particularly regarding agricultural land use, can have adverse effects on food security. This necessitates interdisciplinary design of climate policies that consider cross-sector synergies and trade-offs so as not to inadvertently undermine other sustainability goals (Liu et al. 2020).

While economists grapple with the costs of mitigation versus adaptation (Köberle et al. 2021), our ethical responsibility to address climate change in the present to avoid exposing future generations to its harmful consequences is ever more pressing (Jones et al. 2018). Echoing Lyon et al. (2021), the results of this investigation highlight that each passing year of unabated emissions will force policymakers to strike an increasingly delicate balance between proactive mitigation and reactive adaptation.

On technology versus behaviour, Figure 5.7 indicates that risk of starvation under climate change decreases with increased implementation of renewable energy sources, such as geothermal and solar, and energy efficient or low carbon technologies as well as with decreased material and energy consumption. Figure 5.6 shows that risk of starvation decreases with increased agricultural productivity and decreased food demand. This suggests that both supply side technology and demand side lifestyle changes are important to climate change mitigation and adaptation with respect to food security.

However, neither solution is perfect. Some mitigation and adaptation technologies, such as renewable energy (Bogdanov et al. 2019) and closed environment agriculture (Tzachor et al. 2021) systems, are increasingly proven as technically and socially viable. Other technologies lack feasibility due to technical uncertainty, such as with carbon capture and storage (Lane et al. 2021), governance risks where the 'cure may be worse than the disease', such as with stratospheric aerosol injection (Tang and Kemp 2021), and ethical dilemmas, such as relocating to 'Planet B' (Rees 2018). Similarly, while demand side action could be taken immediately (Allwood et al. 2019), voluntary behavioural shifts require uniform personal norms from a heterogenous global society or involuntary behavioural shifts through legislation currently lacking amongst political obstacles (Bouman et al. 2021). This further necessitates interdisciplinary and universally balanced supply and demand side strategies (Spillias et al. 2020).

While techno-optimists and -pessimists remain at odds, both technical and behavioural realism is clearly warranted. Echoing Nelson and Allwood (2021), the results of this investigation suggest that tackling climate change requires both behavioural and technological disruption with prioritisation of tangible near-term actions over slow-burn solutions-in-the-making.

5.3.3 Influence of socioeconomic development decision factors

The decision factor trends observed in the results are further contextualised below by considering the two issues of resilience and vulnerability to climate change, both of which are influenced by a plethora of confounding socioeconomic factors.

Figure 5.4 indicates that risk of starvation under climate change increases with population growth, a critical aspect of demand side intervention as documented by Molotoks et al. (2021). While other studies have demonstrates the negative impact of poor urban sprawl governance (Bren d'Amour et al. 2017), these results indicate that risk of starvation decreases amongst urban populations (Davies 2018, Gu et al. 2019) with better access to services, such as education, gender equality and social cohesion (Cole et al. 2018).

Figure 5.5 and Figure 5.6 show that risk of starvation decreases with increasing wealth and income equality as well as improved institutional capacity and international cooperation. This demonstrates need for investment capacity toward technological capabilities and nature-based solutions for mitigation and adaptation (UNEP 2021), and policies supporting decarbonisation of international supply chains (Mercure et al. 2021), global market transformation (Zamarioli et al. 2021) and responsible financing by universal owners (Mathiesen 2018, Campiglio et al. 2018).

This investigation highlights that reliable infrastructure and persistent governance to support sustainable populations, cities and lifestyles (O'Neill et al. 2020) is essential to increase resilience and decrease vulnerability to climate change from global to local scale (Molina et al. 2020, Karatayev et al. 2021).

5.3.4 Inequalities manifesting as global climate injustice

Figure 5.8 shows that wealthy nations maintain excess lifestyles with high emissions at the expense of developing nations most vulnerable to climate change despite contributing less to the problem. This

highlights the ethical issue of whether people from developed nations hold a moral obligation to prevent collective human suffering, to which global justice scholars increasingly propose interventions.

On the demand side, Hickel et al. (2021) urges 'post-growth' strategies for developed nations to curb excess lifestyles, unnecessary for wellbeing. Reducing energy consumption aids mitigation through reduced emissions, while reducing food demand and waste aids mitigation through reduced emissions and adaptation through decreased international trade competition (Bajželj et al. 2014). On the supply side, Rees (2021) encourages wealthy countries to invest in technology both domestically and internationally. Arezki (2021) and Ameli et al. (2021) show that climate financing to 'leap frog' large populations of developing nations from conventional to renewable energy is essential for mitigation, while Queiroz et al. (2021) demonstrate its utility in building adaptative capacity, such as risk resilient food systems (Tzachor et al. 2021), in vulnerable populations. As highlighted in Chapter 4, mitigation commitments by emerging superpowers are critical to reducing the risk of human suffering and global climate injustice.

This investigation emphasises the importance of global and intergenerational cooperation and coordination to address anthropogenic climate change. It buttresses conclusions made in Chapter 4 regarding the need to tailor intervention strategies to local context and the importance of international law to protect human rights (Viglione 2020).

5.4 Chapter summary: key findings

This investigation developed a quantitative model and performed a comparative analysis to explore the influence of climate policy and socioeconomic development on climate change, food insecurity and societal collapse at global scale and country-level granularity through to the end of the century, to satisfy the refined research objective of component RQ3.

The computational simulation provides insights into the danger of human suffering under low- to mid-range global warming, the influence of climate policy decision factors, the influence of socioeconomic development decision factors and how inequalities may manifest global climate injustice. Even under low- to mid-range global warming (1.5–4.5°C by 2100), agricultural failures and competition for international food supply may see some 2.5 billion people at risk of starvation, which may cascade to migration and conflict, if we do not act urgently to tackle anthropogenic climate change. Socioeconomic

development will also have a strong influence on whether fellow humans will suffer by the end of the century. The comparative analysis highlighted that climate policy should prioritise urgent mitigation via behavioural disruption, while supporting slow-burn technological solutions-in-the-making. Additionally, socioeconomic development supporting education, income and gender equality, social cohesion and investment in sustainable infrastructure and services is essential to build resilience and decrease vulnerability. Strong global institutional coordination, international cooperation and inclusive national governance is essential for tackling existing inequalities, including emissions through to wealth, that may manifest the ethical problem of global climate injustice.

Good risk management requires informed prioritisation of factors in decision-making in the present. A lack of urgency to tackle climate change coupled with poorly informed socioeconomic development decisions in the present could prove catastrophic for society. These insights emphasise that humanity may face significant suffering under low- to mid-range global warming by the end of the century should we not act globally with haste to reduce anthropogenic emissions, build resilience and decrease vulnerability. The moral obligation of high emitting countries to prevent human suffering worldwide and the need for international collaboration to address existing inequalities that may manifest global climate injustice is demonstrated. This third investigation of the three-part research framework provides an incremental contribution to knowledge with respect to component RQ3, which has broader implications for society discussed in Chapter 6.

[blank page]

Chapter 6

Conclusion: toward better risk management

This chapter reflects on the aim of this thesis to investigate the worst-case impacts of anthropogenic climate change, prompted by the motivation that reframing the threat of global warming may facilitate better risk management by articulating tangible risk of everyday relevance to individuals, business and governments (see Chapter 1). Section 6.1 summarises contributions to knowledge yielded from the three-part research framework of this thesis. Section 6.2 suggests opportunities for future research to build on these contributions. Section **Error! Reference source not found.** contextualises this line of work by reflecting on its broader implications for society. Section 6.4 provides a brief close to this thesis.

6.1 Research contributions to knowledge

The three-part investigation contained in this thesis made contributions to knowledge pertaining to the complex risk landscape of climate change, food insecurity and societal collapse, as follows.

6.1.1 Contribution 1: learning from the past

Good risk management requires learning from the past to inform decision-making in the present. The first investigation was prompted by RQ1: *How can systematically documenting historical evidence improve our understanding of the complex risk landscape of climate change, food insecurity and societal collapse?*

In Chapter 3, an original empirical evidence base of climate change, food insecurity and societal collapse in contemporary society was established and systematically structured using a novel format causal loop diagram defined at global scale and national granularity. Thousands of feedback loops were unfurled, demonstrating fragile interdependencies that may see climate change undermine agricultural productivity and food supply chains, leading to cascading or synchronous sociocultural unrest, economic loss, political dysfunction, starvation, migration and conflict, with the potential to trigger a reinforcing 'global systems death spiral'.

This systematic documentation of evidence facilitates succinct visual consideration and communication of the complex risk landscape and spread of established empirical evidence, providing a basis for interdisciplinary collaboration and identification of critical feedback loops and intervention points.

6.1.2 Contribution 2: surveying end-game futures

Good risk management requires surveying 'end-game' futures to inform decision-making in the present. The second investigation was prompted by RQ2: *What insights into the future international risk landscape can be gained by illustrating climate change, food insecurity and societal collapse under 'extreme global warming'?*

In Chapter 4, an original quantitative model was developed to illustrate the future international risk landscape of climate change, food insecurity and societal collapse at global scale and national granularity under an original high-range global warming (8°C+ by 2100) scenario. This simulation shows that we may face societal collapse as early as 2050, plummeting to 32% of the current population by 2100. The distribution of risk will not be equal, with the least prepared countries of the Global South hit the hardest, experiencing 93% of cumulative human suffering by 2100. Emerging superpowers have a unique role to play in mitigating climate change, not only in the best interests of the rest of the world but for their own sake, with China and India alone at risk of 1.2 billion and 1.6 billion people facing starvation. These insights highlight the impending danger of societal collapse should we not act with haste to reduce anthropogenic emissions, build resilience and decrease vulnerability.

6.1.3 Contribution 3: prioritising decision factors in the present

Good risk management requires informed prioritisation of factors in decision-making in the present. The third investigation was prompted by *RQ3. How might decisions in the present regarding climate policy and socioeconomic development influence climate change, food insecurity and societal collapse?*

In Chapter 5, a quantitative model was used to conduct an original comparative analysis of the influence of climate policy and socioeconomic development on climate change, food insecurity and societal collapse at global scale and national granularity under the 15 RCP-SSP-SPA scenarios of low- to mid-range global warming (1.5-4.5°C+ by 2100). These simulations show that some 2.5 billion people may face starvation, conflict or migration by 2100. The comparative analysis suggests that climate policy should prioritise urgent mitigation via immediate behavioural disruption, while supporting slow-burn technological solutions-in-the-making. Socioeconomic development supporting education, income and gender equality, social cohesion and investment in sustainable infrastructure and services is essential to build resilience and decrease vulnerability. High emitters hold a moral responsibility to address existing inequalities that will manifest global climate injustice. These insights emphasise that strong global coordination and international cooperation is needed to tackle climate change with proactive and well-balanced decisions if we are to prevent immense human suffering into the future.

6.1.4 Overarching contribution: an investigation of the worst-case impacts of climate change

In line with its aim, this thesis provides a systematic and quantitative investigation of the worst-case impacts of climate change through the mechanism of food insecurity and societal collapse. Collectively, this investigation demonstrates that climate change, while also having dangerous direct impacts, will play a major role as an X-risk via the potential for indirect cascading effects and synchronous failures to trigger reinforcing systemic lock-in of collapse. Both technological and socio-politico-economic interventions may help society mitigate and adapt to the threat of climate change, but we must be mindful of the potential for such interventions to backfire and exacerbate rather than solve the problem.

In *'Assessing climate change's contribution to global catastrophic risk'*—published just as this investigation was being finalised—Beard et al. (2021) theoretically describe the concept of a 'global systems death spiral' and call for further research into the systemic impacts of climate change. Coincidentally responding to

this call, the research contained in this thesis may be thought of as providing a proof-of-concept. Yet, the fact remains that the traditional risk management paradigm is inadequate to deal with X-risks while X-risk scholars tend to neglect climate change relative to 'sexier' risks like artificial intelligence. While this thesis makes an incremental contribution to this line of work, there is still much work to be done in developing a deeper understanding of the worst-case impacts of, and solutions, to climate change.

6.2 Future research opportunities

The contributions to knowledge of this thesis, as well as issues identified during the process of conducting this research, provide 'micro' and 'macro' opportunities for X-risk scholars, as well as researchers and practitioners in interfacing fields, to conduct further work. Examples within three themes related to data availability (Section 6.3.1), methodology (Section 6.3.2) and extending beyond the boundaries of this research (Section 6.3.3) are provided in turn below.

6.2.1 Addressing data availability issues

The fact that contemporary society has not yet experienced an anthropogenic climate change induced societal collapse, means that there is limited data available to understand the complex risk landscape. The first investigation (Chapter 3) identified 41 empirical evidence points investigating emerging climate change, food insecurity and societal collapse relationships. It would be useful for future work to keep abreast of the emerging effects of climate change and continue to update empirical analyses. Identification of gaps in the spread of evidence across the causal loop diagram may guide future data-driven efforts to examine these causal relationships and define thresholds.

An 'extreme global warming' scenario was approximated in the second investigation (Chapter 4) due to a lack of available data on high-end global warming. Future work leveraging detailed climate models to produce high resolution datasets of various climate change impacts under high-end global warming scenarios would support research on 'extreme climate change'. On this front, researchers may find it useful to extend Tokarska et al. (2016)'s study of climate response to five trillion tonnes of carbon. Similarly, a growth shock threshold and growth shock period were estimated based on recent coronavirus disruptions, due to a lack of otherwise defined data. Future work may attempt to track and quantify socioeconomic disruption thresholds and lag periods caused by climate change catastrophes.

Climate impacted total crop yields were proxied using maize, rice, soybean and wheat yields in the second and third investigation (Chapter 4, 5) due to a lack of available data on other crops. Future work to develop consistent high-resolution data sets on different crop yields, would support subsequent studies on food security. Furthermore, it was not possible to isolate climate change impact from technological influence on crop yields in the scenario-based high-resolution datasets. Future work toward distinct and bias-corrected high-resolution data sets of scenario components, in a similar vein to Beyer et al. (2020), would support more precise future climate change impacts research.

In the second and third investigation (Chapter 4, 5) values were estimated where a country was missing from established datasets. Future work toward complete coverage of countries in historical datasets and future scenarios, where expert estimates could be provided if 'real' data is not available, would improve comprehensive characterisation of the international risk landscape (Reichstein et al. 2021).

6.2.2 Addressing methodological issues

The first investigation (Chapter 3) examined climate change, food insecurity and societal collapse in contemporary society only. Future work could implement the same methodology to systematically document the plethora of empirical evidence pre-dating contemporary society and/or the 'foresight studies' surveying potential futures. Although most of this evidence dates to ancient history, this exercise would likely still yield lessons from the past.

Climate change was considered only in the form of temperature effect on crop yields in the second and third investigations (Chapter 4, 5). Future work could incorporate other potential impacts. Researchers may find it useful to extend from recent studies on precipitation (Fischer et al. 2021), physical natural disasters, such as fires and floods (Tabari 2020), biological natural disasters, such as pests and diseases (Ma et al. 2021), sea level rise (Tebaldi et al. 2021), and heat stress (Vicedo-Cabrera et al. 2021), which will likely exacerbate the risk of societal collapse. Additionally, the influence of climate change on crop yields assumed no CO_2 fertilisation and future work could examine related sensitivities.

Food insecurity was considered only in the form of food availability in the second and third investigations (Chapter 4, 5). Future work could consider the other pillars of accessibility, utilisation and stability, which will likely exacerbate the unequal distribution of suffering. Researchers interested in the complexity of food insecurity may find it useful to extend from Nicholson et al. (2021)'s analysis of international stability of the food system to inform crop diversification strategies and Natalini et al.

(2017)'s study of food prices and the risk of riots. Additionally, food production was considered only in the form of crop-based agriculture. Future work could extend these methodologies by including animal-based agriculture. On this front, researchers may find it useful to leverage Froehlich et al. (2018)'s and Godde et al. (2021)'s analysis of aquaculture and livestock. International food trade was simulated in 'free form', without accounting for trade agreements, in the second and third investigations (Chapter 4, 5). Future work could extend this methodology to explore the effect of different geopolitical and economic futures, in a similar vein to Janssens et al. (2020).

The comparative analysis of the third investigation (Chapter 5) explored general trends only. Future work may conduct rigorous statistical examinations to flesh out complex multivariate interdependencies that may outpace univariate effects of climate change (Abatzoglou et al. 2020). On this front, researchers may find it useful to extend from Guo et al. (2018)'s study of the confounding effect of land-use change on climate-driven species redistribution and Korell et al. (2021)'s study of confounding effects on the influence of precipitation on plant diversity.

Six determinants of societal collapse were established in Chapter 2, namely: population loss via natural mortality, conflict mortality and emigration, and institutional breakdown via economic loss, political dysfunction and sociocultural unrest. The first investigation (Chapter 3) examined only the population set of determinants as proxies of societal collapse, while the second and third investigations (Chapter 4, 5) examined only the natural mortality determinant in the form of starvation. Future work could apply the same methodologies to examine the other determinants. Concerted research effort on the quantification and simulation of migration and conflict, as well as the institutional breakdown set of determinants, is particularly needed given that these cascading reactions of individuals and nations and the dynamic feedbacks between them, termed a 'global systems death spiral' by Beard et al. (2021), would likely exacerbate the risk of societal collapse and human suffering highlighted in this thesis.

6.2.3 Extending beyond the boundaries of this investigation

At a macro-level, the work contained in this thesis raises new research questions. For instance, this thesis examined the relationship between climate change, food insecurity and societal collapse, but is food shortage the key or are there other climate change impacts that will cause collapse sooner? Future work could examine other causal pathways between climate change and societal collapse such as the indirect impacts via water insecurity instead of food insecurity, or the direct impact of extreme weather events on infrastructure and people.

How will climate change interact with other X-risks? Future work could explore both how climate change may exacerbate the potential for other global catastrophes, including biological threats such as pandemics, and how other global catastrophic risks may amplify the effects of climate change, such as the occurrence of nuclear winters associated with the threat of nuclear war.

How would societal collapse influence an individual's insurance costs, business supply chain stability, stock market valuations, government security risk and world peace? Future work could look to systematically quantify the broader implications (Section 6.2) of this thesis. Additionally, by asking who should do what and how to reduce the risk of societal collapse, future research could consider the effect of intervention strategies.

How does response to the messaging of societal collapse differ across different demographics, such as race, ethnicity, gender or sexual orientation? To what extent does better foresight of societal collapse motivate more rapid action on climate mitigation versus adaptation? Future work, including psychology-based studies, could look to quantify the response of different stakeholders across society to the consideration and communication of 'societal collapse' compared to 'global warming' to optimise the effect of the reframing proposed in this thesis.

There are several opportunities for future work to build on this thesis with practical applications. For example, the financial sector is increasingly turning to existential risk researchers for advice on incorporating existential risk externalities into traditional financial models. Research in this space could provide a basis for developing such advisory services on climate change. Similarly, governmental departments increasingly seek expert advice on existential risks. This research could be extended to develop a monitoring 'dashboard' or 'early warning system' of key metrics providing policy makers with a snapshot of the international risk landscape of climate change and societal collapse. Research in this space could also be used as a basis for designing a scenario-based role-playing game (RPG) to strategically explore climate change futures (Carfí et al. 2021). Such games are useful for education, increasing stakeholder collaboration and crowdsourcing solutions (Jacobson et al. 2019). On this front, researchers may find it useful to reflect on the exemplar implementation of the recently launched Intelligence Rising RPG for the X-risk of artificial intelligence by Avin and Greutzemacher (2021).

6.3 Broader implications for society

This investigation was prompted by the motivation that reframing the threat of global warming may facilitate better risk management by articulating more tangible risk of everyday relevance. To 'close the loop' on this thesis, this section contextualises the contributions to knowledge and opportunities for future research by reflecting on this motivation with respect to society and current trends more broadly. The framing of 'societal collapse' used to conduct this research is defined by determinants of institutional breakdown in the form of economic loss, political dysfunction and sociocultural unrest as well as population loss in the form of natural mortality, conflict mortality and emigration. As such, unlike 'global warming', this framing links to tangible everyday risks presently dealt with by individuals (Section 6.2.1), businesses (Section 6.2.2) and governments (Section 6.2.3), considered in turn below.

6.3.1 Individuals, media and cultural institutions

For individuals, the framing of societal collapse relates to the personal and interpersonal risk they manage every day to prevent harm to themselves. For instance, people will quickly abandon their swim at an idyllic beach in the summer if a shark alarm sounds to prevent loss of life. Similarly, people will quickly change holiday plans if their destination suddenly has an outbreak of civil war or terrorism. Thus, a deeper understanding of the worst-case impacts of climate change may provide individuals with more reason to mitigate the threat through behavioural changes (Wagner and Weitzman 2015). This need not be at the cost of living well, with the synergies between demand side mitigation and personal wellbeing increasingly recognised (Creutzig et al. 2021). Furthermore, people pay for home, car and life insurance to reduce potential financial damage. If climate change could be considered in similar terms of economic loss, individuals may be more amenable to insuring against its potential damages, which could be used to rapidly finance slow-burn technological solutions (Hinkel et al. 2020).

Media and cultural institutions play a significant role in communicating the risk of climate change (Olausson 2011). The framing of societal collapse could further support these influential bodies to generate ownership and understanding by educating individuals about the threat of climate change. In fact, evidence of this is already emerging. BBC Futures recently shared an article by Kemp (2019a) on the risk of societal collapse related to climate change with its regular audience of ~10 million (BBC Future 2021). Famous universities, such as Cambridge (Taylor 2020) and Harvard (Oreskes and Andrade 2021), have recently made fossil fuel divestment announcements, making international

headlines. Pope Francis is increasingly vocal on climate change as an existential threat (Schiermeier 2015), calling some 1.2 billion Catholics for urgent climate action (Lowen 2021).

6.3.2 Businesses, universal owners and financial regulators

For businesses, the framing of societal collapse relates to the internal and external risks they manage every day to prevent financial loss. Environmental, Social and Corporate Governance (ESG) is an increasingly hot topic. This suggests that if climate change was considered beyond its environmental roots as a tangible socio-cultural risk, then businesses may feel more urgent reputational pressure to mitigate the threat through behavioural changes (Fiedler et al. 2021). This need not be at odds with the bottom line, as there exists a plethora of opportunities for entrepreneurs to profit from investments in climate mitigation and adaptation, including 'clean' and 'green' technologies and advisory services (Allwood 2021). Like individuals, businesses insure their operations against risks, including extreme weather events, yet the incorporation of anthropogenic climate change externalities into traditional financial risk models remains a challenge (Pieper et al. 2020). Additionally, businesses quickly spend money on the latest technologies to optimise supply chains to maximise profit (Denis et al. 2020). If businesses could consider climate change across a more tangible span of economic losses, they may be more amenable to incrementally insuring against its potential damages, which could be used to rapidly finance 'nature based' solutions (McKinsey & Company 2020).

Universal owners and regulators, themselves extremely exposed to the threat of climate change, play a significant role in communicating and distributing the risk (Quigley 2020). Thus, a deeper understanding of the worst-case impacts of climate change may further support these influential bodies to generate more urgent climate action by creating mechanisms that support sustainable economics and responsible investment. In fact, evidence of this is already emerging. Calls for transformation of financial markets (Zamarioli et al. 2021) and ESG and responsible investment standards (Schumacher 2020) are gaining traction, as are proposals of regulatory incentives for businesses to decarbonise international supply chains (Mercure et al. 2021). Central banks, such as the Bank of England, are redefining macroeconomics policies and operations to support the transition to a net-zero economy (Bank of England 2021). The (re)insurance sector is leveraging its prolific money, expertise and perspective to tackle climate change head on, with PoolRe recently launching a strategic initiative to quantify the causal link between climate change and terrorism (Pool Re 2021). There exists a unique opportunity for philanthropists to partner with the (re)insurance sector to build risk literacy and influence discourse

across society, as well as to advise the development of innovative climate change insurance products and support penetration of such products through subsidisation in developing nations (Browne 2021).

6.3.3 Government, intergovernmental and international institutions

For governments, the framing of societal collapse relates to the domestic and international risks they manage every day to safeguard their citizens and prevent world war. For instance, governments have long held the responsibility of ensuring adequate provision of water, food, energy and shelter for residents, as well as migrants seeking asylum, in the face of traditional risks. If governments had the opportunity to consider climate change in terms of mass international migrations and political dysfunction that may undermine basic security for both residents and those seeking asylum, they may be more urgently motivated to promote and legislate mitigation through behavioural changes (Xu et al. 2020). As incumbent governments tend to pander to the popular vote, opposition party politics can play a key role in generating urgent climate action. Furthermore, governments have a long history of spending large sums on national security and defence. If governments could consider climate change in terms of tangible conflict outcomes, they may be more amenable to incrementally redirect funds to offset sunk military costs, which could be used to rapidly finance 'regenerative security' solutions (Schröder and Evans 2021). The USA Department of Defence has long been cognizant of the security risks of climate change, with their most recent Climate Risk Analysis emphasising the evolving existential threat that climate changes poses to national security (DOD 2021).

Intergovernmental organisations and international institutions play a significant role in communicating the risk of climate change. A deeper understanding of the worst-case impacts of climate change may support these influential bodies to generate urgent climate action by establishing intergenerational governance systems and global laws of existential security to educate and bind nations to tackling the threat of climate change (Sears 2020). In fact, evidence of this is already emerging. The World Economic Forum produces annual *Global Risks Reports* (WEF 2021) and the United Nations Office for Disaster Risk Management is addressing needs for new existential risk management frameworks, with a focus on raising awareness of geo-economic implications and the need for multi-stakeholder approaches in managing uncertainty. Recently, the United Nations Human Rights Committee made a landmark ruling that refugees fleeing climate crises cannot be forced away by their adoptive countries (UN 2020).

6.4 Chapter summary: denouement

Good risk management requires consideration and communication of tangible worst-case impacts. The research contained in this thesis was prompted by the motivation that reframing imperceptible global warming in terms of more tangible human suffering may support better risk management to safeguard our globalised contemporary civilization against the existential threat of anthropogenic climate change. This investigation provides a theoretical proof-of-concept of climate change as an X-risk via indirect cascading effects and synchronous failures that may trigger a mode of systemic lock-in that may be thought of as a 'global systems death spiral', in which even possible technological and socio-politico-economic interventions may have unintended consequences or backfire to reinforce. There remains much work to be done to develop a deeper understanding of the worst-case impacts of, and solutions, to the unprecedented challenge of anthropogenic climate change, building from the incremental contribution to knowledge made by this thesis. The recent occurrence of low probability events, including COVID-19, the 2021 Suez Canal obstruction and the 2022 Russian invasion of Ukraine, relative lack of analysis of indirect impacts and high-range global warming highlighted by the most recent IPCC (2021) reports and initiation of major research projects into systemic resilience and vulnerability (Oxford Martin School 2022) demonstrates the ongoing importance of this line of work.

[blank page]

References

Abatzoglou JT, Dobrowski SZ, Parks SA (2020) Multivariate climate departures have outpaced univariate changes across global lands. Sci Rep 10:1–9. https://doi.org/10.1038/s41598-020-60270-5

Acemoglu D, Robinson JA (2012) Why Nations Fail: The Origins of Power, Prosperity, and Poverty. Crown Publishers, New York, USA

Acharjee TK, van Halsema G, Ludwig F, et al (2019) Shifting planting date of Boro rice as a climate change adaptation strategy to reduce water use. Agric Syst 168:131–143. https://doi.org/https://doi.org/10.1016/j.agsy.2018.11.006

Acharya SR, Saeed K (1996) An attempt to operationalize the recommendations of the "Limits to growth" study to sustain the future of mankind. Syst Dyn Rev 12:281–304

Afifi, T., Liwenga, E. and Kwezi, L. (2014) 'Rainfall-induced crop failure, food insecurity and out-migration in Same-Kilimanjaro, Tanzania', Climate and Development, 6(1), pp. 53–60. doi: 10.1080/17565529.2013.826128.

Agboola, M. O. (2017) 'Impact of food availability on child mortality: a cross country comparative analysis', Agricultural Economics - Czech, 63, pp. 283–297. doi: 10.17221/333/2015-AGRICECON.

Ahmad I, Ahmad B, Boote K, Hoogenboom G (2020) Adaptation strategies for maize production under climate change for semi-arid environments. Eur J Agron 115:126040. https://doi.org/https://doi.org/10.1016/j.eja.2020.126040

Alexander P, Brown C, Arneth A, et al (2017) Losses, inefficiencies and waste in the global food system. Agric Syst 153:190–200. https://doi.org/10.1016/j.agsy.2017.01.014

Ali MGM, Ibrahim MM, El Baroudy A, et al (2020) Climate change impact and adaptation on wheat yield, water use and water use efficiency at North Nile Delta. Front Earth Sci 14:522–536. https://doi.org/10.1007/s11707-019-0806-4

Allen RC, Heldring L (2021) The Collapse of Civilization in Southern Mesopotamia. Cliometrica. https://doi.org/10.1007/s11698-021-00229-2

Allwood JM (2021) Entrepreneurs not Emissions: New business opportunities to fill the gap in UK emissions policy UK FI RE S Entrepreneurs not Emissions

Allwood JM, Cullen JM (2012) Sustainable Materials: With Both Eyes Open. UIT Cambridge Ltd

Allwood JM, Dunant CF, Lupton RC, et al (2019) Absolute Zero: Delivering the UK's climate change commitment with incremental changes to today's technologies. Cambridge, UK

Althaus D, Gloor L (2016) Reducing Risks of Astronomical Suffering: A Neglected Priority. Cent. Long-Term Risk

Alvar-Beltrán J, Gobin A, Orlandini S, Dao A (2021) Climate resilience of irrigated quinoa in semi-arid West Africa . Clim Res 84:97–111

Ameli N, Dessens O, Winning M, et al (2021) Higher cost of finance exacerbates a climate investment trap in developing economies. Nat Commun 12:1–12. https://doi.org/10.1038/s41467-021-24305-3

Amouzou KA, Lamers JPA, Naab JB, et al (2019) Climate change impact on water- and nitrogen-use efficiencies and yields of maize and sorghum in the northern Benin dry savanna, West Africa. F Crop Res 235:104–117. https://doi.org/https://doi.org/10.1016/j.fcr.2019.02.021

Anapalli SS, Pinnamaneni SR, Fisher DK, Reddy KN (2021) Vulnerabilities of irrigated and rainfed corn to climate change in a humid climate in the Lower Mississippi Delta. Clim Change 164:5. https://doi.org/10.1007/s10584-021-02999-0

Andrijevic M, Crespo Cuaresma J, Lissner T, et al (2020) Overcoming gender inequality for climate resilient development. Nat Commun 11:1–8. https://doi.org/10.1038/s41467-020-19856-w

Ansell T, Cayzer S (2018) Limits to growth redux: A system dynamics model for assessing energy and climate change constraints to global growth. Energy Policy 514–525. https://doi.org/10.1016/j.enpol.2018.05.053

Arbesman S (2011) The Life-Spans of Empires. Hist Methods A J Quant Interdiscip Hist 44:127–129. https://doi.org/10.1080/01615440.2011.577733

Arezki R (2021) Climate finance for Africa requires overcoming bottlenecks in domestic capacity. Nat Clim Chang 11:888. https://doi.org/10.1038/s41558-021-01191-7

Arezki, R. and Brueckner, M. (2014) 'Effects of International Food Price Shocks on Political Institutions in Low-Income Countries: Evidence from an International Food Net-Export Price Index', World Development, 61, pp. 142–153. doi: 10.1016/j.worlddev.2014.04.009.

Arnold TE, Hillman AL, Abbott MB, et al (2021) Drought and the collapse of the Tiwanaku Civilization: New evidence from Lake Orurillo, Peru. Quat Sci Rev 251:106693. https://doi.org/https://doi.org/10.1016/j.quascirev.2020.106693

Arrhenius S (1896) On the influence of carbonic acid in the air upon the temperature of the ground. Philos Mag J Sci 41:237–276. https://doi.org/10.1080/14786449608620846

Arunrat N, Pumijumnong N, Hatano R (2018) Predicting local-scale impact of climate change on rice yield and soil organic carbon sequestration: A case study in Roi Et Province, Northeast Thailand. Agric Syst 164:58–70. https://doi.org/https://doi.org/10.1016/j.agsy.2018.04.001

Avin S, Greutzemacher R (2021) Intelligence Rising: A Strategic Exploration of AI Futures. https://intelligencerising.org

Avin S, Wintle BC, Weitzerdörfer J, et al (2018) Classifying global catastrophic risks. Futures 102:20–26. https://doi.org/10.1016/j.futures.2018.02.001

Bajželj B, Richards KS, Allwood JM, et al (2014) Importance of food-demand management for climate mitigation. Nat Clim Chang 4:924–929. https://doi.org/10.1038/nclimate2353

Bank of England (2021) Climate Change. https://www.bankofengland.co.uk/climate-change

Bar-Matthews M, Ayalon A (2011) Mid-holocene climate variations revealed by high-resolution speleothem records from soreq cave, israel and their correlation with cultural changes. Holocene 21:163–171. https://doi.org/10.1177/0959683610384165

Bar-Oz G, Weissbrod L, Erickson-Gini T, et al (2019) Ancient trash mounds unravel urban collapse a century before the end of Byzantine hegemony in the southern Levant. Proc Natl Acad Sci 116:8239–8248. https://doi.org/10.1073/pnas.1900233116

Bar-Yosef O, Bar-Matthews M, Ayalon A (2017) 12,000-11,700 cal BP: The Collapse of Foraging and Origins of Cultivation in Western Asia. In: Weiss H (ed) Megadrought and Collapse: From Early Agriculture to Angkor. Oxford University Press

Bardi U (2011) The Limits to Growth Revisited. Springer, New York, USA

Bardi U (2013) Mind Sized World Models. Sustainability 5

Bardi U, Falsini S, Perissi I (2019) Toward a General Theory of Societal Collapse: A Biophysical Examination of Tainter's Model of the Diminishing Returns of Complexity. Biophys Econ Resour Qual 4:. https://doi.org/10.1007/s41247-018-0049-0

Bauer N, Calvin K, Emmerling J, et al (2017) Shared Socio-Economic Pathways of the Energy Sector – Quantifying the Narratives. Glob Environ Chang 42:316–330. https://doi.org/10.1016/j.gloenvcha.2016.07.006

Baum SD, Handoh IC (2014) Integrating the planetary boundaries and global catastrophic risk paradigms. Ecol Econ 107:13–21. https://doi.org/10.1016/j.ecolecon.2014.07.024

BBC Future (2021) BBC Future at a glance. https://www.bbcglobalnews.com/platforms/bbc-future/

Beard S, Holt L, Tzachor A, et al (2021) Assessing Climate Change's Contribution to Global Catastrophic Risk. Futures. https://doi.org/https://doi.org/10.1016/j.futures.2020.102673

Beard S, Rowe T, Fox J (2020) An analysis and evaluation of methods currently used to quantify the likelihood of existential hazards. Futures 115:102469. https://doi.org/10.1016/j.futures.2019.102469

Beard S, Torres P (2020) Ripples on the Great Sea of Life: A Brief History of Existential Risk Studies. https://doi.org/10.2139/ssrn.3730000

Bellemare, M. F. (2014) 'Rising food prices, food price volatility, and social unrest', American Journal of Agricultural Economics, 97(1), pp. 1–21. doi: 10.1093/ajae/aau038.

Below A (2019) Climate change: The existential threat multiplier. In: Understanding New Security Threats. Routledge

Beltrán-Tolosa LM, Navarro-Racines C, Pradhan P, et al (2020) Action needed for staple crops in the Andean-Amazon foothills because of climate change. Mitig Adapt Strateg Glob Chang 25:1103–1127. https://doi.org/10.1007/s11027-020-09923-4

Berazneva, J. and Lee, D. R. (2013) 'Explaining the African food riots of 2007–2008: An empirical analysis', Food Policy, 39, pp. 28–39. doi: 10.1016/j.foodpol.2012.12.007.

Bereiter B, Eggleston S, Schmitt J, et al (2015) Revision of the EPICA Dome C CO2 record from 800 to 600 kyr before present. Geophys Res Lett 42:542–549. https://doi.org/10.1002/2014GL061957

Berners-Lee M (2019) There Is No Planet B: A Handbook for the Make or Break Years. Cambridge University Press

Bernstein PL (1996) Against the Gods: The Remarkable Story of Risk. John Wiley & Sons, New York, USA

Best J (2014) The Vatican Has a Farm, and Pope Francis Is Going to Open It Up to the Public. TakePart

Beyer RM, Krapp M, Manica A (2020) High-resolution terrestrial climate, bioclimate and vegetation for the last 120,000 years. Sci Data 7:1–9. https://doi.org/10.1038/s41597-020-0552-1

Bijl DL, Bogaart PW, Dekker SC, et al (2017) A physically-based model of long-term food demand. Glob Environ Chang 45:47–62. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2017.04.003

Bogdanov D, Farfan J, Sadovskaia K, et al (2019) Radical transformation pathway towards sustainable electricity via evolutionary steps. Nat Commun 10:1–16. https://doi.org/10.1038/s41467-019-08855-1

Bonnet R-M, Woltjer L (2008) Surviving 1000 Centuries: Can We Do It? Praxis Publishing, Chichester, UK

Bostrom A, Böhm G, Hayes AL, O'Connor RE (2020) Credible Threat: Perceptions of Pandemic Coronavirus, Climate Change and the Morality and Management of Global Risks. Front Psychol 11:1–11. https://doi.org/10.3389/fpsyg.2020.578562

Bostrom N (2002a) Existential Risks: Analyzing Human Extinction Scenarios and Related Hazards. J Evol Technol 9:

Bostrom N (2002b) Anthropic Bias: Observation Selection Effects in Science and Philosophy. Routledge

Bostrom N (2013) Existential Risk Prevention as Global Priority. Glob Policy 4:15–31. https://doi.org/10.1111/1758-5899.12002

Bostrom N, Ćirković MM (2008) Global Catastrophic Risks. Oxford University Press, Oxford, UK

Bouman T, Steg L, Dietz T (2021) Insights from early COVID-19 responses about promoting sustainable action. Nat Sustain 4:194–200. https://doi.org/10.1038/s41893-020-00626-x

Brander JA, Taylor MS (1998) The Simple Economics of Easter Island: A Ricardo-Malthus Model of Renewable Resource Use. Am Econ Rev 88:119–138

Brannen P (2017) The Ends of the World: Volcanic Apocalypses, Lethal Oceans, and Our Quest to Understand Earth's Past Mass Extinctions. Ecco, New York, USA

Bray J (1972) A Model of Doom. Nature 238:

Bregaglio S, Hossard L, Cappelli G, et al (2017) Identifying trends and associated uncertainties in potential rice production under climate change in Mediterranean areas. Agric For Meteorol 237–238:219–232. https://doi.org/https://doi.org/10.1016/j.agrformet.2017.02.015

Bren d'Amour C, Reitsma F, Baiocchi G, et al (2017) Future urban land expansion and implications for global croplands. Proc Natl Acad Sci 114:8939 LP – 8944. https://doi.org/10.1073/pnas.1606036114

Bridle SL (2020) Food and Climate Change - without the hot air. UIT Cambridge Ltd

Briggs S, Kennel CF, Victor DG (2015) Planetary vital signs. Nat Clim Chang 5:969–970. https://doi.org/10.1038/nclimate2828

Brinton W, Rosenberg GH, Wolfe J (1974) CHINA 1: a model of growth for the People's Republic of China. Simulation 23:133–141. https://doi.org/10.1177/003754977402300501

Brooke JL (2014) Climate Change and the Course of Global History: A Rough Journey. Cambridge University Press, New York

Browne D (2021) Utilising Insurance for Climate RIsk Reduction in the UK. In: Cargill N, John TM (eds) The Long View. FIRST Strategic Insight Ltd

Buckley BM, Anchukaitis KJ, Penny D, et al (2010) Climate as a contributing factor in the demise of Angkor, Cambodia. Proc Natl Acad Sci U S A 107:6748–6752. https://doi.org/doi.org/10.1073/pnas.0910827107

Buckley BM, Fletcher R, Wang S-YS, et al (2014) Monsoon extremes and society over the past millennium on mainland Southeast Asia. Quat Sci Rev 95:1–19. https://doi.org/10.1016/j.quascirev.2014.04.022

Budyko MI (1969) The effect of solar radiation variations on the climate of the Earth. Tellus 21:611–619. https://doi.org/10.1111/j.2153-3490.1969.tb00466.x

Buldyrev S V., Parshani R, Paul G, et al (2010) Catastrophic cascade of failures in interdependent networks. Nature 464:1025–1028. https://doi.org/10.1038/nature08932

Büntgen U, Myglan VS, Ljungqvist FC, et al (2016) Cooling and societal change during the Late Antique Little Ice Age from 536 to around 660 AD. Nat Geosci 9:231–236. https://doi.org/10.1038/ngeo2652

Büntgen U, Tegel W, Nicolussi K, et al (2011) 2500 Years of European Climate Variability and Human Susceptibility. Science (80-) 331:578–582. https://doi.org/10.1126/science.1197175

Butzer KW (2012) Collapse, environment and society. Proc Natl Acad Sci U S A 109:3628–3631. https://doi.org/10.1073/pnas.1114845109

Butzer KW, Endfield GH (2012) Critical perspectives on historical collapse. Proc Natl Acad Sci U S A 109:3628–3631. https://doi.org/10.1073/pnas.1114772109

Byers E, Gidden M, Leclere D, et al (2018) Global exposure and vulnerability to multi-sector development and climate change hotspots. Environ Res Lett 13:. https://doi.org/10.1088/1748-9326/aabf45

Callendar GS (1938) The artificial production of carbon dioxide and its influence on temperature. Q J R Meterological Soc 64:223–240. https://doi.org/10.1002/qj.49706427503

Calvin K, Bond-Lamberty B, Clarke L, et al (2017) The SSP4: A world of deepening inequality. Glob Environ Chang 42:284–296. https://doi.org/10.1016/j.gloenvcha.2016.06.010

Campbell, A. A. et al. (2009) 'Relationship of household food insecurity to neonatal, infant, and under-five child mortality among families in rural Indonesia', Food and Nutrition Bulletin, 30(2), pp. 112–119. doi: 10.1177/156482650903000202.

Campiglio E, Dafermos Y, Monnin P, et al (2018) Climate change challenges for central banks and financial regulators. Nat Clim Chang 8:462–468. https://doi.org/10.1038/s41558-018-0175-0

Canadell JG, Meyer CPM, Cook GD, et al (2021) Multi-decadal increase of forest burned area in Australia is linked to climate change. Nat Commun 12:. https://doi.org/10.1038/s41467-021-27225-4

Carfí D, Donato A, Fredella MI, Squillante M (2021) Coopetitive games for environmental sustainability: Climate change and decision global policies. Socioecon Plann Sci 75:100807. https://doi.org/10.1016/j.seps.2020.100807

Carolin SA, Walker RT, Day CC, et al (2019) Precise timing of abrupt increase in dust activity in the Middle East coincident with 4.2 ka social change. Proc Natl Acad Sci 116:67–72. https://doi.org/10.1073/pnas.1808103115

Carrère C, Mrázová M, Neary JP (2020) Gravity Without Apology: the Science of Elasticities, Distance and Trade. Econ J 130:880–910. https://doi.org/10.1093/ej/ueaa034

Caruso, R., Petrarca, I. and Ricciuti, R. (2016) 'Climate change, rice crops, and violence: Evidence from Indonesia', Journal of Peace Research, 53(1), pp. 66–83. doi: 10.1177/0022343315616061.

Castro R (2012) Arguments on the imminence of global collapse are premature when based on simulation models. Gaia 21:271–273. https://doi.org/10.14512/gaia.21.4.9

Castro R, Jacovkis P (2015) Computer-Based Global Models: From Early Experiences to Complex Systems. J Artif Soc Soc Simul 18:13. https://doi.org/10.18564/jasss.2651

Catton WR (1980) Overshoot: The Ecological Basis of Revolutionary Change. Board of Trustees of the University of Illinois, USA

Cernev T, Fenner R (2020) The importance of achieving foundational Sustainable Development Goals in reducing global risk. Futures 115:102492. https://doi.org/10.1016/j.futures.2019.102492

Chamberlin TC (1899) An Attempt to Frame a Working Hypothesis of the Cause of Glacial Periods on an Atmospheric Basis. J Geol 7:545–584. https://doi.org/10.1086/608449

Chen L, Chang J, Wang Y, et al (2021) Disclosing the future food security risk of China based on crop production and water scarcity under diverse socioeconomic and climate scenarios. Sci Total Environ 790:148110. https://doi.org/10.1016/j.scitotenv.2021.148110

Chen M, Vernon CR, Graham NT, et al (2020) Global land use for 2015–2100 at 0.05° resolution under diverse socioeconomic and climate scenarios. Sci Data 7:. https://doi.org/10.1038/s41597-020-00669-x

Chhogyel N, Kumar L, Bajgai Y, Sadeeka Jayasinghe L (2020) Prediction of Bhutan's ecological distribution of rice (Oryza sativa L.) under the impact of climate change through maximum entropy modelling. J Agric Sci 158:25–37. https://doi.org/DOI: 10.1017/S0021859620000350

Chiang F, Mazdiyasni O, AghaKouchak A (2021) Evidence of anthropogenic impacts on global drought frequency, duration, and intensity. Nat Commun 12:1–10. https://doi.org/10.1038/s41467-021-22314-w

Choi C (2020) Ancient megadrought may explain civilization's 'missing millennia'' in Southeast Asia.' Science (80-.).

Christie P (2008) The Curse of the Akkad: Climate Upheavals That Rocked Human History. Annick Press

Chun JA, Li S, Wang Q, et al (2016) Assessing rice productivity and adaptation strategies for Southeast Asia under climate change through multi-scale crop modeling. Agric Syst 143:14–21. https://doi.org/https://doi.org/10.1016/j.agsy.2015.12.001

CIA (2020) Country Comparison - Real GDP per capita. In: World Factbook, Cent. Intell. Agency. https://www.cia.gov/the-world-factbook/field/real-gdp-per-capita/country-comparison

CIA (2021a) Country Comparisons - Real GDP per capita. In: World Factbook, Cent. Intell. Agency

CIA (2021b) Country Comparison - Area. In: World Factb. https://www.cia.gov/the-world-factbook/field/area/country-comparison

Cleveland CJ, Costanza R, Hall CAS, Kaufmann R (1984) Energy and the U.S. Economy: A Biophysical Perspective. Science (80-) 225:890–897. https://doi.org/10.1126/science.225.4665.890

Cline EH (2014) 1177 BC: The Year Civilization Collapsed. Princeton, USA

Cole H, Freeman C, Jahoda M, Pavitt K (1973) Models of doom: A critique of The Limits to Growth. Sussex University Press, Sussex

Cole MB, Augustin MA, Robertson MJ, Manners JM (2018) The science of food security. npj Sci Food 2:1–8. https://doi.org/10.1038/s41538-018-0021-9

Coleman K, Whitmore AP, Hassall KL, et al (2021) The potential for soybean to diversify the production of plant-based protein in the UK. Sci Total Environ 767:144903. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.144903

Coletta VR, Pagano A, Pluchinotta I, et al (2021) Causal Loop Diagrams for supporting Nature Based Solutions participatory design and performance assessment. J Environ Manage 280:111668. https://doi.org/https://doi.org/10.1016/j.jenvman.2020.111668

Cookson E, Hill DJ, Lawrence D (2019) Impacts of long term climate change during the collapse of the Akkadian Empire. J Archaeol Sci 106:1–9. https://doi.org/10.1016/j.jas.2019.03.009

Cotton-Barratt O, Daniel M, Sandberg A (2020) Defence in Depth Against Human Extinction: Prevention, Response, Resilience, and Why They All Matter. Glob Policy 11:271–282. https://doi.org/10.1111/1758-5899.12786

Craig C (2018) Risk management in a policy environment: The particular challenges associated with extreme risks. Futures 102:146–152. https://doi.org/https://doi.org/10.1016/j.futures.2018.04.001

Crespo Cuaresma J (2017) Income projections for climate change research: A framework based on human capital dynamics. Glob Environ Chang 42:226–236. https://doi.org/10.1016/j.gloenvcha.2015.02.012

Creutzig F, Niamir L, Cullen J, et al (2021) Demand-side solutions to climate change mitigation consistent with high levels of wellbeing. Nat Clim Chang. https://doi.org/10.1038/s41558-021-01219-y

CSER (2021a) Centre for the Study of Existential Risk. In: Univ. Cambridge. https://www.cser.ac.uk

CSER (2021b) A Science of Global Risk. In: Res. Areas. https://www.cser.ac.uk/research/science-global-risk/

Cubillo AM, Ferreira JG, Lencart-Silva J, et al (2021) Direct effects of climate change on productivity of European aquaculture. Aquac Int 29:1561–1590. https://doi.org/10.1007/s10499-021-00694-6

Cullen HM, B. DMP, Hemming S, et al (2000) Climate change and the collapse of the Akkadian empire: Evidence from the deep sea. Geology 28:. https://doi.org/10.1130/0091-7613(2000)28<379:CCATCO>2.0.CO;2

Currie A, Ó hÉigeartaigh S (2018) Working together to face humanity's greatest threats: Introduction to the Future of Research on Catastrophic and Existential Risk. Futures 102:1–5. https://doi.org/10.1016/j.futures.2018.07.003

Curtis JH, Hodell DA, Brenner M (1996) Climate variability on the Yucatan Peninsula (Mexico) during the past 3500 years, and implications for Maya cultural evolution. Quat Res 46:37–47. https://doi.org/10.1006/qres.1996.0042

Dalio R (2021) The Changing World Order: Where We Are and Where We're Going. Simon & Schuster

Dang S, Yu K, Tao S, et al (2020) El Niño/Southern Oscillation during the 4.2 ka event recorded by growth rates of corals from the North South China Sea. Acta Oceanol Sin 39:110–117. https://doi.org/10.1007/s13131-019-1520-5

Davies EGR (2018) Cities drive food and water security. Nat Sustain 1:120–121. https://doi.org/10.1038/s41893-018-0038-8

Davis KF, Downs S, Gephart JA (2021) Towards food supply chain resilience to environmental shocks. Nat Food 2:54–65. https://doi.org/10.1038/s43016-020-00196-3

Day MB, Hodell DA, Brenner M, et al (2012) Paleoenvironmental history of the West Baray, Angkor (Cambodia). Proc Natl Acad Sci 109:1046–1051. https://doi.org/10.1073/pnas.1111282109

Degife AW, Zabel F, Mauser W (2021) Climate change impacts on potential maize yields in Gambella Region, Ethiopia. Reg Environ Chang 21:60. https://doi.org/10.1007/s10113-021-01773-3

del Barrio R, Fernandez E, Brendel AS, et al (2021) Climate change impacts on agriculture's southern frontier – Perspectives for farming in North Patagonia. Int J Climatol 41:726–742. https://doi.org/10.1002/joc.6649

Dellink R, Chateau J, Lanzi E, Magné B (2017) Long-term economic growth projections in the Shared Socioeconomic Pathways. Glob Environ Chang 42:200–214. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2015.06.004

DeMenocal PB (2001) Cultural responses to climate change during the late holocene. Science (80-) 292:667–673. https://doi.org/10.1126/science.1059827

Denis B, Dilda V, Kalouche R, Sabah R (2020) Agriculture supply-chain optimization and value creation

Derex M, Beugin M-P, Godelle B, Raymond M (2013) Experimental evidence for the influence of group size on cultural complexity. Nature 503:389–391. https://doi.org/10.1038/nature12774

Deryng D, Conway D, Ramankutty N, et al (2014) Global crop yield response to extreme heat stress under multiple climate change futures. Environ Res Lett 9:. https://doi.org/10.1088/1748-9326/9/3/034011

Di Paola A, Caporaso L, Di Paola F, et al (2018) The expansion of wheat thermal suitability of Russia in response to climate change. Land use policy 78:70–77. https://doi.org/https://doi.org/10.1016/j.landusepol.2018.06.035

Diamond J (1997) Guns, Germs and Steel: A Short History of Everybody for the Last 13,000 Years. Vintage, London, UK

Diamond J (2005) Collapse: How Societies Choose to Fail or Succeed. Penguin Group, London, UK

DiNapoli RJ, Rieth TM, Lipo CP, Hunt TL (2020) A model-based approach to the tempo of "collapse": The case of Rapa Nui (Easter Island). J Archaeol Sci 116:105094. https://doi.org/10.1016/j.jas.2020.105094

DOD (2021) Climate Risk Analysis

Dodd MS, Papineau D, Grenne T, et al (2017) Evidence for early life in Earth's oldest hydrothermal vent precipitates. Nature 543:60–64. https://doi.org/10.1038/nature21377

Doos, B. R. (1994) 'Environmental Degradation, Global Food Production, and Risk for Large-Scale Migrations', Ambio, 23(2), pp. 124–130.

Douglas PMJ, Demarest AA, Brenner M, Canuto MA (2016) Impacts of Climate Change on the Collapse of Lowland Maya Civilization. Annu Rev Earth Planet Sci 44:613–645. https://doi.org/10.1146/annurev-earth-060115-012512

Douglas PMJ, Pagani M, Canuto MA, et al (2015) Drought, agricultural adaptation, and sociopolitical collapse in the Maya Lowlands. Proc Natl Acad Sci 112:5607–5612. https://doi.org/10.1073/pnas.1419133112

Drake BL (2012) The influence of climatic change on the Late Bronze Age Collapse and the Greek Dark Ages. J Archaeol Sci 39:1862–1870. https://doi.org/https://doi.org/10.1016/j.jas.2012.01.029

Dueri S, Guillotreau P, Jiménez-Toribio R, et al (2016) Food security or economic profitability? Projecting the effects of climate and socioeconomic changes on global skipjack tuna fisheries under three management strategies. Glob Environ Chang 41:1–12. https://doi.org/10.1016/j.gloenvcha.2016.08.003

Duku C, Zwart SJ, Hein L (2018a) Impacts of climate change on cropping patterns in a tropical, sub-humid watershed. PLoS One 13:1–21. https://doi.org/10.1371/journal.pone.0192642

Duku C, Zwart SJ, van Bussel LGJ, Hein L (2018b) Quantifying trade-offs between future yield levels, food availability and forest and woodland conservation in Benin. Sci Total Environ 610–611:1581–1589. https://doi.org/10.1016/j.scitotenv.2017.06.115

Edmonds B, Le Page C, Bithell M, et al (2019) Different Modelling Purposes. J Artif Soc Soc Simul 22:6. https://doi.org/10.18564/jasss.3993

edraw (2020) Wondershare EdrawMax. In: edraw A Wondershare Co. https://www.edrawsoft.com/edraw-max/

Eggen M, Ozdogan M, Zaitchik B, et al (2019) Vulnerability of sorghum production to extreme, sub-seasonal weather under climate change. Environ Res Lett 14:. https://doi.org/10.1088/1748-9326/aafe19

Ehrlich P, Ehrlich A (2013) Can a collapse of global civilization be avoided? Proc R Soc B 280:. https://doi.org/10.1098/rspb.2012.2845

Else H (2021) Climate change implicated in Germany's deadly floods. Nature. https://doi.org/10.1038/d41586-021-02330-y

Emmerich R (2004) The Day After Tomorrow. Twentieth Century Fox

Encyclopædia Britannica Inc. (2021) Countries of the World. In: Britannica. https://www.britannica.com/browse/Countries-of-the-World

Erickson JD, Gowdy JM (2000) Resource use, institutions, and sustainability: A tale of two Pacific Island cultures. Land Econ 76:345–354. https://doi.org/10.2307/3147033

Erisman JW, Brasseur G, Ciais P, et al (2015) Global change: Put people at the centre of global risk management. Nature 519:151–153. https://doi.org/10.1038/519151a

Erwin DH, Valentine JW (2013) The Cambrian Explosion: The Construction of Animal Biodiversity. Reoberts and Company, Greenwood Village, Colorado

Estrada F, Tol RSJ, Gay-García C (2015) The persistence of shocks in GDP and the estimation of the potential economic costs of climate change. Environ Model Softw 69:155–165. https://doi.org/https://doi.org/10.1016/j.envsoft.2015.03.010

Etzold, B. et al. (2014) 'Clouds gather in the sky, but no rain falls. Vulnerability to rainfall variability and food insecurity in Northern Bangladesh and its effects on migration', Climate and Development, 6(1), pp. 18–27. doi: 10.1080/17565529.2013.833078.

Fagan B (2009) Floods, Famines and Emperors: El Niño and the Fate of Civilizations, 2nd edn. Basic Books, New York, USA

Fagan BM (2008) The Great Warming: Climate Change and the Rise and Fall of Civilizations. Bloomsbury Press, New York, USA

FAO (1995) Food and People: Staple foods. In: Dimens. need An atlas food Agric. http://www.fao.org/3/u8480e/U8480E07.htm#Staple foods What do people eat

FAO (2004) Human energy requirements. Report of a Joint FAO/WHO/UNU Expert Consultation. Rome, Italy

FAO (2009) World Summit on Food Security. Rome

FAO (2021) FAOSTAT. In: Food Agric. Organ. United Nations

FAO, IFAD, UNICEF, et al (2021) The State of Food Security and Nutrition in the World 2021. Transforming food systems for food security, improved nutrition and affordable healthy diets for all. Rome

Fei J, Zhou J, Hou Y (2007) Circa a.d. 626 volcanic eruption, climatic cooling, and the collapse of the Eastern Turkic Empire. Clim Change 81:469–475. https://doi.org/10.1007/s10584-006-9199-y

Feichtinger G, Novak AJ (1994) Differential game model of the dynastic cycle: 3D-canonical system with a stable limit cycle. J Optim Theory Appl 80:407–423. https://doi.org/10.1007/BF02207772

Feinberg M, Willer R (2010) Apocalypse Soon?: Dire Messages Reduce Belief in Global Warming by Contradicting Just-World Beliefs. Psychol Sci 22:34–38. https://doi.org/10.1177/0956797610391911

Fernandez E, Whitney C, Cuneo IF, Luedeling E (2020) Prospects of decreasing winter chill for deciduous fruit production in Chile throughout the 21st century. Clim Change 159:423–439. https://doi.org/10.1007/s10584-019-02608-1

FHI (2021) Future of Humanity Institute. In: Univ. Oxford. https://www.fhi.ox.ac.uk

Fiedler T, Pitman AJ, Mackenzie K, et al (2021) Business risk and the emergence of climate analytics. Nat Clim Chang 11:87–94. https://doi.org/10.1038/s41558-020-00984-6

Figueiredo Moura da Silva EH, Silva Antolin LA, Zanon AJ, et al (2021) Impact assessment of soybean yield and water productivity in Brazil due to climate change. Eur J Agron 129:126329. https://doi.org/https://doi.org/10.1016/j.eja.2021.126329

Finné M, Holmgren K, Shen C-C, et al (2017) Late Bronze Age climate change and the destruction of the Mycenaean Palace of Nestor at Pylos. PLoS One 12:. https://doi.org/10.1371/journal.pone.0189447

Fischer EM, Sippel S, Knutti R (2021) Increasing probability of record-shattering climate extremes. Nat Clim Chang 11:689–695. https://doi.org/10.1038/s41558-021-01092-9

Fisher L (2021) To build resilience, study complex systems. Nature 595:. https://doi.org/10.1038/d41586-021-01925-9

Fledderjohann, J. et al. (2016) 'Quantifying the impact of rising food prices on child mortality in India: a cross-district statistical analysis of the District Level Household Survey', International Journal of Epidemiology, 45(2), pp. 554–564. doi: 10.1093/ije/dyv359.

Flenley JR, King SM (1984) Late Quaternary Pollen records from Easter Island. Nature 307:47–50. https://doi.org/10.1038/307047a0

Fletcher R, Buckley BM, Pottier C, Wang S-YS (2017) Fourteenth to Sixteenth Centuries AD: The Case of Angkor and Monsoon Extremes in Mainland Southeast Asia. In: Weiss H (ed) Megadrought and Collapse: From Early Agriculture to Angkor. Oxford University Press

Flores JC (2015) A phase-transition model for the rise and collapse of ancient civilizations: A pre-ceramic Andean case study. Physica A 440:155–160. https://doi.org/10.1016/j.physa.2015.08.025

Flores JC, Bologna M, Urzagasti D (2011) A mathematical model for the Andean Tiwanaku civilization collapse: Climate variations. J Theor Biol 291:29–32. https://doi.org/10.1016/j.jtbi.2011.09.018

FM Global (2021) Resilience Index. https://www.fmglobal.com/research-and-resources/tools-and-resources/resilienceindex/explore-the-data/?

Forrester JW (1961) Industrial Dynamics. MIT Press, Cambridge, USA

Forrester JW (1969) Urban Dynamics. MIT Press, Cambridge, USA

Forrester JW (1971) World Dynamics. Wright-Allen Press, Inc., Cambridge, USA

Franke JA, Müller C, Minoli S, et al (2021) Agricultural breadbaskets shift poleward given adaptive farmer behavior under climate change. Glob Chang Biol 1–15. https://doi.org/10.1111/gcb.15868

Freeman L (2020) How Long Did the Empires of Ancient Civilizations Last? Owlcation

Fricko O, Havlik P, Rogelj J, et al (2017) The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. Glob Environ Chang 42:251–267. https://doi.org/10.1016/j.gloenvcha.2016.06.004

Friedlingstein P, Jones MW, O'Sullivan M, et al (2021) Global Carbon Budget 2021. Earth Syst Sci Data Discuss 2021:1–191. https://doi.org/10.5194/essd-2021-386

Froehlich HE, Gentry RR, Halpern BS (2018) Global change in marine aquaculture production potential under climate change. Nat Ecol Evol 2:1745–1750. https://doi.org/10.1038/s41559-018-0669-1

Fujimori S, Hasegawa T, Krey V, et al (2019) A multi-model assessment of food security implications of climate change mitigation. Nat Sustain 2:386–396. https://doi.org/10.1038/s41893-019-0286-2

Fujimori S, Hasegawa T, Masui T, et al (2017) SSP3: AIM implementation of Shared Socioeconomic Pathways. Glob Environ Chang 42:268–283. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2016.06.009

Funk CC (2021) Drought, Flood, Fire: How Climate Change Contributes to Catastrophes. Cambridge University Press

Gann T, Thompson JE (1931) The History of The Maya, From The Earliest Times to The Present Day. Charles Scribner's Sons, London

Gao C, Ludlow F, Matthews JA, et al (2021) Volcanic climate impacts can act as ultimate and proximate causes of Chinese dynastic collapse. Commun Earth Environ 2:234. https://doi.org/10.1038/s43247-021-00284-7

Gao H, Zhu C, Xu W (2007) Environmental change and cultural response around 4200 cal. yr BP in the Yishu River Basin, Shandong. J Geogr Sci 17:285–292. https://doi.org/10.1007/s11442-007-0285-5

Gates B (2021) How to avoid a climate disaster – the solutions we have and the breakthroughs we need. Allen Lane

Gaupp F, Hall J, Hochrainer-Stigler S, Dadson S (2020) Changing risks of simultaneous global breadbasket failure. Nat Clim Chang 10:54–57. https://doi.org/10.1038/s41558-019-0600-z

GCF (2016) Global Catastrophic Risks 2016

GCF (2017) Global Catastrophic Risks 2017

GCF (2018) Global Catastrophic Risks 2018

GCF (2019) Global Catastrophic Risks 2019

GCF (2020) Global Catastrophic Risks 2020

GCF (2021) Global Catastrophic Risks 2021: Navigating the Complex Intersections

Gérardeaux E, Falconnier G, Gozé E, et al (2021) Adapting rainfed rice to climate change: a case study in Senegal. Agron Sustain Dev 41:57. https://doi.org/10.1007/s13593-021-00710-2

Gibbon E (1789) The History of the Decline and Fall of the Roman Empire (Vol I - VI). Strahan & Caddell, London, England

Gibbons A (1993) How the Akkadian empire was hung out to dry. Science (80-) 261:985. https://doi.org/10.1126/science.261.5124.985

Giosan L, Clift PD, Macklin MG, et al (2012) Fluvial landscapes of the Harappan civilization. Proc Natl Acad Sci U S A 109:E1688–E1694. https://doi.org/10.1073/pnas.1112743109

Godde CM, Mason-D'Croz D, Mayberry DE, et al (2021) Impacts of climate change on the livestock food supply chain; a review of the evidence. Glob Food Sec 28:100488. https://doi.org/10.1016/j.gfs.2020.100488

Gohar LK, Lowe JA, Bernie D (2017) The Impact of Bias Correction and Model Selection on Passing Temperature Thresholds. JGR Atmos 122:12045–12061. https://doi.org/10.1002/2017JD026797

Goldblatt C, Watson AJ (2012) The runaway greenhouse: Implications for future climate change, geoengineering and planetary atmospheres. Philos Trans R Soc A Math Phys Eng Sci 370:4197–4216. https://doi.org/10.1098/rsta.2012.0004

Google (2021) Google Earth Pro

Gordon DS (2021) Extrinsic and Existential Mortality Risk in Reproductive Decision-Making: Examining the Effects of COVID-19 Experience and Climate Change Beliefs. Front Psychol 12:. https://doi.org/10.3389/fpsyg.2021.644600

Gore A (2007) An Inconvenient Truth: The Planetary Emergency of Global Warming and What We Can Do About It. Pengiun

Gouel C, Guimbard H (2019) Nutrition transition and the structure of global food demand. Am J Agric Econ 101:383–403. https://doi.org/10.1093/ajae/aay030

Government of the Pitcairn Islands (2013) Pitcairn Islands Strategic Development Plan: 2012-2016

Gowdy J (2020) Our hunter-gatherer future: Climate change, agriculture and uncivilization. Futures 115:102488. https://doi.org/10.1016/j.futures.2019.102488

Griffiths ML, Johnson KR, Pausata FSR, et al (2020) End of Green Sahara amplified mid- to late Holocene megadroughts in mainland Southeast Asia. Nat Commun 11:4204. https://doi.org/10.1038/s41467-020-17927-6

Gu B, Zhang X, Bai X, et al (2019) Four steps to food seecurity for swelling cities. Nature 566:31–33. https://doi.org/10.1038/d41586-019-00407-3

Guarin JR, Emberson L, Simpson D, et al (2019) Impacts of tropospheric ozone and climate change on Mexico wheat production. Clim Change 155:157–174. https://doi.org/10.1007/s10584-019-02451-4

Gul F, Ahmed I, Ashfaq M, et al (2020) Use of crop growth model to simulate the impact of climate change on yield of various wheat cultivars under different agro-environmental conditions in Khyber Pakhtunkhwa, Pakistan. Arab J Geosci 13:112. https://doi.org/10.1007/s12517-020-5118-1

Gundersen, C. et al. (2018) 'Food insecurity status and mortality among adults in Ontario, Canada', PLoS ONE, 13(8). doi: 10.1371/journal.pone.0202642.

Gunn JD (2000) The Years Without Summer: Tracing A.D. 536 and its Aftermath. Archaeopress

Guo F, Lenoir J, Bonebrake TC (2018) Land-use change interacts with climate to determine elevational species redistribution. Nat Commun 9:1–7. https://doi.org/10.1038/s41467-018-03786-9

Guo H, Wang R, Garfin GM, et al (2021) Rice drought risk assessment under climate change: Based on physical vulnerability a quantitative assessment method. Sci Total Environ 751:141481. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.141481

Guzmán RA, Drobny S, Rodríguez-Sickert C (2018) The Ecosystems of Simple and Complex Societies: Social and Geographical Dynamics. J Artif Soc Soc Simul 21:. https://doi.org/10.18564/jasss.3799

Häggström O (2016) Here Be Dragons: Science, Technology and the Future of Humanity. Oxford University Press, Oxford, UK

Hales R, Mackay B (2021) The ultimate guide to why the COP26 summit ended in failure and disappointment (despite a few bright spots). Conversat.

Hall CA, Day JW (2009) Revisiting the Limits to Growth After Peak Oil. Am Sci 97:230. https://doi.org/10.1511/2009.78.230

Hamdan MA, Hassan FA, Flower RJ, et al (2019) Source of Nile sediments in the floodplain at Saqqara inferred from mineralogical, geochemical, and pollen data, and their palaeoclimatic and geoarchaeological significance. Quat Int 501:272–288. https://doi.org/10.1016/j.quaint.2018.02.021

Han J, Yang Y (2021) The socioeconomic effects of extreme drought events in northern China on the Ming dynasty in the late fifteenth century. Clim Change 164:26. https://doi.org/10.1007/s10584-021-02972-x

Hansen J, Sato M, Russell G, Kharecha P (2013) Climate sensitivity, sea level and atmospheric carbon dioxideClimate sensitivity, sea level and atmospheric carbon dioxide. Philos Trans R Soc A Math Phys Eng Sci 371:. https://doi.org/10.1098/rsta.2012.0294

Hardin G (1968) The tragedy of the commons. Science (80-) 162:1243–1248. https://doi.org/10.1126/science.162.3859.1243

Harper K (2017) The Fate of Rome: Climate, Disease, and the End of an Empire. Princeton University Press, Princeton, USA

Harrington LJ, Schleussner C-F, Otto FEL (2021) Quantifying uncertainty in aggregated climate change risk assessments. Nat Commun 12:7140. https://doi.org/10.1038/s41467-021-27491-2

Hasegawa T, Fujimori S, Havlík P, et al (2018) Risk of increased food insecurity under stringent global climate change mitigation policy. Nat Clim Chang 8:699–703. https://doi.org/10.1038/s41558-018-0230-x

Hasegawa T, Fujimori S, Shin Y, et al (2014) Climate change impact and adaptation assessment on food consumption utilizing a new scenario framework. Environ Sci Technol 48:438–445. https://doi.org/10.1021/es4034149

Hasegawa T, Fujimori S, Takahashi K, Masui T (2015) Scenarios for the risk of hunger in the twenty-first century using Shared Socioeconomic Pathways. Environ Res Lett 10:014010. https://doi.org/10.1088/1748-9326/10/1/014010

Hasegawa T, Sakurai G, Fujimori S, et al (2021) Extreme climate events increase risk of global food insecurity and adaptation needs. Nat Food 2:587–595. https://doi.org/10.1038/s43016-021-00335-4

Haug GH, Günther D, Peterson LC, et al (2003) Climate and the collapse of Maya civilization. Science (80-) 299:1731–1735. https://doi.org/10.1126/science.1080444

Hausfather Z, Drake HF, Abbott T, Schmidt GA (2020) Evaluating the Performance of Past Climate Model Projections. Geophys Res Lett 47:. https://doi.org/10.1029/2019GL085378

Hausfather Z, Peters GP (2020) Emissions - the "business as usual" story is misleading. Nature 577:618–620. https://doi.org/10.1038/d41586-020-00177-3

Hazen RM (2012) The Story of Earth: The First 4.5 Billion Years, from Stardust to Living Planet. Viking, New York

Heath AW, Stappenbolt B, Ros M (2019) Uncertainty analysis of the Limits to Growth model: sensitivity is high, but trends are stable. GAIA 28:275-283(9). https://doi.org/10.14512/gaia.28.3.8

Heather P (2006) The Fall of the Roman Empire: A New History of Rome and the Barbarians. Oxford University Press, Oxford, England

Heather P (2009) Empires and Barbarians. Migration, Development and the Birth of Europe. Pan Macmillan

Heinemann AB, Ramirez-Villegas J, Stone LF, Didonet AD (2017) Climate change determined drought stress profiles in rainfed common bean production systems in Brazil. Agric For Meteorol 246:64–77. https://doi.org/https://doi.org/10.1016/j.agrformet.2017.06.005

Hendrix, C. S. and Haggard, S. (2015) 'Global food prices, regime type, and urban unrest in the developing world', Journal of Peace Research, 52(2), pp. 143–157. doi: 10.1177/0022343314561599.

Herrera AO, Scolnik HD, Chichilnisky G, et al (1976) Catastrophe or New Society? A Latin American World Model. International Development Research Centre, Ottawa, Canada

Herrington G (2021) Update to limits to growth: Comparing the World3 model with empirical data. J Ind Ecol 25:614–626. https://doi.org/10.1111/jiec.13084

Hewer MJ, Gough WA (2021) Climate change impact assessment on grape growth and wine production in the Okanagan Valley (Canada). Clim Risk Manag 33:100343. https://doi.org/https://doi.org/10.1016/j.crm.2021.100343

Hickel J, Brockway P, Kallis G, et al (2021) Urgent need for post-growth climate mitigation scenarios. Nat Energy 6:766–768. https://doi.org/10.1038/s41560-021-00884-9

Hines A, Gary J, Daheim C, van der Laan L (2017) Building Foresight Capacity: Toward a Foresight Competency Model. World Futur Rev 9:123–141. https://doi.org/10.1177/1946756717715637

Hinkel J, Mangalagiu D, Bisaro A, Tàbara JD (2020) Transformative narratives for climate action. Clim Change 160:495–506. https://doi.org/10.1007/s10584-020-02761-y

Hintze A, Olson RS, Adami C, Hertwig R (2015) Risk sensitivity as an evolutionary adaptation. Sci Rep 5:8242. https://doi.org/10.1038/srep08242

Hirst D (2020) The history of global climate change negotiations

Hodell D, Curtis JH, Brenner M (1995) Possible role of climate in the collapse of Classic Maya civilization. Nature 375:391–394. https://doi.org/10.1038/375391a0

Hoffmann R, Dimitrova A, Muttarak R, et al (2020) A meta-analysis of country-level studies on environmental change and migration. Nat Clim Chang 10:904–912. https://doi.org/10.1038/s41558-020-0898-6

Holsman KK, Haynie AC, Hollowed AB, et al (2020) Ecosystem-based fisheries management forestalls climate-driven collapse. Nat Commun 11:4579. https://doi.org/10.1038/s41467-020-18300-3

Homer-Dixon T (2006) The Upside of Down: Catastrophe, Creativity, and the Renewal of Civilization. Random House of Canada, Canada

Homer-Dixon T, Walker B, Biggs R, et al (2015) Synchronous failure: the emerging causal architecture of global crisis. Ecol Soc 20:6. https://doi.org/10.5751/ES-07681-200306

Huang CC, Pang J, Zha X, et al (2011) Extraordinary floods related to the climatic event at 4200 a BP on the Qishuihe River, middle reaches of the Yellow River, China. Quat Sci Rev 30:460–468. https://doi.org/https://doi.org/10.1016/j.quascirev.2010.12.007

Hubau W, Lewis SL, Phillips OL, et al (2020) Asynchronous carbon sink saturation in African and Amazonian tropical forests. Nature 579:80–87. https://doi.org/10.1038/s41586-020-2035-0

Hughes B (1985) World Futures: A Critical Analysis of Alternatives. Johns Hopkins University Press, Baltimore, US

Hung L-S, Bayrak MM (2020) Comparing the effects of climate change labelling on reactions of the Taiwanese public. Nat Commun 11:6052. https://doi.org/10.1038/s41467-020-19979-0

Huntington E (1915) Civilization and Climate. Yale University Press

IAMC, IIASA (2018) IAMC 1.5°C Scenario Explorer hosted by IIASA release 2.0. In: Integr. Assess. Model. Consort. Int. Inst. Appl. Syst. Anal. https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/#/workspaces

IIASA (2009) RCP Database Version 2.0.5. In: Int. Inst. Appl. Syst. Anal.

IIASA (2018) SSP Public Database Version 2.0. In: Int. Inst. Appl. Syst. Anal. https://tntcat.iiasa.ac.at/SspDb/

Iizumi T, Furuya J, Shen Z, et al (2017) Responses of crop yield growth to global temperature and socioeconomic changes. Sci Rep 7:. https://doi.org/10.1038/s41598-017-08214-4

Iizumi T, Shen Z, Furuya J, et al (2020) Climate change adaptation cost and residual damage to global crop production. Clim Res 80:203–218. https://doi.org/10.3354/cr01605

Imada Y, Shiogama H, Takahashi C, et al (2018) Climate Change Increased the Likelihood of the 2016 Heat Extremes in Asia. Bull Am Meterological Soc 99:S97–S101. https://doi.org/10.1175/BAMS-D-17-0109.1

IMF (2021) World Economic Outlook: Recovery During a Pandemic - Health Concerns, Supply Disruptions and Price Pressures

Innes JB, Zong Y, Wang Z, Chen Z (2014) Climatic and palaeoecological changes during the mid- to Late Holocene transition in eastern China: high-resolution pollen and non-pollen palynomorph analysis at Pingwang, Yangtze coastal lowlands. Quat Sci Rev 99:164–175. https://doi.org/10.1016/j.quascirev.2014.06.013

IOM GMDAC (2019) Migration Data Portal: The Bigger Picture. https://migrationdataportal.org

IPCC (1995) Second Assessment Report

IPCC (2000) First Assessment Report

IPCC (2001) Third Assessment Report

IPCC (2007) Fourth Assessment Report

IPCC (2014) Fifth Assessment Report

IPCC (2018) Global Warming of 1.5 oC.: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate chang

IPCC (2019a) Climate Change and Land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems

IPCC (2019b) IPCC Special Report on the Ocean and Cryosphere in a Changing Climate

IPCC (2021) Sixth Assessment Report

Isard W (1954) Location Theory and Trade Theory: Short-Run Analysis. Q J Econ 68:305–320. https://doi.org/10.2307/1884452

ISO (2021) ISO 3166 - Country Codes. In: Standards. https://www.iso.org/iso-3166-country-codes

Jackson T, Webster R (2016) Limites Revisited: A review of the limits to growth debate. All-Party Paliamentary Group on Limits to Growth

Jacobson C, Crevello S, Chea C, Jarihani B (2019) When is migration a maladaptive response to climate change? Reg Environ Chang 19:101–112. https://doi.org/10.1007/s10113-018-1387-6

Jacobson, C. et al. (2019) 'When is migration a maladaptive response to climate change?', Regional Environmental Change, 19, pp. 101–112. doi: 10.1007/s10113-018-1387-6.

Jägermeyr J, Müller C, Ruane AC, et al (2021) Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. Nat Food 2:. https://doi.org/10.1038/s43016-021-00400-y

Janssen MA, Scheffer M (2004) Overexploitation of renewable resources by ancient societies and the role of sunk-cost effects. Ecol Soc 9:. https://doi.org/10.5751/ES-00620-090106

Janssens C, Havlík P, Krisztin T, et al (2020) Global hunger and climate change adaptation through international trade. Nat Clim Chang 10:829–835. https://doi.org/10.1038/s41558-020-0847-4

Jehn FU, Schneider M, Wang JR, et al (2021) Betting on the best case: Higher end warming is underrepresented in research. Environ Res Lett 16:. https://doi.org/10.1088/1748-9326/ac13ef

JHU CSSE (2021) COVID-19 Dashboard. https://www.arcgis.com/apps/dashboards/bda7594740fd40299423467b48e9ecf6. Accessed 6 Nov 2021

Jiang L, O'Neill BC (2017) Global urbanization projections for the Shared Socioeconomic Pathways. Glob Environ Chang 42:193–199. https://doi.org/10.1016/j.gloenvcha.2015.03.008

Johnson SAJ (2017) Why did ancient societies fail? Routledge, New York, USA

Jones D (2021) Barbarigenesis and the collapse of complex societies: Rome and after. PLoS One 16:e0254240. https://doi.org/10.1371/journal.pone.0254240

Jones N, O'Brien M, Ryan T (2018) Representation of future generations in United Kingdom policy-making. Futures 102:153–163. https://doi.org/10.1016/j.futures.2018.01.007

Jones, B. T., Mattiacci, E. and Braumoeller, B. F. (2017) 'Food scarcity and state vulnerability: Unpacking the link between climate variability and violent unrest', Journal of Peace Research, 54(3), pp. 335–350. doi: 10.1177/0022343316684662.

Jouzel J, Masson-Delmotte V (2007) EPICA Dome C Ice Core 800KYr deuterium data and temperature estimates. PANGAEA. https://doi.org/10.1594/PANGAEA.683655

Jusup M, Matsuo T, Iwasa Y (2014) Barriers to Cooperation Aid Ideological Rigidity and Threaten Societal Collapse. Plos Comput Biol 10:. https://doi.org/10.1371/journal.pcbi.1003618

Kang H, Sridhar V, Mainuddin M, Trung LD (2021) Future rice farming threatened by drought in the Lower Mekong Basin. Sci Rep 11:9383. https://doi.org/10.1038/s41598-021-88405-2

Kaniewski D, Van Campo E (2017) 3.2 ka BP: Megadrought and the Late Bronze Age Collapse. In: Weiss H (ed) Megadrought and Collapse: From Early Agriculture to Angkor. Oxford University Press

Kaniewski D, Van Campo E, Guiot J, et al (2013) Environmental Roots of the Late Bronze Age Crisis. PLoS One 8:e71004

Kaniewski D, Van Campo E, Weiss H (2012) Drought is a recurring challenge in the Middle East. Proc Natl Acad Sci 109:3862–3867. https://doi.org/10.1073/pnas.1116304109

Karatayev VA, Vasconcelos V V., Lafuite AS, et al (2021) A well-timed shift from local to global agreements accelerates climate change mitigation. Nat Commun 12:1–7. https://doi.org/10.1038/s41467-021-23056-5

Kareiva P, Carranza V (2018) Existential risk due to ecosystem collapse: Nature strikes back. Futures 102:39–50. https://doi.org/10.1016/j.futures.2018.01.001

Kassie BT, Asseng S, Rotter RP, et al (2015) Exploring climate change impacts and adaptation options for maize production in the Central Rift Valley of Ethiopia using different climate change scenarios and crop models. Clim Change 129:145–158. https://doi.org/10.1007/s10584-014-1322-x

Kawahata H, Yamamoto H, Ohkushi K, et al (2009) Changes of environments and human activity at the Sannai-Maruyama ruins in Japan during the mid-Holocene Hypsithermal climatic interval. Quat Sci Rev 28:964–974. https://doi.org/10.1016/j.quascirev.2008.12.009

KC S, Lutz W (2017) The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Glob Environ Chang 42:181–192. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2014.06.004

Keeling CD (1960) The Concentration and Isotopic Abundances of Carbon Dioxide in the Atmosphere. Tellus 12:200–203. https://doi.org/10.1111/j.2153-3490.1960.tb01300.x

Kemp L (2019a) Are we on the road to civilization collapse? BBC Futur.

Kemp L (2019b) The lifespans of ancient civilisations. BBC Futur.

Kemp L (2021) MOROS: Mortality of States Database

Kemp L, Xu C, Depledge J, et al (2022) Climate Endgame: A Research Agenda for Exploring Catastrophic Global Warming Scenarios. Proc Natl Acad Sci U S A. https://doi.org/(in review)

Kennett DJ, Breitenbach SFM, Aquino V V., et al (2012) Development and Disintegration of Maya Political Systems in Response to Climate Change. Science (80-) 338:788–791. https://doi.org/10.1126/science.1226299

Kennett DJ, Hodell DA (2017) AD 750–1100: Climate Change and Critical Transitions in Classic Maya Sociopolitical Networks. Oxford University Press

Kerr RA (1998) Sea-Floor Dust Shows Drought Felled Akkadian Empire. Science (80-) 279:325–326. https://doi.org/10.1126/science.279.5349.325

Kimura M, Binder RM (2016) Population and Human Welfare Scenarios for the Island of Hawai‘i Up to the Year 2100. Pacific Sci 70:143–157. https://doi.org/10.2984/70.2.2

Kinose Y, Masutomi Y, Shiotsu F, et al (2020) Impact assessment of climate change on the major rice cultivar ciherang in Indonesia. J Agric Meteorol 76:19–28. https://doi.org/10.2480/agrmet.D-19-00045

Kintigh KW, Altschul JH, Beaudry MC, et al (2014) Grand Challenges for Archaeology. Proc Natl Acad Sci 111:879–880. https://doi.org/10.7183/0002-7316.79.1.5

Köberle AC, Vandyck T, Guivarch C, et al (2021) The cost of mitigation revisited. Nat Clim Chang. https://doi.org/10.1038/s41558-021-01203-6

Kolbert E (2014) The Sixth Extinction: An Unnatural History. Henry Holt and Company,

Korell L, Auge H, Chase JM, et al (2021) Responses of plant diversity to precipitation change are strongest at local spatial scales and in drylands. Nat Commun 12:1–7. https://doi.org/10.1038/s41467-021-22766-0

Koren, O. and Bagozzi, B. E. (2016) 'From global to local, food insecurity is associated with contemporary armed conflicts', Food Security, 8, pp. 999–1010. doi: 10.1007/s12571-016-0610-x.

Kriegler E, Bauer N, Popp A, et al (2017) Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. Glob Environ Chang 42:297–315. https://doi.org/10.1016/j.gloenvcha.2016.05.015

Kriegler E, Edmonds J, Hallegatte S, et al (2014) A new scenario framework for climate change research: The concept of shared climate policy assumptions. Clim Change 122:401–414. https://doi.org/10.1007/s10584-013-0971-5

Kriegler E, O'Neill BC, Hallegatte S, et al (2012) The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. Glob Environ Chang 22:807–822. https://doi.org/10.1016/j.gloenvcha.2012.05.005

Kuhlemann K (2019) Complexity, creeping normalcy and conceit: sexy and unsexy catastrophic risks. Foresight 21:35–52. https://doi.org/10.1108/FS-05-2018-0047

Kunreuther H, Heal G, Allen M, et al (2013) Risk management and climate change. Nat Clim Chang 2:447–450. https://doi.org/10.1038/NCLIMATE1740

Lachniet MS, Bernal JP, Asmerom Y, et al (2012) A 2400 yr Mesoamerican rainfall reconstruction links climate and cultural change. Geology 40:259–262. https://doi.org/10.1130/G32471.1

Lachniet MS, Bernal-Uruchurtu JP (2017) AD 550–600: Collapse at Teotihuacan. In: Weiss H (ed) Megadrought and Collapse: From Early Agriculture to Angkor. Oxford University Press

Lana MA, Vasconcelos ACF, Gornott C, et al (2018) Is dry soil planting an adaptation strategy for maize cultivation in semi-arid Tanzania? Food Secur 10:897–910. https://doi.org/10.1007/s12571-017-0742-7

Lane J, Greig C, Garnett A (2021) Uncertain storage prospects create a conundrum for carbon capture and storage ambitions. Nat Clim Chang 11:925–936. https://doi.org/10.1038/s41558-021-01175-7

Lawler A (2008) Unmasking the Indus: Indus collapse: The end or the beginning of an Asian culture? Science (80-) 320:1281–1284. https://doi.org/10.1126/science.320.5881.1281

Lawrence J, Blackett P, Cradock-Henry NA (2020) Cascading climate change impacts and implications. Clim Risk Manag 29:100234. https://doi.org/10.1016/j.crm.2020.100234

Lawson DJ, Oak N (2014) Apparent strength conceals instability in a model for the collapse of historical states. PLoS One 9:e96523. https://doi.org/10.1371/journal.pone.0096523

Lee, H. et al. (2016) 'Effects of food price inflation on infant and child mortality in developing countries', European Journal of Health Economics, 17, pp. 535–551. doi: 10.1007/s10198-015-0697-6.

Legwegoh, A. F. et al. (2015) 'Do Dietary Changes Increase the Propensity of Food Riots? An Exploratory Study of Changing Consumption Patterns and the Inclination to Engage in Food-Related Protests', Sustainability, 7, pp. 14112–14132. doi: 10.3390/su71014112.

Leimbach M, Kriegler E, Roming N, Schwanitz J (2017) Future growth patterns of world regions – A GDP scenario approach. Glob Environ Chang 42:215–225. https://doi.org/10.1016/j.gloenvcha.2015.02.005

Lenton TM, Held H, Kriegler E, et al (2008) Tipping elements in the Earth's climate system. Proc Natl Acad Sci 105:1786–1793. https://doi.org/10.1073/pnas.0705414105

Lenton TM, Rockström J, Gaffney O, et al (2019) Climate tipping points — too risky to bet against. Nature 575:592–595. https://doi.org/10.1038/d41586-019-03595-0

Leslie JA (1996) The End of the World: The Science and Ethics of Human Extinction. Routledge, London

Li CH, Li YX, Zheng YF, et al (2018) A high-resolution pollen record from East China reveals large climate variability near the Northgrippian-Meghalayan boundary (around 4200 years ago) exerted societal influence. Palaeogeogr Palaeoclimatol Palaeoecol 512:156–165. https://doi.org/10.1016/j.palaeo.2018.07.031

Li Z, Chen Y, Wang Y, Weihong L (2016) Drought promoted the disappearance of civilization along the ancient Silk Road. Environ Earth Sci 75:. https://doi.org/10.1007/s12665-016-5925-6

Liersch S, Drews M, Pilz T, et al (2020) One simulation, different conclusions—the baseline period makes the difference! Environ Res Lett 15:104014. https://doi.org/10.1088/1748-9326/aba3d7

Lillios KT, Blanco-González A, Drake BL, López-Sáez JA (2016) Mid-late Holocene climate, demography, and cultural dynamics in Iberia: A multi-proxy approach. Quat Sci Rev 135:138–153. https://doi.org/10.1016/j.quascirev.2016.01.011

Lima M, Gayo EM, Latorre C, et al (2020) Ecology of the collapse of Rapa Nui society. Proc R Soc B Biol Sci 287:20200662. https://doi.org/10.1098/rspb.2020.0662

Lin Y, Feng Z, Wu W, et al (2017) Potential impacts of climate change and adaptation on maize in Northeast China. Agron J 109:1476–1490. https://doi.org/10.2134/agronj2016.05.0275

Lin YC (2020) The Risk Zoo. https://datartathon.com/theriskzoo/

Linneman H, de Hoogh J, Keyzer MA, van Heemst HDJ (1979) MOIRA: Model of International Relations in Agriculture. Report of the project group "Food for a doubling world population". North Holland Publishing Company, Amsterdam, Netherlands

Lisiecki LE, Raymon ME (2005) A Pliocene-Pleistocene stack of 57 globally distributed benthic δ18O records. Paleoceanogr Paleoclimatology 20:. https://doi.org/10.1029/2004PA001071

Liu H-Y, Lauta KC, Maas MM (2018) Governing Boring Apocalypses: A new typology of existential vulnerabilities and exposures for existential risk research. Futures 102:6–19. https://doi.org/10.1016/j.futures.2018.04.009

Liu JY, Fujimori S, Takahashi K, et al (2020) The importance of socioeconomic conditions in mitigating climate change impacts and achieving Sustainable Development Goals. Environ Res Lett 16:. https://doi.org/10.1088/1748-9326/abcac4

Liu W, Ye T, Jagermeyr J, et al (2021) Future climate change significantly alters interannual wheat yield variability over half of harvested areas. Environ Res Lett 16:. https://doi.org/10.1088/1748-9326/ac1fbb

Liu X, Desai AR (2021) Significant Reductions in Crop Yields From Air Pollution and Heat Stress in the United States. Earth's Futur 9:1–14. https://doi.org/10.1029/2021EF002000

Livni J (2019) Investigation of collapse of complex socio-political systems using classical stability theory. Physica A 524:553–562. https://doi.org/10.1016/j.physa.2019.04.167

Lloyd WF (1833) Two Lectures on the Checks to Population. Oxford University, Oxford, England

Lomborg B, Rubin O (2002) The Dustbin of History: Limits to Growth. Foreign Policy 133:42–44. https://doi.org/10.2307/3183554

Lopes GM, Fontanari JF (2019) Influence of technological progress and renewability on the sustainability of ecosystem engineers populations. Math Biosci Eng 16:3450–3464. https://doi.org/10.3934/mbe.2019173

Lowen M (2021) Pope urges "radical" climate response in exclusive BBC message. BBC News

Luhunga PM (2017) Assessment of the impacts of climate change on maize production in the southern and western highlands sub-agro ecological Zones of Tanzania. Front Environ Sci 5:. https://doi.org/10.3389/fenvs.2017.00051

Luitel DR, Siwakoti M, Joshi MD, et al (2021) Potential suitable habitat of Buckwheat (Fagopyrum spp) under the climate change scenarios in Nepal. J Crop Sci Biotechnol 24:401–410. https://doi.org/10.1007/s12892-021-00089-2

Lunt, T. et al. (2016) 'Vulnerabilities to agricultural production shocks: An extreme, plausible scenario for assessment of risk for the insurance sector', Climate Risk Management, 13, pp. 1–9. doi: 10.1016/j.crm.2016.05.001.

Lynas M (2007) Six Degrees: Our Future on a Hotter Planet. Fourth Estate

Lynas M, Houlton BZ, Perry S (2021) Greater than 99% consensus on human caused climate change in the peer-reviewed scientific literature. Environ Res Lett 16:114005. https://doi.org/10.1088/1748-9326/ac2966

Lyon C, Saupe EE, Smith CJ, et al (2021) Climate change research and action must look beyond 2100. Glob Chang Biol 1–13. https://doi.org/10.1111/gcb.15871

Ma C Sen, Zhang W, Peng Y, et al (2021) Climate warming promotes pesticide resistance through expanding overwintering range of a global pest. Nat Commun 12:1–10. https://doi.org/10.1038/s41467-021-25505-7

MacDonald G (2011) Potential influence of the Pacific Ocean on the Indian summer monsoon and Harappan decline. Quat Int 229:140–148. https://doi.org/10.1016/j.quaint.2009.11.012

Mach KJ, Kraan CM, Adger WN, et al (2019) Climate as a risk factor for armed conflict. Nature 571:193–197. https://doi.org/10.1038/s41586-019-1300-6

MacKay DJC (2009) Sustainable energy – without the hot air. UIT Cambridge Ltd

MacKenzie D (2012) Boom and doom: Revisting prophecies of collapse. New Sci.

Magnan AK, Pörtner H-O, Duvat VKE, et al (2021) Estimating the global risk of anthropogenic climate change. Nat Clim Chang 11:879–885. https://doi.org/10.1038/s41558-021-01156-w

Mallapaty S (2021) China creates vast research infrastructure to support ambitious climate goals. Nature 600:19–20. https://doi.org/10.1038/d41586-021-03491-6

Malthus TR (1798) An Essay on the Principle of Population. London, UK

Manabe S, Wetherald RT (1975) The Effects of Doubling the CO2 Concentration on the climate of a General Circulation Model. J Atmos Sci 32:3–15. https://doi.org/10.1175/1520-0469(1975)032<0003:TEODTC>2.0.CO;2

Marangoni G, Tavoni M, Bosetti V, et al (2017) Sensitivity of projected long-term CO 2 emissions across the Shared Socioeconomic Pathways. Nat Clim Chang 7:113–117. https://doi.org/10.1038/nclimate3199

Martin MA, Sendra OA, Bastos A, et al (2021) Ten new insights in climate science 2021: a horizon scan. Glob Sustain 4:e25. https://doi.org/DOI: 10.1017/sus.2021.25

Marushka L, Kenny T-A, Batal M, et al (2019) Potential impacts of climate-related decline of seafood harvest on nutritional status of coastal First Nations in British Columbia, Canada. PLoS One 14:e0211473

Masood E (2021) COP architects furious at lack of climate justice at pivotal summit. Nature. https://doi.org/10.1038/d41586-021-03088-z

Masui T, Matsumoto K, Hijioka Y, et al (2011) An emission pathway for stabilization at 6 Wm-2 radiative forcing. Clim Change 109:59–76. https://doi.org/10.1007/s10584-011-0150-5

Matheny JG (2007) Reducing the risk of human extinction. Risk Anal 5:1335–1344. https://doi.org/10.1111/j.1539-6924.2007.00960.x

Mathiesen K (2018) Rating climate risks to credit worthiness. Nat Clim Chang 8:454–456. https://doi.org/10.1038/s41558-018-0184-z

Mausio K, Miura T, Lincoln NK (2020) Cultivation potential projections of breadfruit (Artocarpus altilis) under climate change scenarios using an empirically validated suitability model calibrated in Hawai'i. PLoS One 15:e0228552

Mayer A, Smith EK (2019) Unstoppable climate change? The influence of fatalistic beliefs about climate change on behavioural change and willingness to pay cross-nationally. Clim Policy 19:511–523. https://doi.org/10.1080/14693062.2018.1532872

Mayer T, Zignano S (2011) Notes on CEPII's distances measures: The GeoDist database

Maystadt, J., Trinh Tan, J. and Breisinger, C. (2014) 'Does food security matter for transition in Arab countries?', Food Policy, 46, pp. 106–115. doi: 10.1016/j.foodpol.2014.01.005.

Mazoyer M (2006) A History of World Agriculture: From the Neolithic Age to the Current Crisis. Earthscan

McAnany PA, Yoffee N (2012) Questioning Collapse: Human Resilience, Ecological Vulnerability, and the Aftermath of Empire. Cambridge University Press, New York, USA

McCormick M, Büntgen U, Cane MA, et al (2012) Climate Change during and after the Roman Empire: Reconstructing the Past from Scientific and Historical Evidence. J Interdiscip Hist 43:169–220. https://doi.org/10.1162/JINH_a_00379

McKay C (2021) The Tomorrow War. Amazon Studios

McKinsey & Company (2020) Risk, resilience, and rebalancing in global value chains

McMichael AJ (1993) Planetary Overload: Global Environmental Change and the Health of the Human Species. Cambridge University Press, Cambridge, England

McMichael AJ (2012) Insights from past millennia into climatic impacts on human health and survival. Proc Natl Acad Sci U S A 109:4730–4737. https://doi.org/10.1073/pnas.1120177109

McMichael AJ (2017) Climate Change and the Health of Nations: Famines, Fevers and the Fate of Populations. Oxford University Press, Oxford, UK

Meadows DH, Meadows DL, Bruckmann G (1982) Groping in the Dark: The First Decade of Global Modeling. John Wiley & Sons, Chichester, UK

Meadows DH, Meadows DL, Randers J (1992) Beyond the Limits: Confronting Global Collapse, Envisioning a Sustainable Future. Chelsea Green Publishing Company, Vermont, USA

Meadows DH, Meadows DL, Randers J (2004) The Limits to Growth: The 30-Year Update. Chelsea Green Publishing Company, Vermont, USA

Meadows DH, Meadows DL, Randers J, Behrens WW (1972) The Limits to Growth: A Report to the Club of Rome. Universe Books, New York, USA

Meadows DH, Meadows DL, Randers J, Behrens WW (1973) A response to Sussex. Futures 5:135–152. https://doi.org/10.1016/0016-3287(73)90062-1

Meadows DL (2001) Tools for understanding the limits to growth: Comparing a simulation and a game. Simul Gaming 32:522–536. https://doi.org/10.1177/104687810103200408

Meadows DL, Behrens WW, Meadows DH, et al (1974) The Dynamics of Growth in a Finite World. Wright-Allen Press, Inc., Cambridge, USA

Meadows, D. H., Meadows, D. L. and Randers, J. (2004) The Limits to Growth: The 30-Year Update. Vermont, USA: Chelsea Green Publishing Company.

Medina-Elizalde M, Rohling EJ (2012) Collapse of classic maya civilization related to modest reduction in precipitation. Science (80-) 335:956–959. https://doi.org/10.1126/science.1216629

Mehrabi Z (2020) Food system collapse. Nat Clim Chang 10:16–17. https://doi.org/10.1038/s41558-019-0643-1

Mercure J-F, Salas P, Vercoulen P, et al (2021) Reframing incentives for climate policy action. Nat Energy. https://doi.org/10.1038/s41560-021-00934-2

Mesarović MD, Pestel E (1974) Mankind at the turning point: the second report to the Club of Rome. Dutton, New York, USA

Mi CR, Zu Q, He L, et al (2017) Climate change would enlarge suitable planting areas of sugarcanes in China. Int J Plant Prod 11:151–165. https://doi.org/10.22069/ijpp.2017.3315

Middleton GD (2017) Understanding Collapse: Ancient History and Modern Myths. Cambridge University Press

Milan, A. and Ho, R. (2014) 'Livelihood and migration patterns at different altitudes in the Central Highlands of Peru', Climate and Development, 6(1), pp. 69–76. doi: 10.1080/17565529.2013.826127.

Milan, A. and Ruano, S. (2014) 'Rainfall variability, food insecurity and migration in Cabricán, Guatemala', Climate and Development, 6(1), pp. 61–68. doi: 10.1080/17565529.2013.857589.

Miroslav T, Song F, A. SM, et al (2021) Mitigation efforts will not fully alleviate the increase in water scarcity occurrence probability in wheat-producing areas. Sci Adv 5:eaau2406. https://doi.org/10.1126/sciadv.aau2406

Molina C, Akçay E, Dieckmann U, et al (2020) Combating climate change with matching-commitment agreements. Sci Rep 10:1–12. https://doi.org/10.1038/s41598-020-63446-1

Molotoks A, Smith P, Dawson TP (2021) Impacts of land use, population, and climate change on global food security. Food Energy Secur 10:1–20. https://doi.org/10.1002/fes3.261

Monasterolo I, Tonelli F, Jones A, Natalini D (2014) An hybrid System Dynamics – Agent Based model to simulate Complex Adaptive Systems: a new model for sustainability analysis. In: Proceedings of the 32nd International Conference of the System Dynamics Society

Monastersky R (2015) The greatest vanishing act in prehistoric America. Nature 527:26–29. https://doi.org/10.1038/527026a

Morrow A (2020) Green is the new glam for Monaco's princely urban farming set. Radio Fr. Int.

Morton O (2016) The Planet Remade: How Geoengineering Could Change the World. Princeton University Press, Princeton, USA

Moss RH, Edmonds JA, Hibbard KA, et al (2010) The next generation of scenarios for climate change research and assessment. Nature 463:747–756. https://doi.org/10.1038/nature08823

Motesharrei S, Rivas J, Kalnay E (2014) Human and nature dynamics (HANDY): Modeling inequality and use of resources in the collapse or sustainability of societies. Ecol Econ 90–102. https://doi.org/10.1016/j.ecolecon.2014.02.014

Moynihan T (2020) Existential risk and human extinction: An intellectual history. Futures 116:102495. https://doi.org/10.1016/j.futures.2019.102495

Mpandeli S, Nhamo L, Moeletsi M, et al (2019) Assessing climate change and adaptive capacity at local scale using observed and remotely sensed data. Weather Clim Extrem 26:100240. https://doi.org/10.1016/j.wace.2019.100240

Mumo L, Yu J, Ojara M, et al (2021) Assessing changes in climate suitability and yields of maize and sorghum crops over Kenya in the twenty-first century. Theor Appl Climatol 146:381–394. https://doi.org/10.1007/s00704-021-03718-6

Murali, J. and Afifi, T. (2014) 'Rainfall variability, food security and human mobility in the Janjgir-Champa district of Chhattisgarh state, India', Climate and Development, 6(1), pp. 28–37. doi: 10.1080/17565529.2013.867248.

MyFitnessPal (2021) Generic - Sugar Beet - Raw. In: Food Anal.

Nandy, S., Daoud, A. and Gordon, D. (2016) 'Examining the changing profile of undernutrition in the context of food price rises and greater inequality', Social Science & Medicine, 149, pp. 153–163. doi: 10.1016/j.socscimed.2015.11.036.

Natali SM (2019) Large loss of CO2 in winter observed across the northern permafrost region. Nat Clim Chang 9:852–857. https://doi.org/10.1038/s41558-019-0592-8

Natalini, D., Bravo, G. and Jones, A. W. (2017) 'Global food security and food riots – an agent-based modelling approach', Food Security, pp. 1–21. doi: 10.1007/s12571-017-0693-z.

Natalini, D., Jones, A. W. and Bravo, G. (2015) 'Quantitative Assessment of Political Fragility Indices and Food Prices as Indicators of Food Riots in Countries', Sustainability, 7, pp. 4360–4385. doi: 10.3390/su7044360.

Natural Earth (2021) 1:10 Cultural Vectors. In: Downloads

Nelson S, Allwood JM (2021) Technology or behaviour? Balanced disruption in the race to net zero emissions. Energy Res Soc Sci 78:102124. https://doi.org/10.1016/j.erss.2021.102124

Newman, E. (2018) 'Hungry, or Hungry for Change? Food Riots and Political Conflict, 2005–2015', Studies in Conflict & Terrorism. doi: 10.1080/1057610X.2018.1454042.

Nicholson CC, Emery BF, Niles MT (2021) Global relationships between crop diversity and nutritional stability. Nat Commun 12:. https://doi.org/10.1038/s41467-021-25615-2

Nicoll K, Zerboni A (2020) Is the past key to the present? Observations of cultural continuity and resilience reconstructed from geoarchaeological records. Quat Int 545:119–127. https://doi.org/10.1016/j.quaint.2019.02.012

Nielsen KS, Nicholas KA, Creutzig F, et al (2021) The role of high-socioeconomic-status people in locking in or rapidly reducing energy-driven greenhouse gas emissions. Nat Energy 6:1011–1016. https://doi.org/10.1038/s41560-021-00900-y

Nóia Júnior RDS, Martre P, Finger R, et al (2021) Extreme lows of wheat production in Brazil. Environ Res Lett 16:. https://doi.org/10.1088/1748-9326/ac26f3

Nordhaus WD (1975) The Political Business Cycle. The Review of Economic Studies. Am Econ Rev 42:169–190. https://doi.org/10.2307/2296528

Nørgård JS, Peet J, Ragnarsdóttir KV (2016) The History of The Limits to Growth. Solutions

Nunn P, Carson M (2015) Collapses of Island societies from environmental forcing: Does history hold lessons for the future? Glob Environ 8:110–133. https://doi.org/10.3197/ge.2015.080106

O'Neill BC, Carter TR, Ebi K, et al (2020) Achievements and needs for the climate change scenario framework. Nat Clim Chang 10:1074–1084. https://doi.org/10.1038/s41558-020-00952-0

O'Neill BC, Jiang L, Kc S, et al (2020) The effect of education on determinants of climate change risks. Nat Sustain 3:520–528. https://doi.org/10.1038/s41893-020-0512-y

O'Neill BC, Kriegler E, Ebi KL, et al (2017) The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob Environ Chang 42:169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004

O'Neill BC, Kriegler E, Riahi K, et al (2014) A new scenario framework for climate change research: The concept of shared socioeconomic pathways. Clim Change 122:387–400. https://doi.org/10.1007/s10584-013-0905-2

O'Neill BC, Oppenheimer M, Warren R, et al (2017b) IPCC reasons for concern regarding climate change risks. Nat Clim Chang 7:28–37. https://doi.org/10.1038/nclimate3179

OECD (2021) Regions and Cities: Regional Statistics: Regional Economy: Gross Domestic Product, Small regions TL3. In: OECD.Stat, Organ. Econ. Co-Operation Dev.

Okom S, Russell A, Chaudhary AJ, et al (2017) Impacts of projected precipitation changes on sugar beet yield in eastern England. Meteorol Appl 24:52–61. https://doi.org/10.1002/met.1604

Olausson U (2011) We're the ones to blame: Citizens' representations of climate change and the role of the media. Environ Commun 5:281–299. https://doi.org/10.1080/17524032.2011.585026

Onishi A (1977) Report on Project FUGI - Future of Global Interdependence. In: Fifth IIASA Global Modelling Conference. IIASA, Laxenburg, Austria

Ord T (2020) The Precipice: Existential Risk and the Future of Humanity. Bloomsbury Publishing, London, UK

Oreskes N, Andrade S (2021) Harvard and Other Schools Make a Choice on Fossil Fuels. New York Times

Ortloff CR, Kolata AL (1993) Climate and collapse: Agro-ecological perspectives on the decline of the Tiwanaku State. J Archaeol Sci 20:195–221. https://doi.org/10.1006/jasc.1993.1014

Pain S (2017) Power through the ages. Nature 551:S134–S137. https://doi.org/10.1038/d41586-017-07506-z

Palazzo A, Vervoort JM, Mason-D'Croz D, et al (2017) Linking regional stakeholder scenarios and shared socioeconomic pathways: Quantified West African food and climate futures in a global context. Glob Environ Chang 45:227–242. https://doi.org/10.1016/j.gloenvcha.2016.12.002

Palmer T (2020) Resilience in the developing world benefits everyone. Nat Clim Chang 10:794–795. https://doi.org/10.1038/s41558-020-0888-8

Pancost RD (2017) Climate change narratives. Nat Geosci 10:466–468. https://doi.org/10.1038/ngeo2981

Panter-Brick, C. and Eggerman, M. (1997) 'Household Responses to Food Shortages in Western Nepal', Human Organization, 56(2), pp. 190–198. doi: 10.17730/humo.56.2.v2n1m73468h7t614.

Parker AG, Goudie AS, Stokes S, et al (2006) A record of Holocene climate change from lake geochemical analyses in southeastern Arabia. Quat Res 66:465–476. https://doi.org/10.1016/j.yqres.2006.07.001

Pasqualino R, Jones AW, Monasterolo I, Phillips A (2015) Understanding Global Systems Today—A Calibration of the World3-03 Model between 1995 and 2012. Sustainability 7:9864–9889. https://doi.org/10.3390/su7089864

Pasqualino R, Monasterolo I, Jones A (2019) An Integrated Global Food and Energy Security System Dynamics Model for Addressing Systemic Risk. Sustainability 11:. https://doi.org/10.3390/su11143995

Passell P, Roberts M, Ross L (1972) The Limits to Growth. New York Times

Patterson WP, Dietrich KA, Holmden C, Andrews JT (2010) Two millennia of North Atlantic seasonality and implications for Norse colonies. Proc Natl Acad Sci 107:5306–5310. https://doi.org/10.1073/pnas.0902522107

Paymard P, Yaghoubi F, Nouri M, Bannayan M (2019) Projecting climate change impacts on rainfed wheat yield, water demand, and water use efficiency in northeast Iran. Theor Appl Climatol 138:1361–1373. https://doi.org/10.1007/s00704-019-02896-8

Pearson LJ, Pearson CJ (2012) Societal collapse or transformation, and resilience. Proc Natl Acad Sci U S A 109:2030–2031. https://doi.org/10.1073/pnas.1207552109

Peng W, Iyer G, Bosetti V, et al (2021) Climate policy models need to get real about people — here's how. Nature 594:174–176. https://doi.org/10.1038/d41586-021-01500-2

Pequeno DNL, Hernández-Ochoa IM, Reynolds M, et al (2021) Climate impact and adaptation to heat and drought stress of regional and global wheat production. Environ Res Lett 16:. https://doi.org/10.1088/1748-9326/abd970

Peters GP, Andrew RM, Canadell JG, et al (2020) Carbon dioxide emissions continue to grow amidst slowly emerging climate policies. Nat Clim Chang 10:3–10. https://doi.org/10.1038/s41558-019-0659-6

Pieper M, Michalke A, Gaugler T (2020) Calculation of external climate costs for food highlights inadequate pricing of animal products. Nat Commun 11:6117. https://doi.org/10.1038/s41467-020-19474-6

Pinstrup-Andersen, P. and Shimokawa, S. (2008) 'Do poverty and poor health and nutrition increase the risk of armed conflict onset?', Food Policy, 33, pp. 513–520. doi: 10.1016/j.foodpol.2008.05.003.

Ponting C (1991) A New Green History of the World: The Environment and the Collapse of Great Civilizations. Vintage, London, UK

Pool Re (2021) Climate change: fuelling terror and extremism

Popp A, Calvin K, Fujimori S, et al (2017) Land-use futures in the shared socio-economic pathways. Glob Environ Chang 42:331–345. https://doi.org/10.1016/j.gloenvcha.2016.10.002

Posner RA (2004) Catastrophe: Risk and Response. Oxford University Press

Poynting JH (1907) On Prof. Lowell's method for evaluating the surface-temperatures of the planets; with an attempt to represent the effect of day and night on the temperature of the earth. London, Edinburgh, Dublin Philos Mag J Sci 14:749–760. https://doi.org/10.1080/14786440709463737

Prank M, Kenaley SC, Bergstrom GC, et al (2019) Climate change impacts the spread potential of wheat stem rust, a significant crop disease. Environ Res Lett 14:124053. https://doi.org/10.1088/1748-9326/ab57de

Prestele R, Brown C, Polce C, et al (2021) Large variability in response to projected climate and land-use changes among European bumblebee species. Glob Chang Biol 27:4530–4545. https://doi.org/10.1111/gcb.15780

Preston S (2020) COVID-19: Why hoarding supplies is human nature, according to a psychologist. World Econ. Forum Glob. Agenda

Puma, M. J. et al. (2018) 'A developing food crisis and potential refugee movements', Nature Sustainability, 1, pp. 380–382. doi: 10.1038/s41893-018-0123-z.

Queiroz C, Norström A V., Downing A, et al (2021) Investment in resilient food systems in the most vulnerable and fragile regions is critical. Nat Food 2:546–551. https://doi.org/10.1038/s43016-021-00345-2

Quigley E (2020) Universal Ownership in Practice: A Practical Investment Framework for Asset Owners. Win Best Pap Potential Impact Sustain Financ Pract GRASFI 2020. https://doi.org/10.2139/ssrn.3638217

Rademacher-Schulz, C., Schraven, B. and Mahama, E. D. (2014) 'Time matters: shifting seasonal migration in Northern Ghana in response to rainfall variability and food insecurity', Climate and Development, 6(1), pp. 46–52. doi: 10.1080/17565529.2013.830955.

Raftery AE, Zimmer A, Frierson DMW, et al (2017) Less than 2 °C warming by 2100 unlikely. Nat Clim Chang 7:637–641. https://doi.org/10.1038/nclimate3352

Rahimi J, Mutua JY, Notenbaert AMO, et al (2021) Heat stress will detrimentally impact future livestock production in East Africa. Nat Food 2:88–96. https://doi.org/10.1038/s43016-021-00226-8

Raji P, Shiny R, Byju G (2021) Impact of climate change on the potential geographical suitability of cassava and sweet potato vs. rice and potato in India. Theor Appl Climatol. https://doi.org/10.1007/s00704-021-03763-1

Raleigh, C., Choi, H. J. and Kniveton, D. (2015) 'The devil is in the details: An investigation of the relationships between conflict, food price and climate across Africa', Global Environmental Change, 32, pp. 187–199. doi: 10.1016/j.gloenvcha.2015.03.005.

Ramasamy M, Das B, Ramesh R (2021) Predicting climate change impacts on potential worldwide distribution of fall armyworm based on CMIP6 projections. J Pest Sci (2004). https://doi.org/10.1007/s10340-021-01411-1

Randers J (2000) From limits to growth to sustainable development or SD (sustainable development) in a SD (system dynamics) perspective. Syst Dyn Rev 16:213–224. https://doi.org/10.1002/1099-1727(200023)16:3<213::AID-

Randers J (2012) 2052 - A Global Forecast for the Next Forty Years. Chelsea Green Publishing Company, Vermont, USA

Rao S, Klimont Z, Smith SJ, et al (2017) Future air pollution in the Shared Socio-economic Pathways. Glob Environ Chang 42:346–358. https://doi.org/10.1016/j.gloenvcha.2016.05.012

Raworth K (2017) Doughnut Economics: Seven Ways to Think Like a 21st-century Economist. Random House, London

Raymundo R, Asseng S, Robertson R, et al (2018) Climate change impact on global potato production. Eur J Agron 100:87–98. https://doi.org/https://doi.org/10.1016/j.eja.2017.11.008

Redman CL (1999) Human Impact on Ancient Environments. University of Arizona Press, Tucson, USA

Redman CL, James SR, Fish PR, Rogers JF (2004) The archaeology of global change: the impact of humans on their environment. Smithsonian Books, Washington, USA

Rees M (2003) Our Final Century: Will Civilisation Survive the Twenty-first Century? Random House, London, UK

Rees M (2013) Denial of catastrophic risks. Science (80-) 339:1123. https://doi.org/10.1126/science.1236756

Rees MJ (2018) On the Future: Prospects for Humanity. Princeton University Press, Princeton, USA

Rees MJ (2021) Building a fairer, safer world for children through science

Reichstein M, Riede F, Frank D (2021) More floods, fires and cyclones — plan for domino effects on sustainability goals. Nature 592:347–349. https://doi.org/10.1038/d41586-021-00927-x

Reuveny R, Decker CS (2000) Easter Island: historical anecdote or warning for the future? Ecol Econ 35:271–287. https://doi.org/10.1016/S0921-8009(00)00202-0

Reynolds K (1995) Waterworld. Universal Pictures

Riahi K, Rao S, Krey V, et al (2011) RCP 8.5-A scenario of comparatively high greenhouse gas emissions. Clim Change 109:33–57. https://doi.org/10.1007/s10584-011-0149-y

Riahi K, van Vuuren DP, Kriegler E, et al (2017) The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob Environ Chang 42:153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Richards CR, Lupton RC, Allwood JM (2021) Reframing the threat of global warming: An empirical causal loop diagram of climate change, food insecurity and societal collapse. Clim Change 164:. https://doi.org/10.1007/s10584-021-02957-w

Richerson PJ, Boyd R, Bettinger RL (2001) Was Agriculture Impossible during the Pleistocene but Mandatory during the Holocene? A Climate Change Hypothesis. Am Antiq 66:387–411. https://doi.org/10.2307/2694241

Rigolot C, de Voil P, Douxchamps S, et al (2017) Interactions between intervention packages, climatic risk, climate change and food security in mixed crop–livestock systems in Burkina Faso. Agric Syst 151:217–224. https://doi.org/https://doi.org/10.1016/j.agsy.2015.12.017

Rios Rojas C, Rhodes C, Avin S, et al (2021) Foresight for unknown, long-term and emerging risks, Approaches and Recommendations

Ripple WJ, Wolf C, Newsome TM, et al (2020) World Scientists' Warning of a Climate Emergency. Bioscience 70:8–12. https://doi.org/https://doi.org/10.1093/biosci/biz088

Ritchie H, Roser M (2013) Crop Yields. In: Our World Data. https://ourworldindata.org/crop-yields

Ritchie H, Roser M (2020a) CO_2 and Greenhouse Gas Emissions. In: Our World Data. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

Ritchie H, Roser M (2020b) Energy. In: Our World Data. https://ourworldindata.org/energy

Roberts JM, Westad OA (2013) The Penguin History of the World, 6th edn. Pengiun, New York, USA

Roberts JT, Weikmans R, Robinson S ann, et al (2021) Rebooting a failed promise of climate finance. Nat Clim Chang 11:180–182. https://doi.org/10.1038/s41558-021-00990-2

Robinson M, Shine T (2018) Achieving a climate justice pathway to 1.5 °c. Nat Clim Chang 8:564–569. https://doi.org/10.1038/s41558-018-0189-7

Rockström J, Steffen W, Noone K, et al (2009a) Planetary boundaries: Exploring the safe operating space for humanity. Ecol Soc 14:. https://doi.org/10.5751/ES-03180-140232

Rockström J, Steffen W, Noone K, et al (2009b) A safe operating space for humanity. Nature 461:472–475. https://doi.org/10.1038/461472a

Rodríguez A, Pérez-López D, Centeno A, Ruiz-Ramos M (2021) Viability of temperate fruit tree varieties in Spain under climate change according to chilling accumulation. Agric Syst 186:102961. https://doi.org/https://doi.org/10.1016/j.agsy.2020.102961

Rogelj J, Den Elzen M, Höhne N, et al (2016) Paris Agreement climate proposals need a boost to keep warming well below 2 °c. Nature 534:631–639. https://doi.org/10.1038/nature18307

Rohat G, Monaghan A, Hayden MH, et al (2020) Intersecting vulnerabilities: Climatic and demographic contributions to future population exposure to Aedes-borne viruses in the United States. Environ Res Lett 15:. https://doi.org/10.1088/1748-9326/ab9141

Roman S (2021) Historical dynamics of the Chinese dynasties. Heliyon 7:e07293. https://doi.org/10.1016/j.heliyon.2021.e07293

Roman S, Bullock S, Brede M (2017) Coupled Societies are More Robust Against Collapse: A Hypothetical Look at Easter Island. Ecol Econ 132:264–278. https://doi.org/10.1016/j.ecolecon.2016.11.003

Roman S, Palmer E (2019) The growth and decline of the western roman empire: Quantifying the dynamics of army size, territory, and coinage. Cliodynamics 10:1–23. https://doi.org/10.21237/C7clio10243683

Roman S, Palmer E, Brede M (2018) The Dynamics of Human–Environment Interactions in the Collapse of the Classic Maya. Ecol Econ 146:312–324. https://doi.org/10.1016/j.ecolecon.2017.11.007

Rosenzweig C, Elliott J, Deryng D, et al (2014) Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proc Natl Acad Sci U S A 111:3268–3273. https://doi.org/10.1073/pnas.1222463110

Royer DL, Berner RA, Montañez IP, et al (2004) CO2 as a primary driver of Phanerozoic climate. GSA Today 14:4–10. https://doi.org/10.1130/1052-5173(2004)014<4:CAAPDO>2.0.CO;2

Ruane AC, McDermid S, Rosenzweig C, et al (2014) Carbon–Temperature–Water change analysis for peanut production under climate change: a prototype for the AgMIP Coordinated Climate-Crop Modeling Project (C3MP)Carbon–Temperature–Water change analysis for peanut production under climate change: a prototype. Glob Chang Biol 20:394–407. https://doi.org/10.1111/gcb.12412

Runciman WG (2001) The Origin of Human Social Institutions. Proc Br Acad 110:

Sallaba F, Olin S, Engström K, et al (2017) Future supply and demand of net primary production in the Sahel. Earth Syst Dyn 8:1191–1221. https://doi.org/10.5194/esd-8-1191-2017

Satari Yuzbashkandi S, Khalilian S (2020) On Projecting Climate Change Impacts on Soybean Yield in Iran: an Econometric Approach. Environ Process 7:73–87. https://doi.org/10.1007/s40710-019-00400-y

Sati, V. P. and Vangchhia, L. (2016) 'Nutritional status and infant mortality rate in Saiha district, Mizoram, India', Current Science, 110(12), pp. 2280–2285. doi: 10.18520/cs/v110/i12/2280-2285.

Sawyer JS (1972) Man-made Carbon Dioxide and the "Greenhouse" Effect. Nature 239:23–26. https://doi.org/10.1038/239023a0

Scheffer M (2016) Anticipating societal collapse; Hints from the Stone Age. Proc Natl Acad Sci 113:10733–10735. https://doi.org/10.1073/pnas.1612728113

Schiermeier Q (2015) Why the Pope's letter on climate change matters. Nature. https://doi.org/10.1038/nature.2015.17800

Schiermier Q (2018) Droughts, heatwaves and floods: How to tell when climate change is to blame. Nature 560:20–22. https://doi.org/10.1038/d41586-018-05849-9

Schneider T, Kaul CM, Pressel KG (2019) Possible climate transitions from breakup of stratocumulus decks under greenhouse warming. Nat Geosci 12:163–167. https://doi.org/10.1038/s41561-019-0310-1

Schoijet M (1999) Limits to Growth and the Rise of Catastrophism. Environ Hist Durh N C 4:515–530. https://doi.org/10.2307/3985399

Schröder P, Evans T (2021) Building global climate security

Schubert S, Caviola L, Faber NS (2019) The psychology of existential risk: moral judgments about human extinction. Sci Rep 9:. https://doi.org/10.1038/s41598-019-50145-9

Schultes A, Piontek F, Soergel B, et al (2021) Economic damages from on-going climate change imply deeper near-term emission cuts. Environ Res Lett 16:104053. https://doi.org/10.1088/1748-9326/ac27ce

Schumacher K (2020) Green investments need global standards and independent scientific review. Nature 584:524. https://doi.org/10.1038/d41586-020-02472-5

Schwartz GM, Nichols JJ (2010) After Collapse: The Regeneration of Complex Societies. University of Arizona Press, Tucson, USA

Schwindt DM, Bocinsky RK, Ortman SG, et al (2016) The Social Consequences of Climate Change in the Central Mesa Verde Region. Am Antiq 81:74–96. https://doi.org/10.7183/0002-7316.81.1.74

Sears NA (2020) Existential Security: Towards a Security Framework for the Survival of Humanity. Glob Policy 11:255–266. https://doi.org/10.1111/1758-5899.12800

Sellers WD (1969) A Global Climatic Model Based on the Energy Balance of the Earth-Atmosphere System. J Appl Meteorol Climatol 8:392–400. https://doi.org/10.1175/1520-0450(1969)008<0392:AGCMBO>2.0.CO;2

Shabbir G, Khaliq T, Ahmad A, Saqib M (2020) Assessing the climate change impacts and adaptation strategies for rice production in Punjab, Pakistan. Environ Sci Pollut Res 27:22568–22578. https://doi.org/10.1007/s11356-020-08846-6

Shay AM, Shay E (2017) Urban Farming - Gibraltar's next business sector? Gibraltar Mag.

Shiny R, Sreekumar J, Byju G (2019) Coupled multi-model climate and climate suitability change predictions for major cassava growing regions of India under two representative concentration pathways. J Trop Agric 57:140–151

Simmons MR (2000) Revisiting The Limits to Growth: Could The Club of Rome Have Been Correct, After All?

Simon JL (1981) The Ultimate Resource. Princeton University Press, Princeton, USA

Simonovic SP (2002) World water dynamics: global modeling of water resources. J Environ Manage 249–267. https://doi.org/10.1006/jema.2002.0585

Slater T, Lawrence IR, Otosaka IN, et al (2021) Review article: Earth's ice imbalance. Cryosph 15:233–246. https://doi.org/10.5194/tc-15-233-2021

Smil V (2005) Energy at the Crossroads: Global Perspectivees and Uncertainties. MIT Press, Cambridge

Smith, C. D. (2014) 'Modelling migration futures: development and testing of the Rainfalls Agent-Based Migration Model – Tanzania', Climate and Development, 6(1), pp. 77–91. doi: 10.1080/17565529.2013.872593.

Smith, T. G. (2014) 'Feeding unrest: Disentangling the causal relationship between food price shocks and sociopolitical conflict in urban Africa', Journal of Peace Research, 51(6), pp. 679–695. doi: 10.1177/0022343314543722.

Smolenaars WJ, Lutz AF, Biemans H, et al (2021) From narratives to numbers: Spatial downscaling and quantification of future water, food & energy security requirements in the Indus basin. Futures 133:102831. https://doi.org/10.1016/j.futures.2021.102831

Soergel B, Kriegler E, Weindl I, et al (2021) A sustainable development pathway for climate action within the UN 2030 Agenda. Nat Clim Chang 11:656–664. https://doi.org/10.1038/s41558-021-01098-3

Solow RM (1973) Is the End of the World at Hand? Challenge 16:39–50. https://doi.org/10.1080/05775132.1973.11469961

Sovacool BK (2013) The complexity of climate justice. Nat Clim Chang 3:959–960. https://doi.org/10.1038/nclimate2037

Spillias S, Kareiva P, Ruckelshaus M, McDonald-Madden E (2020) Renewable energy targets may undermine their sustainability. Nat Clim Chang 10:974–976. https://doi.org/10.1038/s41558-020-00939-x

Spratt D (2019) Revisiting the climate collapse: The view from Nuuk in the year 2070. Bull At Sci 75:280–285. https://doi.org/10.1080/00963402.2019.1680050

Stahle DW, Burnette DJ, Griffin D, Cook ER (2017) Thirteenth Century AD: Implications of Seasonal and Annual Moisture Reconstructions for Mesa Verde, Colorado. In: Weiss H (ed) Megadrought and Collapse: From Early Agriculture to Angkor. Oxford University Press

Stanley JD, Krom MD, Cliff RA, Woodward JC (2003) Short contribution: Nile flow failure at the end of the Old Kingdom, Egypt: Strontium isotopic and petrologic evidence. Geoarchaeology 18:395–402. https://doi.org/10.1002/gea.10065

Staubwasser M, Sirocko F, Grootes PM, Segl M (2003) Climate change at the 4.2 ka BP termination of the Indus valley civilization and Holocene south Asian monsoon variability. Geophys Res Lett 30:3–6. https://doi.org/10.1029/2002GL016822

Steffen W, Richardson K, Rockström J, et al (2015) Planetary boundaries: Guiding human development on a changing planet. Science (80-) 347:. https://doi.org/10.1126/science.1259855

Steffen W, Richardson K, Rockström J, et al (2020) The emergence and evolution of Earth System Science. Nat Rev Earth Environ 1:54–63. https://doi.org/10.1038/s43017-019-0005-6

Steffen W, Rockström J, Richardson K, et al (2018) Trajectories of the Earth System in the Anthropocene. Proc Natl Acad Sci U S A 115:8252–8259. https://doi.org/10.1073/pnas.1810141115

Stephenson S, Horton P, Allwood JM (2021) Minus 45: Delivering the UK government's pledge to COP26: CUtting UK emissions by 45% from 2018 to 2030

Sterman JD (2000) Business Dynamics: Systems Thinking and Modeling for a Complex World. McGraw-Hill Higher Education, USA

Sterman JD (2002) All models are wrong: reflections on becoming a systems scientist. Syst Dyn Rev 18:501–531. https://doi.org/10.1002/sdr.261

Sterman JD (2011) Communicating climate change risks in a skeptical world. Clim Change 108:811. https://doi.org/10.1007/s10584-011-0189-3

Stern N (2006) Stern Review on the Economics of Climate Change

Sternberg T (2012) Chinese drought, bread and the Arab Spring. Appl Geogr 34:519–524. https://doi.org/10.1016/j.apgeog.2012.02.004

Sternberg, T. (2012) 'Chinese drought, bread and the Arab Spring', Applied Geography, 34, pp. 519–524. doi: 10.1016/j.apgeog.2012.02.004.

Storey R, Storey GR (2017) Rome and the Classic Maya: Comparing the Slow Collapse of Civilizations. Routledge, New York, USA

Strathern P (2019) Rise and Fall: A History of the World in Ten Empires. Hodder & Stoughton

Stringer C, Galway-Witham J (2017) On the origin of our species. Nature 546:212–214. https://doi.org/10.1038/546212a

Su W-H, He H-J, Sun D-W (2017) Non-Destructive and rapid evaluation of staple foods quality by using spectroscopic techniques: A review. Crit Rev Food Sci Nutr 57:1039–1051. https://doi.org/10.1080/10408398.2015.1082966

Sultan B, Defrance D, Iizumi T (2019) Evidence of crop production losses in West Africa due to historical global warming in two crop models. Sci Rep 9:1–15. https://doi.org/10.1038/s41598-019-49167-0

Suthaharan P, Reed EJ, Leptourgos P, et al (2021) Paranoia and belief updating during the COVID-19 crisis. Nat Hum Behav 5:1190–1202. https://doi.org/10.1038/s41562-021-01176-8

Taagepera R (1978a) Size and duration of empires: Systematics of size. Soc Sci Res 7:108–127. https://doi.org/10.1016/0049-089X(78)90007-8

Taagepera R (1978b) Size and duration of empires growth-decline curves, 3000 to 600 b.c. Soc Sci Res 7:180–196. https://doi.org/10.1016/0049-089X(78)90010-8

Tabari H (2020) Climate change impact on flood and extreme precipitation increases with water availability. Sci Rep 10:1–10. https://doi.org/10.1038/s41598-020-70816-2

Tainter JA (1988) The Collapse of Complex Societies. Cambridge University Press, Cambridge, UK

Tainter JA (1995) Sustainability of complex societies. Futures 27:397–407. https://doi.org/10.1016/0016-3287(95)00016-P

Tainter JA (2000) Problem Solving: Complexity, History, Sustainability. Popul Environ 22:3–41. https://doi.org/10.1023/A:1006632214612

Tainter JA (2006) Social complexity and sustainability. Ecol Complex 3:91–103. https://doi.org/10.1016/j.ecocom.2005.07.004

Tainter JA (2011) Energy, complexity, and sustainability: A historical perspective. Environ Innov Soc Transitions 1:89–95. https://doi.org/10.1016/j.eist.2010.12.001

Tainter JA (2014) Collapse and sustainability: Rome, the Maya, and the Modern World. Archeol Pap Am Anthropol Assoc 24:201–214. https://doi.org/10.1111/apaa.12038

Taleb NN (2007) The Black Swan: The Impact of the Highly Improbably. The Random House Publishing Group, New York City, USA

Tang A, Kemp L (2021) A Fate Worse Than Warming? Stratospheric Aerosol Injection and Global Catastrophic Risk. 3:720312. https://doi.org/10.3389/fclim.2021.720312

Taylor A (2008) The Rise and Fall of the Great Empires. Quercus

Taylor KB (2020) The passing of western civilization. Futures 122:102582. https://doi.org/10.1016/j.futures.2020.102582

Taylor M (2020) Cambridge University to divest from fossil fuels by 2030. Guard.

Tebaldi C, Arblaster JM (2014) Pattern scaling: Its strengths and limitations, and an update on the latest model simulations. Clim Change 122:459–471. https://doi.org/10.1007/s10584-013-1032-9

Tebaldi C, Ranasinghe R, Vousdoukas M, et al (2021) Extreme sea levels at different global warming levels. Nat Clim Chang 11:746–751. https://doi.org/10.1038/s41558-021-01127-1

The Fund for Peace (2021) Fragile States Index. https://fragilestatesindex.org

The World Bank (2021a) World Development Indicators. In: DataBank

The World Bank (2021b) Pakistan: Current Climate. In: Clim. Chang. Knowl. Portal. https://climateknowledgeportal.worldbank.org/country/pakistan/climate-data-historical

Thomas Y, Cassou C, Gernez P, Pouvreau S (2018) Oysters as sentinels of climate variability and climate change in coastal ecosystems. Environ Res Lett 13:104009. https://doi.org/10.1088/1748-9326/aae254

Thompson LG, Kolata AL (2017) Twelfth Century AD: Climate, Environment, and the Tiwanaku State. In: Weiss H (ed) Megadrought and Collapse: From Early Agriculture to Angkor. Oxford University Press

Thomson AM, Calvin K V., Smith SJ, et al (2011) RCP4.5: A pathway for stabilization of radiative forcing by 2100. Clim Change 109:77–94. https://doi.org/10.1007/s10584-011-0151-4

Thunberg G (2019) No One is Too Small to Make a Difference. Penguin

Tian Z, Ji Y, Sun L, et al (2018) Changes in production potentials of rapeseed in the Yangtze River Basin of China under climate change: A multi-model ensemble approach. J Geogr Sci 28:1700–1714. https://doi.org/10.1007/s11442-018-1538-1

Tokarska KB, Gillett NP, Weaver AJ, et al (2016) The climate response to five trillion tonnes of carbon. Nat Clim Chang 6:851–855. https://doi.org/10.1038/nclimate3036

Tollefson J (2019) The hard truths of climate change — by the numbers. Nature 573:324–327

Tollefson J (2021a) Carbon emissions rapidly rebounded following COVID pandemic dip. Nature. https://doi.org/10.1038/d41586-021-03036-x

Tollefson J (2021b) Top climate scientists are sceptical that nations will rein in global warming. Nature 599:22–24. https://doi.org/10.1038/d41586-021-02990-w

Toynbee AJ (1961) A Study of History (Vol I - IX). Oxford University Press, Oxford, England

Tsonis AA, Swanson KL, Sugihara G, Tsonis PA (2010) Climate change and the demise of Minoan civilization. Clim Past 6:525–530. https://doi.org/10.5194/cp-6-525-2010

Tu C, Suweis S, D'Odorico P (2019) Impact of globalization on the resilience and sustainability of natural resources. Nat Sustain 2:283–289. https://doi.org/10.1038/s41893-019-0260-z

Turchin A, Denkenberger D (2018) Global catastrophic and existential risks communication scale. Futures 102:27–38. https://doi.org/10.1016/j.futures.2018.01.003

Turchin P (2003) Historical Dynamics: Why States Rise and Fall. Princeton University Press, Princeton, USA

Turchin P (2006) War and Peace and War: The Rise and Fall of Empires. Penguin Group, New York, USA

Turchin P (2008) Arise “cliodynamics.” Nature 454:34–35. https://doi.org/10.1038/454034a

Turchin P, Currie TE, Turner EAL, Gavrilets S (2013) War, space, and the evolution of Old World complex societies. Proc Natl Acad Sci U S A 110:16384–16389. https://doi.org/10.1073/pnas.1308825110

Turchin P, Korotayev A V (2006) Population Dynamics and Internal Warfare: A Reconsideration. Soc Evol Hist 5:112–147

Turchin P, Nefedov SA (2009) Secular Cycles. Princeton University Press, New Jersey

Turner G (2008) A Comparison of the Limits to Growth with Thirty Years of Reality. Glob Environ Chang 18:397–411. https://doi.org/10.1016/j.gloenvcha.2008.05.001

Turner G (2014) Is Global Collapse Imminent? An Updated Comparison of The Limits to Growth with Historical Data. Melbourne

Turner GM (2012) On the cusp of global collapse?: Updated comparison of the Limits to Growth with historical data. Gaia 21:116–124. https://doi.org/10.14512/gaia.21.2.10

Tyndall J (1859) Note on the Transmission of Radiant Heat through Gaseous Bodies. Proc R Soc London 10:37–39. https://doi.org/10.1098/rspl.1859.0017

Tzachor A, Richards CE, Holt L (2021) Future foods for risk resilient diets. Nat Food

Uber Technologies (2021) H3: Hexagonal hierarchical geospatial indexing system. https://h3geo.org

UCDP & PRIO (2019) Uppsala Conflict Data Program. https://ucdp.uu.se/

Ullah A, Ahmad I, Ahmad A, et al (2019) Assessing climate change impacts on pearl millet under arid and semi-arid environments using CSM-CERES-Millet model. Environ Sci Pollut Res 26:6745–6757. https://doi.org/10.1007/s11356-018-3925-7

UN (2020) UN human rights ruling could boost climate change asylum claims. UN News

UNDESA (2019) World Population Prospects 2019. In: United Nations, Dep. Econ. Soc. Aff. Popul. Div.

UNDESA (2021) Sustainable Development Goals. In: United Nations, Dep. Econ. Soc. Aff. Sustain. Dev. https://sdgs.un.org

UNDP (2021) Peoples’ Climate Vote

UNEP (2021) State of Finance for Nature. Nairobi

Ungar S (2000) Knowledge, ignorance and the popular culture: climate change versus the ozone hole. Public Underst Sci 9:297–312. https://doi.org/10.1088/0963-6625/9/3/306

UNSD (2021) Methodology: Standard country codes or area codes for statistical use (M49): Geographic Regions

USDA (2021) FoodData Central. In: U.S. Dep. Agric. Agric. Res. Serv.

Vaidyanathan G (2021) Scientists cheer India's ambitious carbon-zero climate pledge. Nature. https://doi.org/doi.org/10.1038/d41586-021-03044-x

Van de Perre E, Jacxsens L, Liu C, et al (2015) Climate impact on Alternaria moulds and their mycotoxins in fresh produce: The case of the tomato chain. Food Res Int 68:41–46. https://doi.org/https://doi.org/10.1016/j.foodres.2014.10.014

Van Meijl H, Havlik P, Lotze-Campen H, et al (2018) Comparing impacts of climate change and mitigation on global agriculture by 2050. Environ Res Lett 13:. https://doi.org/10.1088/1748-9326/aabdc4

van Meijl H, Tabeau A, Stehfest E, et al (2020) How food secure are the green, rocky and middle roads: Food security effects in different world development paths. Environ Res Commun 2:. https://doi.org/10.1088/2515-7620/ab7aba

Van Valen L (1973) A new evolutionary law. Evol Theory 1:1–30

van Vuuren DP, Edmonds J, Kainuma M, et al (2011a) The representative concentration pathways: An overview. Clim Change 109:5–31. https://doi.org/10.1007/s10584-011-0148-z

van Vuuren DP, Kriegler E, O'Neill BC, et al (2014) A new scenario framework for Climate Change Research: Scenario matrix architecture. Clim Change 122:373–386. https://doi.org/10.1007/s10584-013-0906-1

Van Vuuren DP, Riahi K, Moss R, et al (2012) A proposal for a new scenario framework to support research and assessment in different climate research communities. Glob Environ Chang 22:21–35. https://doi.org/10.1016/j.gloenvcha.2011.08.002

van Vuuren DP, Stehfest E, den Elzen MGJ, et al (2011b) RCP2.6: Exploring the possibility to keep global mean temperature increase below 2°C. Clim Change 109:95–116. https://doi.org/10.1007/s10584-011-0152-3

van Vuuren DP, Stehfest E, Gernaat DEHJ, et al (2017) Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Glob Environ Chang 42:237–250. https://doi.org/10.1016/j.gloenvcha.2016.05.008

van Weezel, S. (2016) 'Food imports, international prices, and violence in Africa', Oxford Economic Papers, 68(3), pp. 758–781. doi: 10.1093/oep/gpw015.

Vanli Ö, Ustundag BB, Ahmad I, et al (2019) Using crop modeling to evaluate the impacts of climate change on wheat in southeastern turkey. Environ Sci Pollut Res 26:29397–29408. https://doi.org/10.1007/s11356-019-06061-6

Varma V, Bebber DP (2019) Climate change impacts on banana yields around the world. Nat Clim Chang 9:752–757. https://doi.org/10.1038/s41558-019-0559-9

Ventana Systems Inc. (2019) Vensim & Ventity Simulation Software. http://vensim.com

Vermeulen PJ, de Jongh DCJ (1976) Parameter sensitivity of the 'Limits to Growth' world model. Appl Math Model 1:29–32. https://doi.org/10.1016/0307-904X(76)90021-4

Verschuur J, Li S, Wolski P, Otto FEL (2021) Climate change as a driver of food insecurity in the 2007 Lesotho-South Africa drought. Sci Rep 11:3852. https://doi.org/10.1038/s41598-021-83375-x

Vespignani A (2010) The fragility of interdependency. Nature 464:984–985. https://doi.org/10.1038/464984a

Vicedo-Cabrera AM, Scovronick N, Sera F, et al (2021) The burden of heat-related mortality attributable to recent human-induced climate change. Nat Clim Chang 11:492–500. https://doi.org/10.1038/s41558-021-01058-x

Viglione G (2020) Climate Lawsuits Break New Ground to Protect the Planet. Nature 579:184–185. https://doi.org/10.1038/d41586-020-00175-5

Wagner G, Weitzman ML (2015) Climate Shock: The Economic Consequences of a Hotter Planet. Princeton University Press, Princeton, USA

Walker, R. J. et al. (2019) 'Assessing the relationship between food insecurity and mortality among U.S. adults', Annals of Epidemiology, 32, pp. 43–48. doi: 10.1016/j.annepidem.2019.01.014.

Wallace-Wells D (2019) The Uninhabitable Earth: Life After Warming. Tim Doggan Books

Wallich HC (1982) "The Limits to Growth" Revisited. Challenge 25:36–42

Wang J, Sun L, Chen L, et al (2016) The abrupt climate change near 4,400 yr BP on the cultural transition in Yuchisi, China and its global linkage. Sci Rep 6:27723. https://doi.org/10.1038/srep27723

Wang W, Yuan S, Wu C, et al (2021) Field experiments and model simulation based evaluation of rice yield response to projected climate change in Southeastern China. Sci Total Environ 761:143206. https://doi.org/https://doi.org/10.1016/j.scitotenv.2020.143206

Warnatzsch EA, Reay DS (2020) Assessing climate change projections and impacts on Central Malawi's maize yield: The risk of maladaptation. Sci Total Environ 711:134845. https://doi.org/https://doi.org/10.1016/j.scitotenv.2019.134845

Warner, K. and Afifi, T. (2014) 'Where the rain falls: Evidence from 8 countries on how vulnerable households use migration to manage the risk of rainfall variability and food insecurity', Climate and Development, 6(1), pp. 1–17. doi: 10.1080/17565529.2013.835707.

Watanabe TK, Watanabe T, Yamazaki A, Pfeiffer M (2019) Oman corals suggest that a stronger winter shamal season caused the Akkadian Empire (Mesopotamia) collapse. Geology 47:1141–1145. https://doi.org/10.1130/G46604.1

Weart S (2021) The Discovery of Global Warming. In: Discov. Glob. Warm. https://history.aip.org/climate/index.htm

Weber EU (2006) Evidence-based and description-based perceptions of long-term risk: Why global warming does not scare us (yet). Clim Change 77:103–120. https://doi.org/10.1007/s10584-006-9060-3

Weber C, McCollum DL, Edmonds J, et al (2018) Mitigation scenarios must cater to new users. Nat Clim Chang 8:843–851. https://doi.org/10.1038/s41558-018-0293-8

WEF (2021) The Global Risks Report 2021. Geneva, Switzerland

Weinberg, J. and Bakker, R. (2015) 'Let them eat cake: Food prices, domestic policy and social unrest', Conflict Management and Peace Science, 32(3), pp. 309–326. doi: 10.1177/0738894214532411.

Weiss H (2017a) Megadrought and Collapse: From Early Agriculture to Angkor. Oxford University Press

Weiss H (2017b) Megadrought, Collapse, and Causality. In: Weiss H (ed) Megadrought and Collapse: From Early Agriculture to Angkor. Oxford University Press

Weiss H (2017c) 4.2 ka BP: Megadrought and the Akkadian Collapse. In: Weiss H (ed) Megadrought and Collapse: From Early Agriculture to Angkor. Oxford University Press

Weiss H, Bradley RS (2001) What Drives Societal Collapse? Science (80-) 291:609–610

Weiss H, Courty M-A, Wetterstrom W, et al (1993) The genesis and collapse of third millennium north Mesopotamian civilization. Science (80-) 261:995–1004. https://doi.org/10.1126/science.261.5124.995

Weitzman ML (2011) Fat-tailed uncertainty in the economics of catastrophic climate change. Rev Environ Econ Policy 5:275–292. https://doi.org/10.1093/reep/rer006

Welc F, Marks L (2014) Climate change at the end of the Old Kingdom in Egypt around 4200 BP: New geoarchaeological evidence. Quat Int 324:124–133. https://doi.org/10.1016/j.quaint.2013.07.035

Weninger B, Clare L (2017) 6600–6000 cal BC: Abrupt Climate Change and Neolithic Dispersal from West Asia. In: Weiss H (ed) Megadrought and Collapse: From Early Agriculture to Angkor. Oxford University Press

Wenxiang W, Tungsheng L (2004) Possible role of the "Holocene Event 3" on the collapse of Neolithic Cultures around the Central Plain of China. Quat Int 117:153–166. https://doi.org/10.1016/S1040-6182(03)00125-3

Wessels C, Merow C, Trisos CH (2021) Climate change risk to southern African wild food plants. Reg Environ Chang 21:. https://doi.org/10.1007/s10113-021-01755-5

Wheeler T, von Braun J (2013) Climate change impacts on global food security. Science (80-) 341:185–197. https://doi.org/10.1126/science.1239402

Wiebe K, Lotze-Campen H, Sands R, et al (2015) Climate change impacts on agriculture in 2050 under a range of plausible socioeconomic and emissions scenarios. Environ Res Lett 10:. https://doi.org/10.1088/1748-9326/10/8/085010

Wischnath, G. and Buhaug, H. (2014) 'Rice or riots: On food production and conflict severity across India', Political Geography, 43, pp. 6–15. doi: 10.1016/j.polgeo.2014.07.004.

Woodwell JC (1998) A simulation model to illustrate feedbacks among resource consumption, production, and factors of production in ecological-economic systems. Ecol Modell 112:227–248. https://doi.org/10.1016/S0304-3800(98)00080-5

Wootten AM, Dixon KW, Adams-Smith DJ, McPherson RA (2020) Statistically downscaled precipitation sensitivity to gridded observation data and downscaling technique. Int J Climatol 41:980–1001. https://doi.org/10.1002/joc.6716

WorldAtlas (2021) Countries of the World. In: WorldAtlas. https://www.worldatlas.com/countries

Wright R (2004) A Short History of Progress. House of Anansi Press Inc., Toronto, Canada

Xoplaki E, Fleitmann D, Luterbacher J, et al (2016) The Medieval Climate Anomaly and Byzantium: A review of the evidence on climatic fluctuations, economic performance and societal change. Quat Sci Rev 136:229–252. https://doi.org/10.1016/j.quascirev.2015.10.004

Xu C, Kohler TA, Lenton TM, et al (2020) Future of the human climate niche. Proc Natl Acad Sci U S A 117:11350–11355. https://doi.org/10.1073/pnas.1910114117

Yancheva G, Nowaczyk NR, Mingram J, et al (2007) Influence of the intertropical convergence zone on the East Asian monsoon. Nature 445:74–77. https://doi.org/10.1038/nature05431

Yaroshenko TY, Krysko D V, Dobriyan V, et al (2015) Wavelet modeling and prediction of the stability of states: the Roman Empire and the European Union. Commun Nonlinear Sci Numer Simul 26:265–275. https://doi.org/10.1016/j.cnsns.2015.02.013

Yeeles A (2019) Counting the future now. Nat Clim Chang 9:801. https://doi.org/10.1038/s41558-019-0624-4

Yegorov Y, Grass D, Mirescu M, et al (2020) Growth and Collapse of Empires: A Dynamic Optimization Model. J Optim Theory Appl 186:620–643. https://doi.org/10.1007/s10957-020-01719-5

Yoffee N, Cowgill GL (1988) The Collapse of Ancient States and Civilizations. University of Arizona Press, Tucson, USA

Yoon PR, Choi J-Y (2020) Effects of shift in growing season due to climate change on rice yield and crop water requirements. Paddy Water Environ 18:291–307. https://doi.org/10.1007/s10333-019-00782-7

Yue Y, Wang L, Li J, Zhu A (2018) An EPIC model-based wheat drought risk assessment using new climate scenarios in China. Clim Change 147:539–553. https://doi.org/10.1007/s10584-018-2150-1

Zachos JC, Dickens GR, Zeebe RE (2008) An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics. Nature 451:279–283. https://doi.org/10.1038/nature06588

Zamarioli LH, Pauw P, König M, Chenet H (2021) The climate consistency goal and the transformation of global finance. Nat Clim Chang 11:578–583. https://doi.org/10.1038/s41558-021-01083-w

Zhang DD, Brecke P, Lee HF, et al (2007) Global climate change, war, and population decline in recent human history. Proc Natl Acad Sci 104:19214–19219. https://doi.org/10.1073/pnas.0703073104

Zhang DD, Jim C., Lin G.-S, et al (2006) Climatic change, wars and dynastic cycles in China over the last millennium. Clim Change 76:459–477. https://doi.org/10.1007/s10584-005-9024-z

Zhang DD, Lee HF, Wang C, et al (2011) The causality analysis of climate change and large-scale human crisis. Proc Natl Acad Sci U S A 108:17296–17301. https://doi.org/10.1073/pnas.1104268108

Zhang Y, Wang Y, Niu H (2019) Effects of temperature, precipitation and carbon dioxide concentrations on the requirements for crop irrigation water in China under future climate scenarios. Sci Total Environ 656:373–387. https://doi.org/10.1016/j.scitotenv.2018.11.362

Zhao C, Liu B, Piao S, et al (2017) Temperature increase reduces global yields of major crops in four independent estimates. Proc Natl Acad Sci U S A 114:9326–9331. https://doi.org/10.1073/pnas.1701762114

Žliobaitė I, Fortelius M (2020) All Sizes Fit the Red Queen. Paleobiology 46:478–494. https://doi.org/DOI: 10.1017/pab.2020.35

[blank page]

Appendix A

Supplementary information for Chapter 3

This appendix provides supporting information for the first investigation of the three-part research framework presented in Chapter 3. A table of contents of this appendix is provided below.

Appendix A: table of contents

A.1 Identification of empirical evidence points 185
A.2 i-CLDs of each empirical evidence point 186
A.3 Standard f-CLD..... 207
A.4 Mapping i-CLDs to construct novel format f-CLD 208

A.1 Identification of empirical evidence points

A TITLE-ABS-KEY search was undertaken in Scopus on 6 Mar 2019 using the keyword strings copied below. The search results were limited to those published from 1990 to present and sorted by relevance; where there were greater than 20 results, the first 20 were reviewed, else all were reviewed. This approach is not exhaustive, however, telescopic snowballing key word combinations were used to isolate relevant results in initially abundant searches, as follows:

["societal collapse" OR "civilization collapse" OR "societal breakdown" OR "civilization breakdown" OR "societal instability" OR "civilization instability" OR "societal chaos" OR "civilization chaos" OR "societal unrest" OR "civilization unrest" OR "societal disorder" OR "civilization disorder" OR ("country" AND "fragility") OR "existential risk" OR "catastrophic risk" OR "extinction" OR "human extinction" OR "conflict" OR "violence" OR "riot" OR "civil unrest" OR "war" OR "emigration" OR "migration" OR "forced migration" OR "refugee" OR "displaced person" OR "mortality" OR "death" OR "human death" OR "loss of life" OR "disease" OR "starvation"] AND

["food" OR "famine" OR "food scarcity" OR "food security" OR "food insecurity" OR ("food" AND "shock") OR "food crisis" OR "food price" OR "food shortage" OR ("food" AND "trade")]

["climate change" OR "climate variability" OR "climate"] AND

["societal collapse" OR "civilization collapse" OR "societal breakdown" OR "civilization breakdown" OR "societal instability" OR "civilization instability" OR "societal chaos" OR "civilization chaos" OR "societal unrest" OR "civilization unrest" OR "societal disorder" OR "civilization disorder" OR ("country" AND "fragility") OR "existential risk" OR "catastrophic risk" OR "extinction" OR "human extinction" OR "conflict" OR "violence" OR "riot" OR "civil unrest" OR "war" OR "emigration" OR "migration" OR "forced migration" OR "refugee" OR "displaced person" OR "mortality" OR "death" OR "human death" OR "loss of life" OR "disease" OR "starvation"] AND

["food" OR "famine" OR "food scarcity" OR "food security" OR "food insecurity" OR ("food" AND "shock") OR "food crisis" OR "food price" OR "food shortage" OR ("food" AND "trade")]

["food"] AND

["conflict" OR "violence" OR "riot" OR "civil unrest" OR "war" OR "emigration" OR "migration" OR "forced migration" OR "refugee" OR "displaced person" OR "mortality" OR "death" OR "extinction" OR "human death" OR "loss of life" OR "disease" OR "starvation" OR "climate change" OR "trade"] AND

["agent-based model" OR "system dynamics model"]

A.2 i-CLDs of each empirical evidence point

One i-CLD was created for each empirical evidence points, except for N1, which has two i-CLDs. The first, below, was created by compiling the main feedback loop presented in figures by Meadows et al. (2004). The second, below, was created by exploring a copy of the STELLA World3-03 model, which was kindly provided by Dr Jorgen Randers. A copy of each i-CLD is provided below.

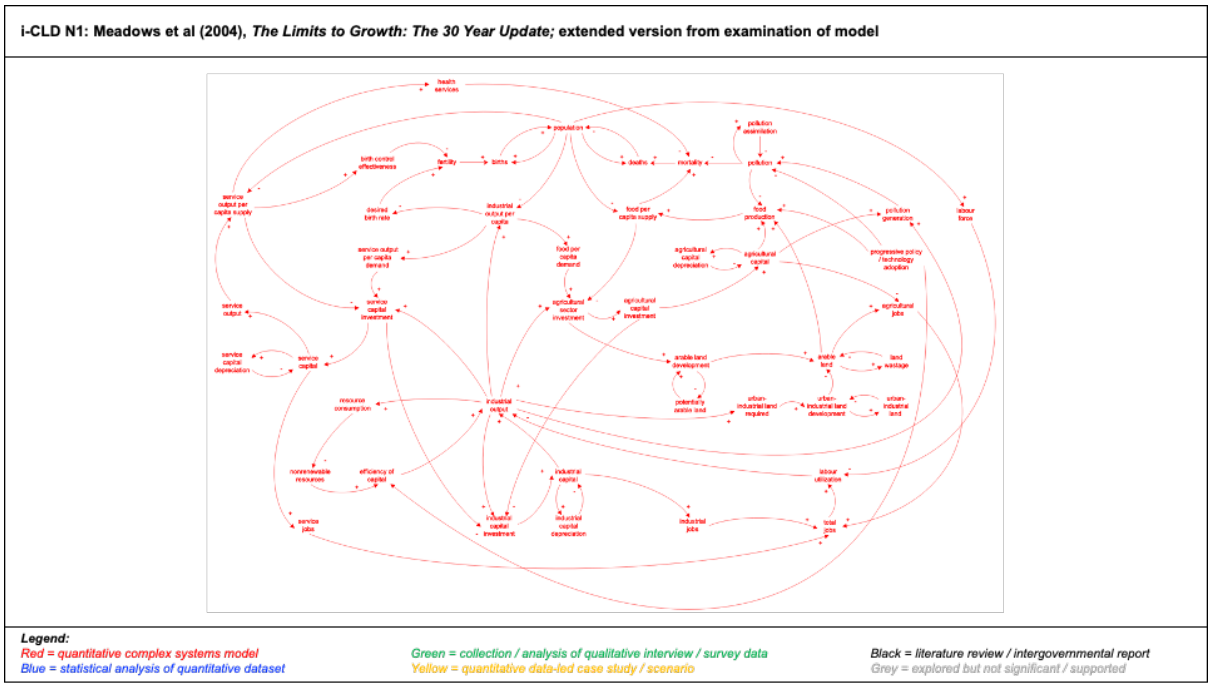
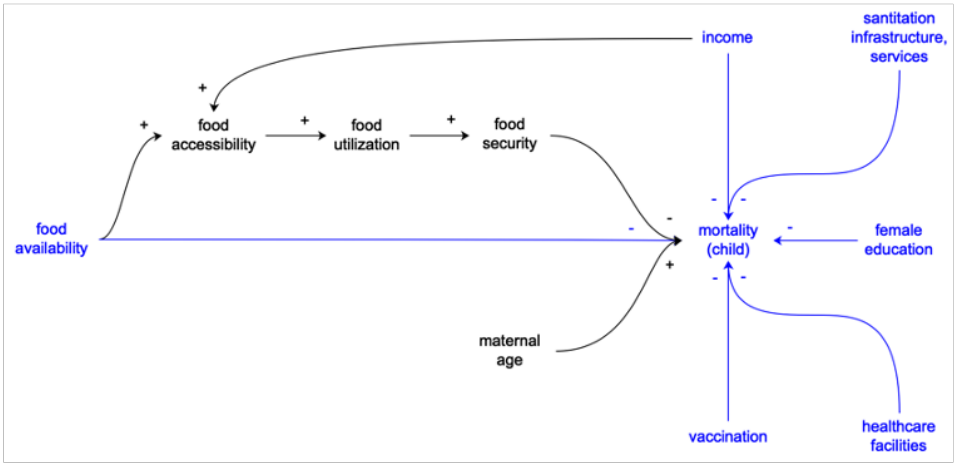


Figure A.1: i-CLD for evidence point N1

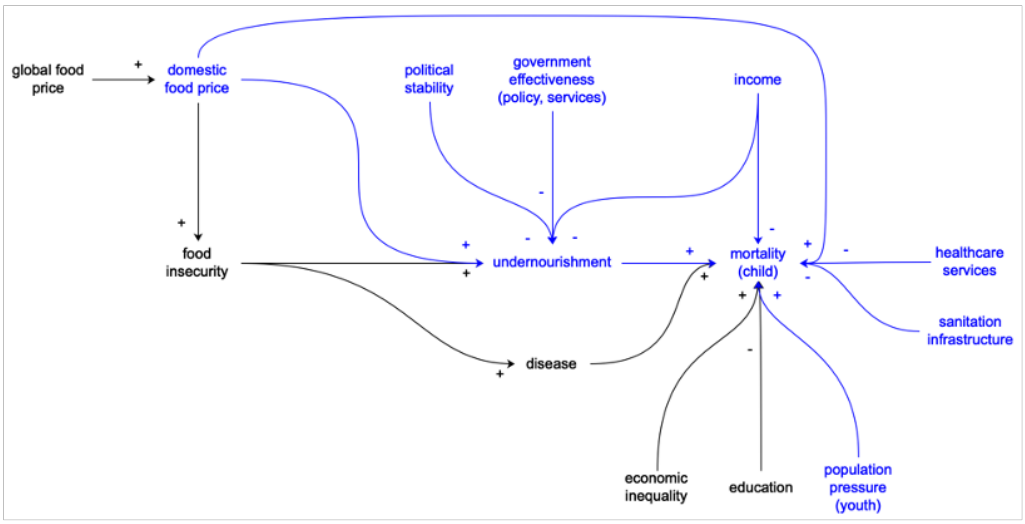
i-CLD N2: Agboola (2017), *Impact of food availability on child mortality: a cross country comparative analysis*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.2: i-CLD for evidence point N2

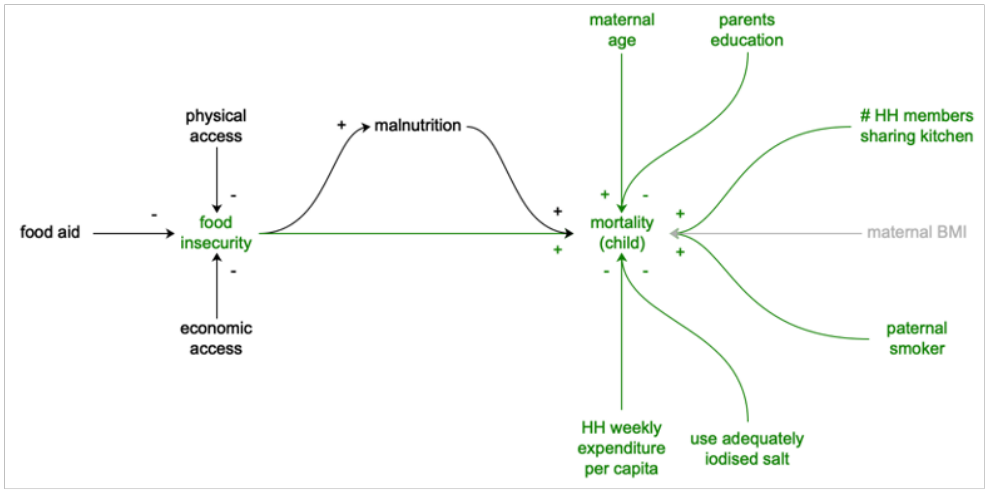
i-CLD N3: Lee et al (2016), *Effects of food price inflation on infant and child mortality in developing countries*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.3: i-CLD for evidence point N3

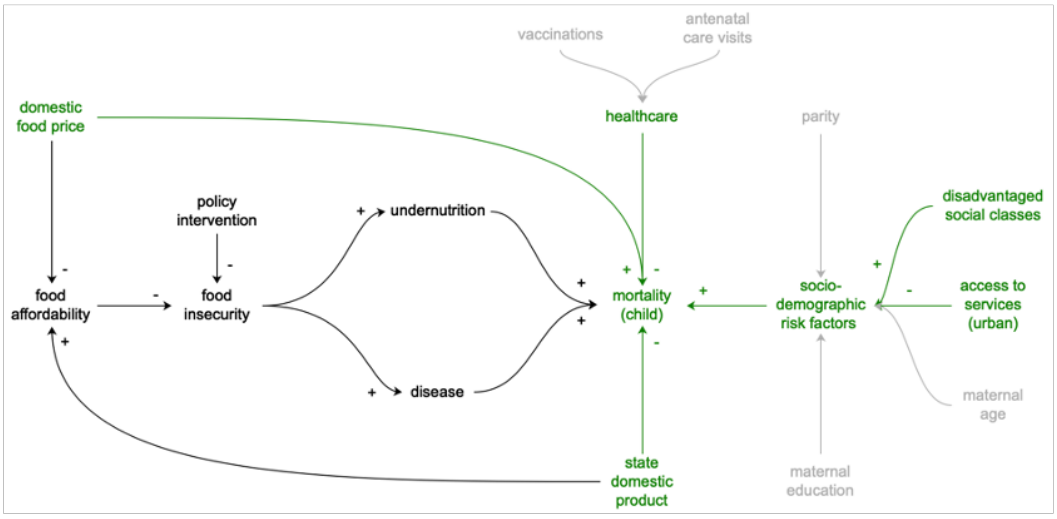
i-CLD N4: Campbell et al (2009), *Relationship of household food insecurity to neonatal, infant, and under-five child mortality among families in rural Indonesia*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.4: i-CLD for evidence point N4

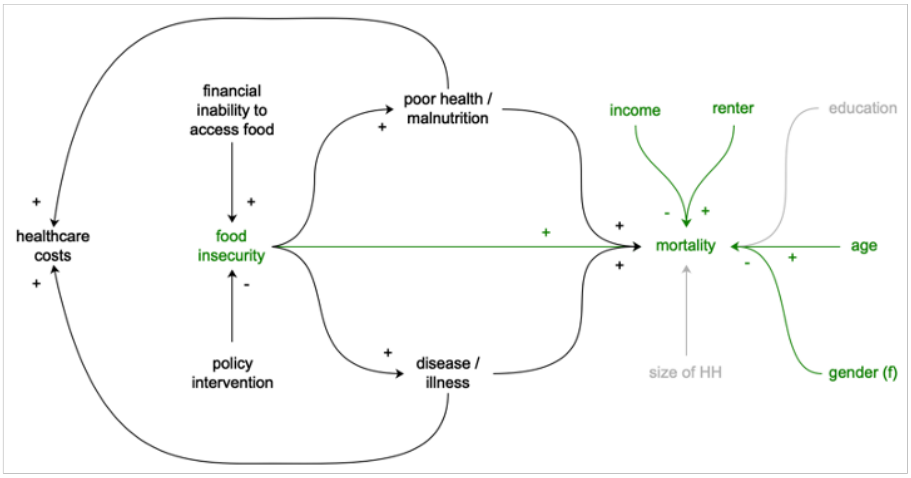
i-CLD N5: Fledderjohann et al (2016), *Quantifying the impact of rising food prices on child mortality in India: a cross-district statistical analysis of the District Level Household Survey*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.5: i-CLD for evidence point N5

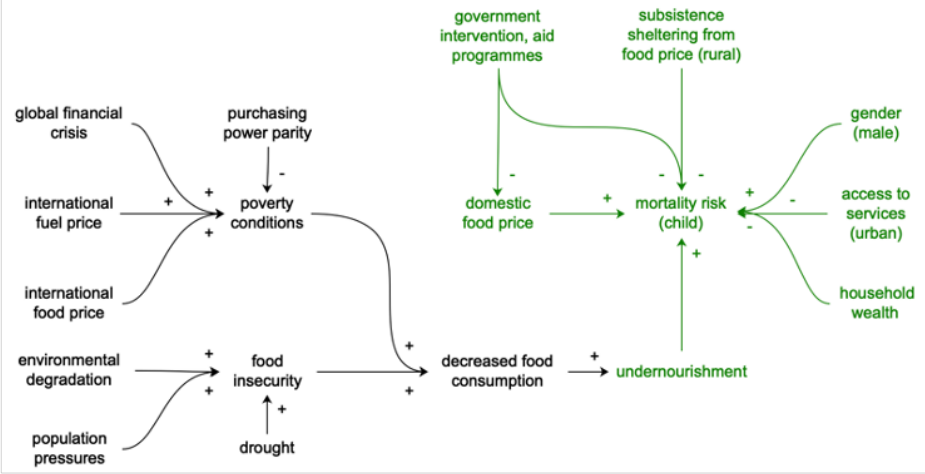
i-CLD N6: Gundersen et al (2018), *Food insecurity status and mortality among adults in Ontario, Canada*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.6: i-CLD for evidence point N6

i-CLD N7: Nandy et al (2016), *Examining the changing profile of undernutrition in the context of food price rises and greater inequality*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.7: i-CLD for evidence point N7

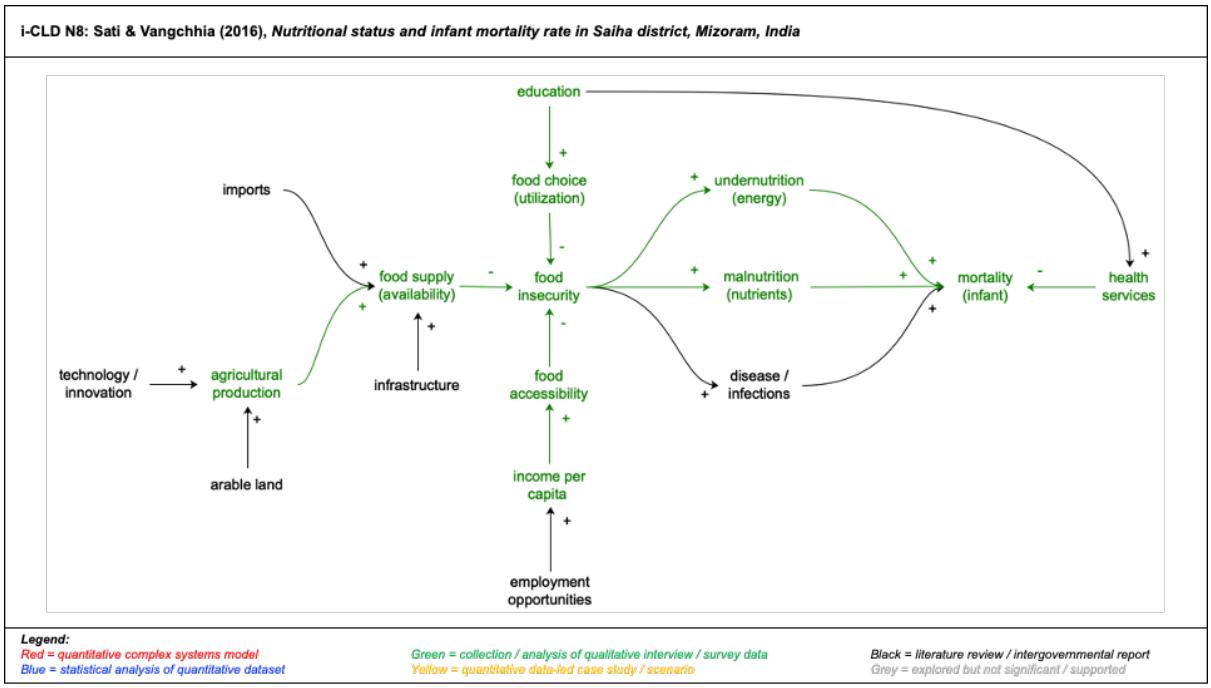


Figure A.8: i-CLD for evidence point N8

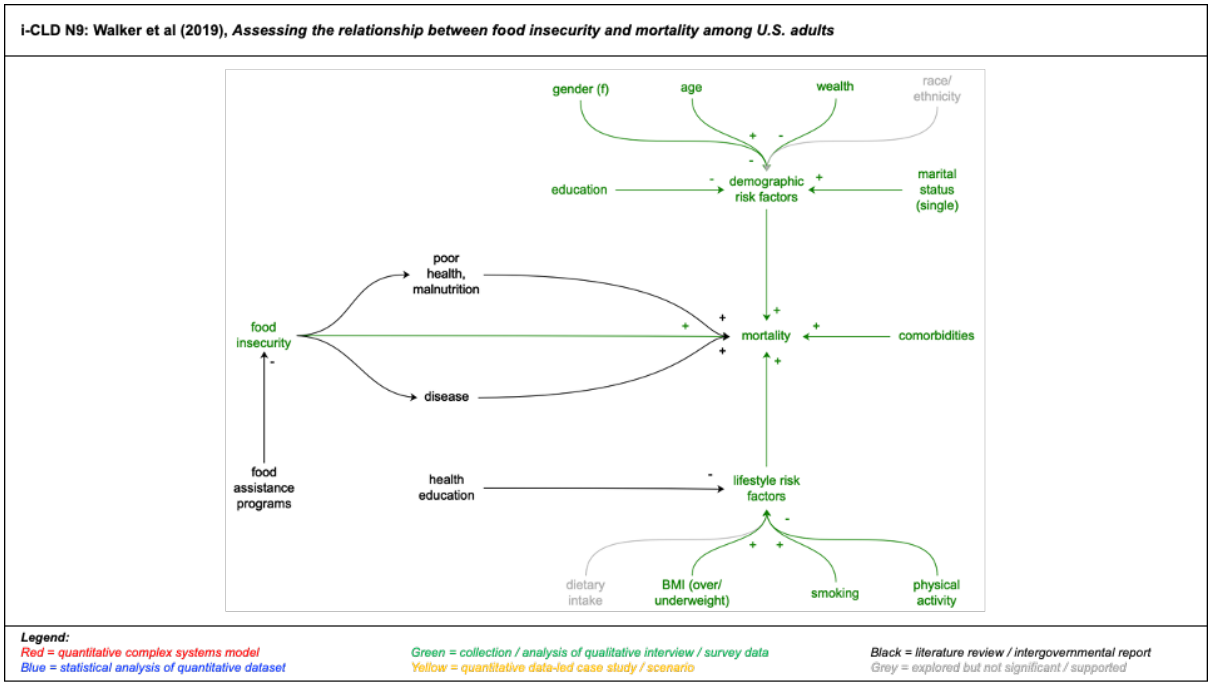
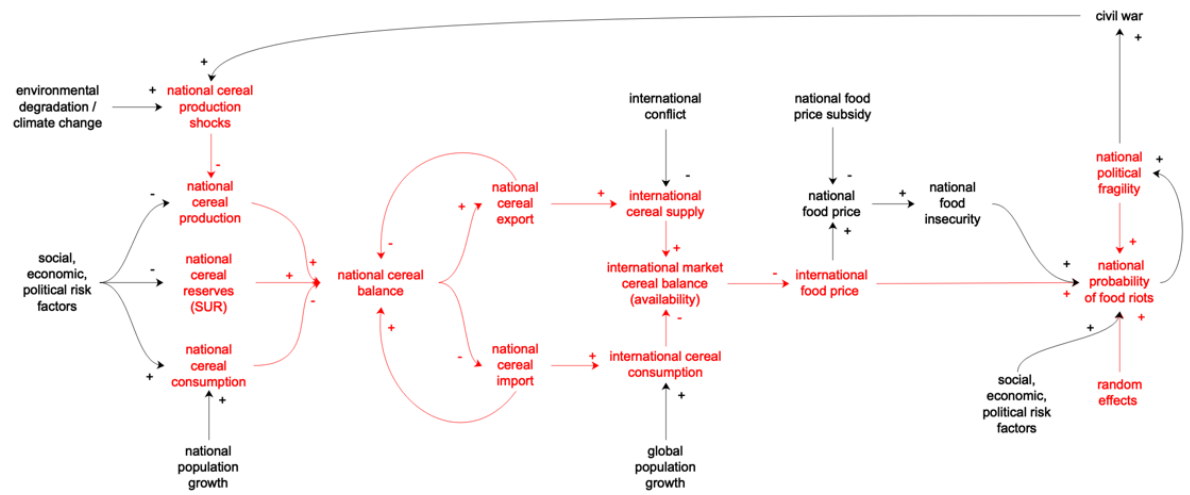


Figure A.9: i-CLD for evidence point N9

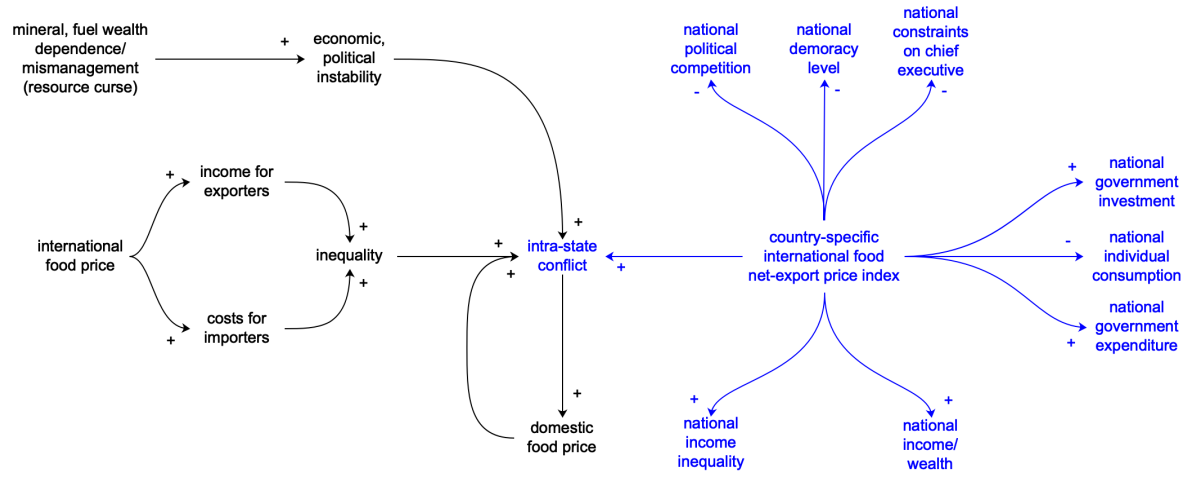
i-CLD C1: Natalini, Bravo & Jones (2017), *Global food security and food riots – an agent-based modelling approach*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.10: i-CLD for evidence point C1

i-CLD C2: Arezki & Brueckner (2014), *Effects of International Food Price Shocks on Political Institutions in Low-Income Countries: Evidence from an International Food Net-Export Price Index*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.11: i-CLD for evidence point C2

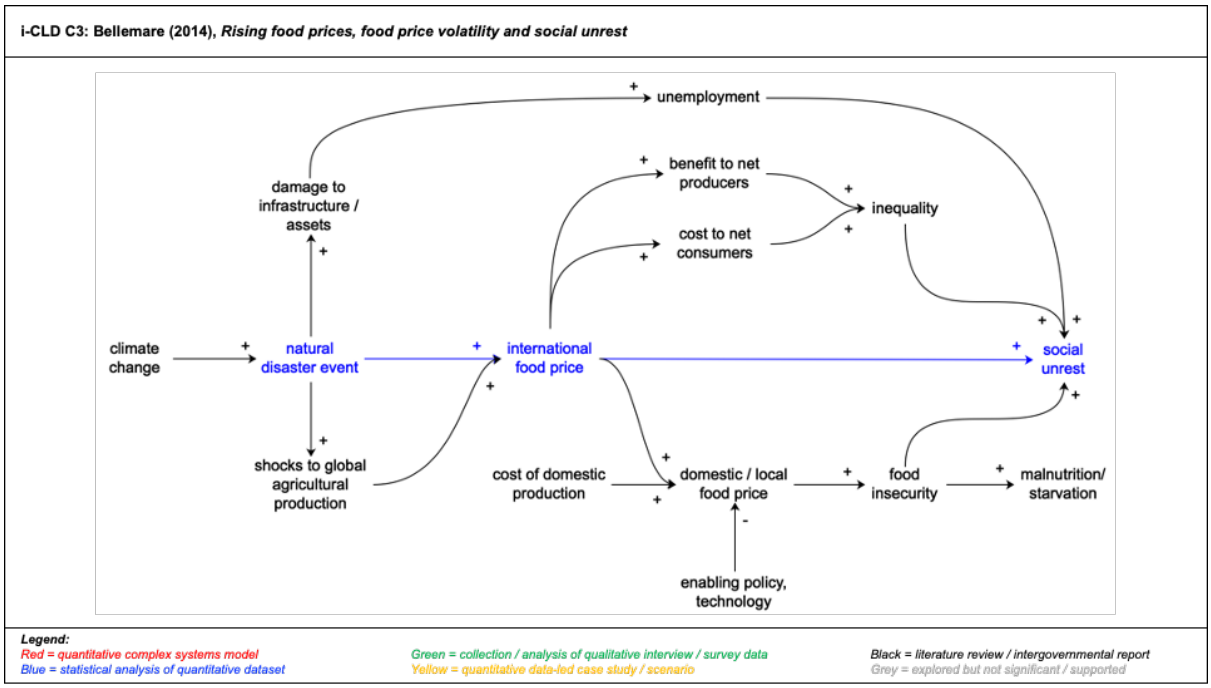


Figure A.12: i-CLD for evidence point C3

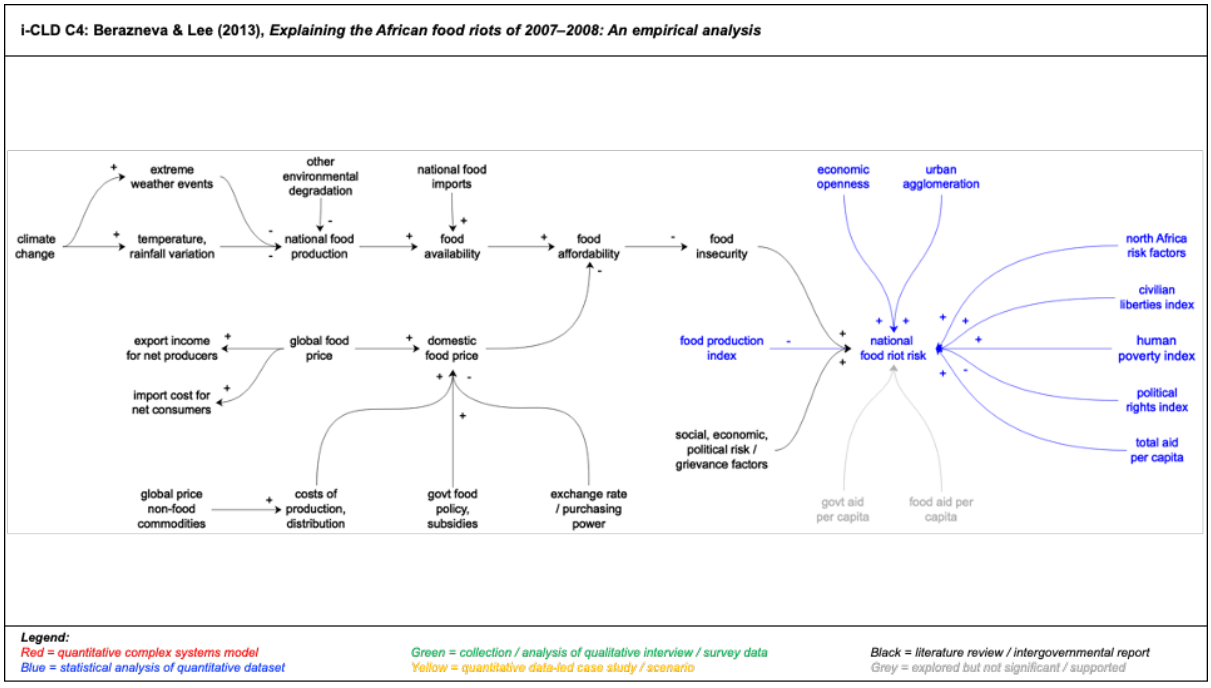
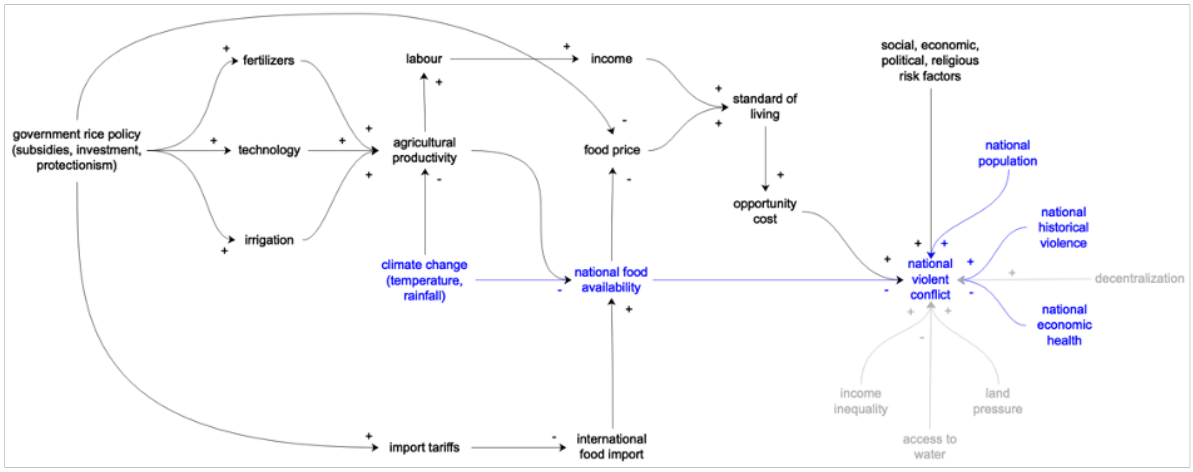


Figure A.13: i-CLD for evidence point C4

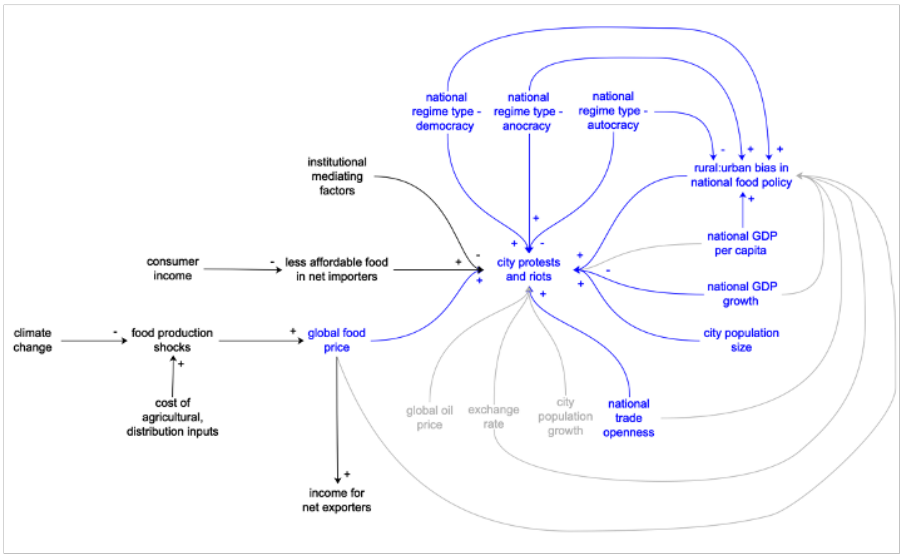
i-CLD C5: Caruso et al (2016), *Climate change, rice crops, and violence: Evidence from Indonesia*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.14: i-CLD for evidence point C5

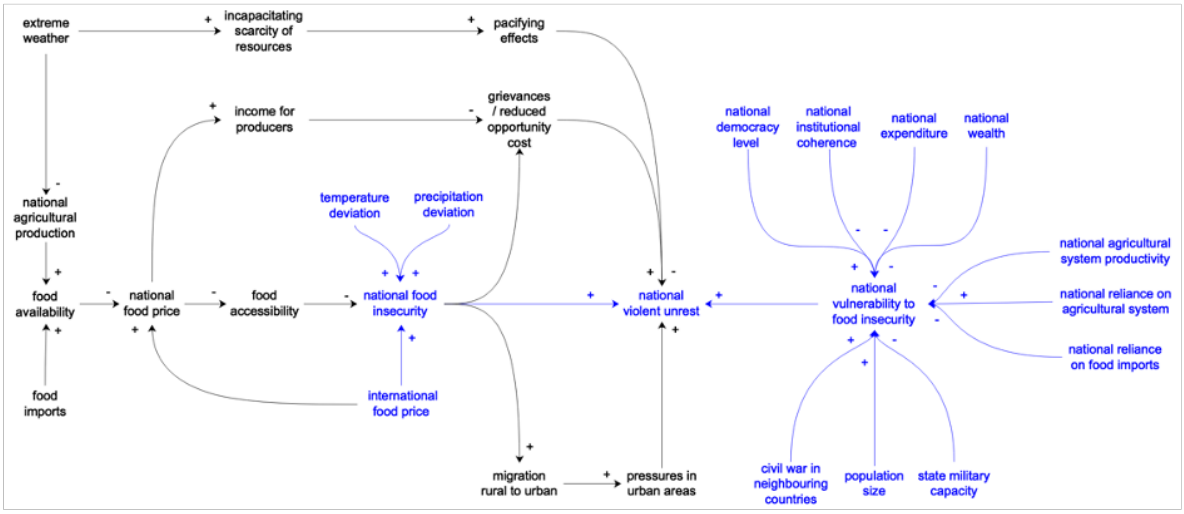
i-CLD C6: Hendrix & Haggard (2015), *Global food prices, regime type, and urban unrest in the developing world*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.15: i-CLD for evidence point C6

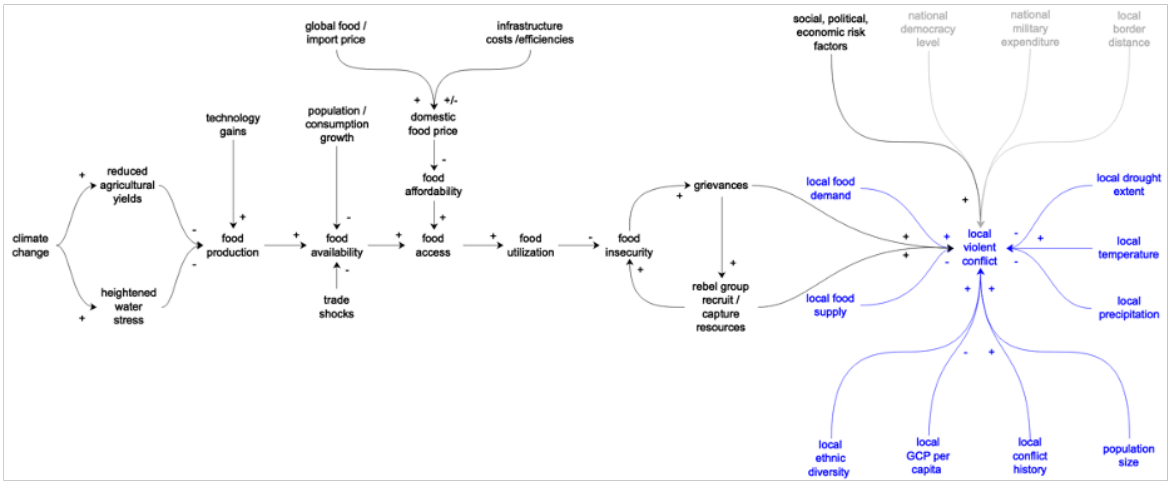
i-CLD C7: Jones et al (2017), *Food scarcity and state vulnerability: Unpacking the link between climate variability and violent unrest*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.16: i-CLD for evidence point C7

i-CLD C8: Koren & Bagozzi (2016), *From global to local, food insecurity is associated with contemporary armed conflicts*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.17: i-CLD for evidence point C8

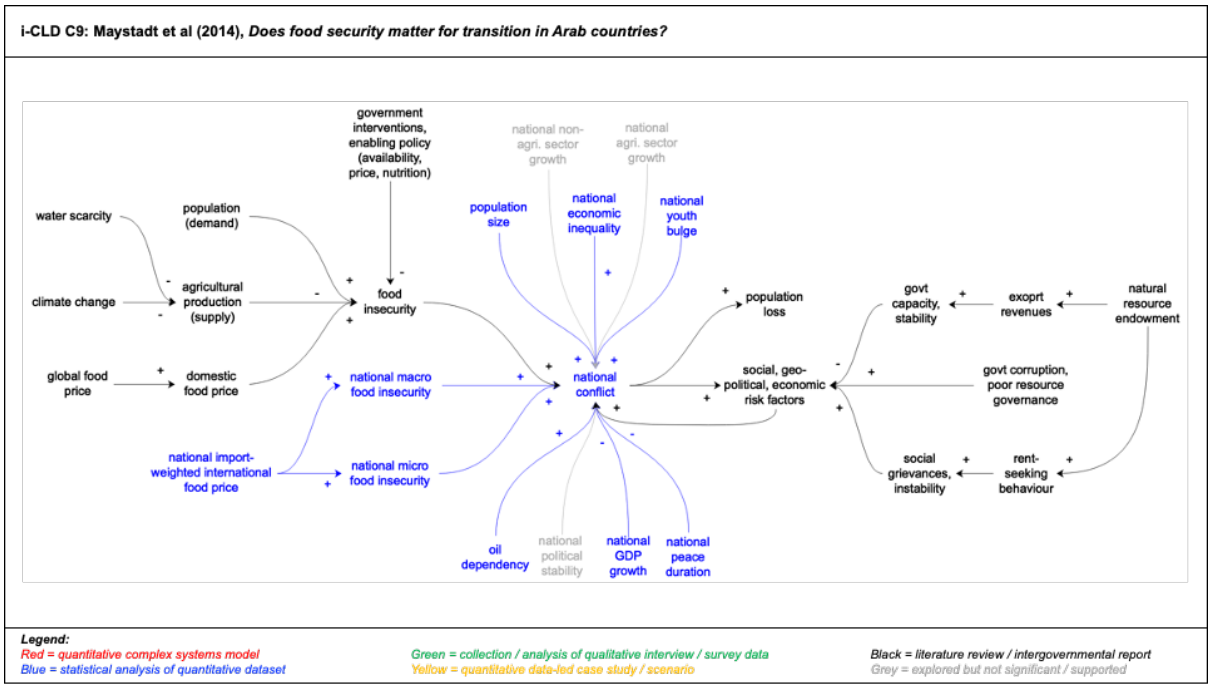


Figure A.18: i-CLD for evidence point C9

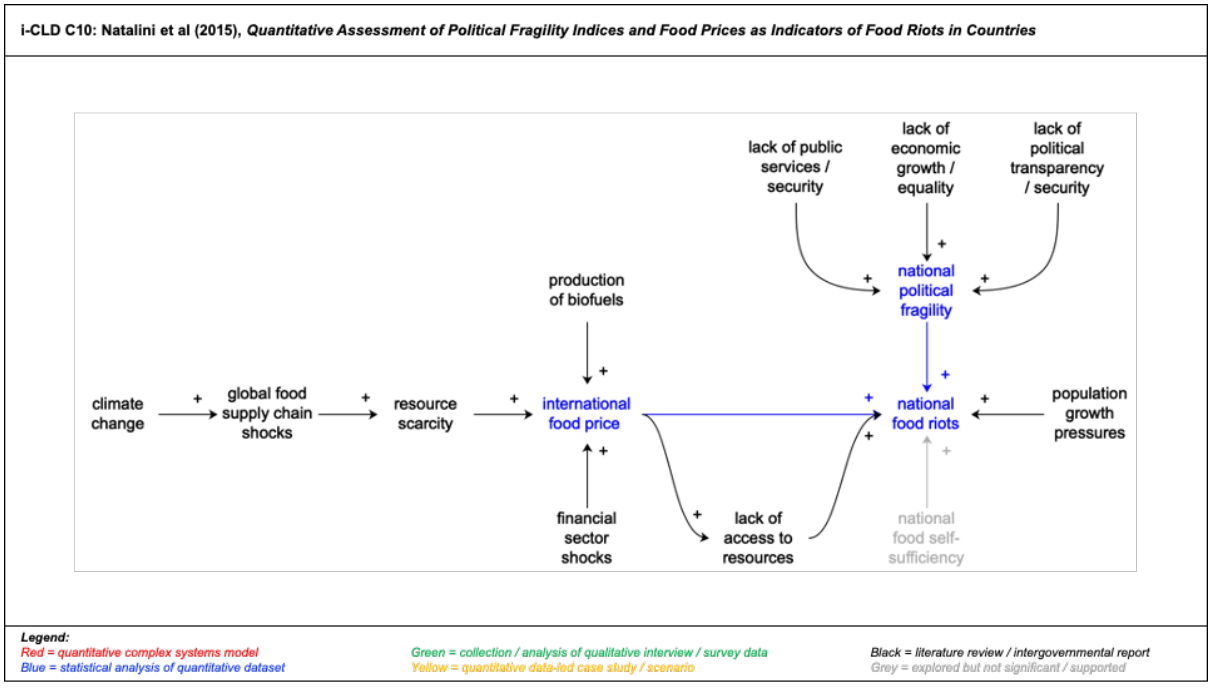
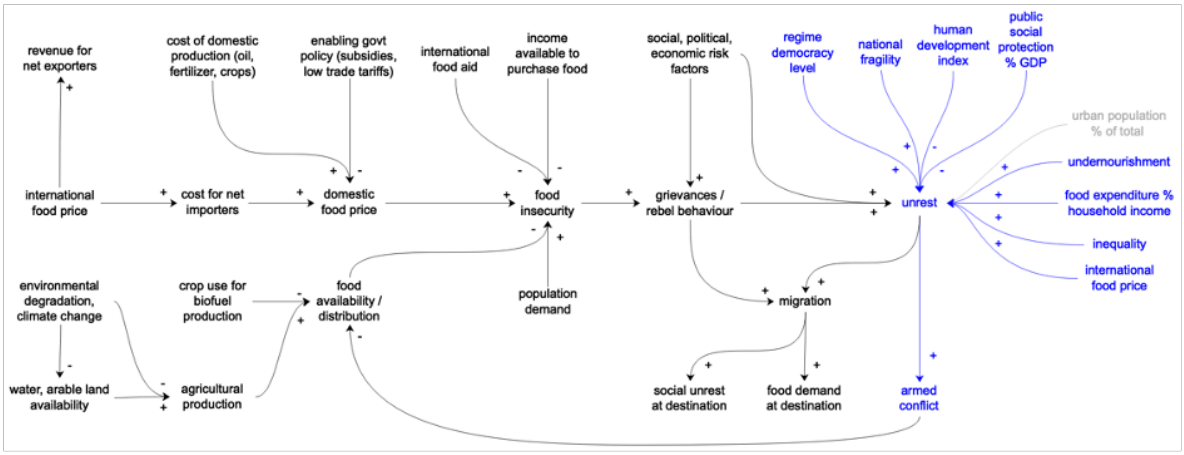


Figure A.19: i-CLD for evidence point C10

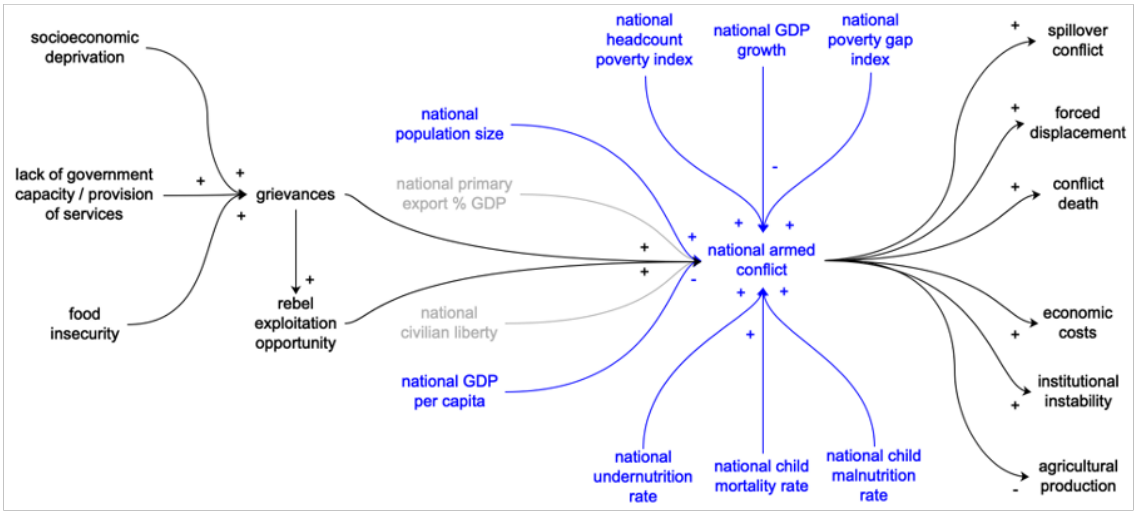
i-CLD C11: Newman (2018), *Hungry, or Hungry for Change? Food Riots and Political Conflict, 2005–2015*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.20: i-CLD for evidence point C11

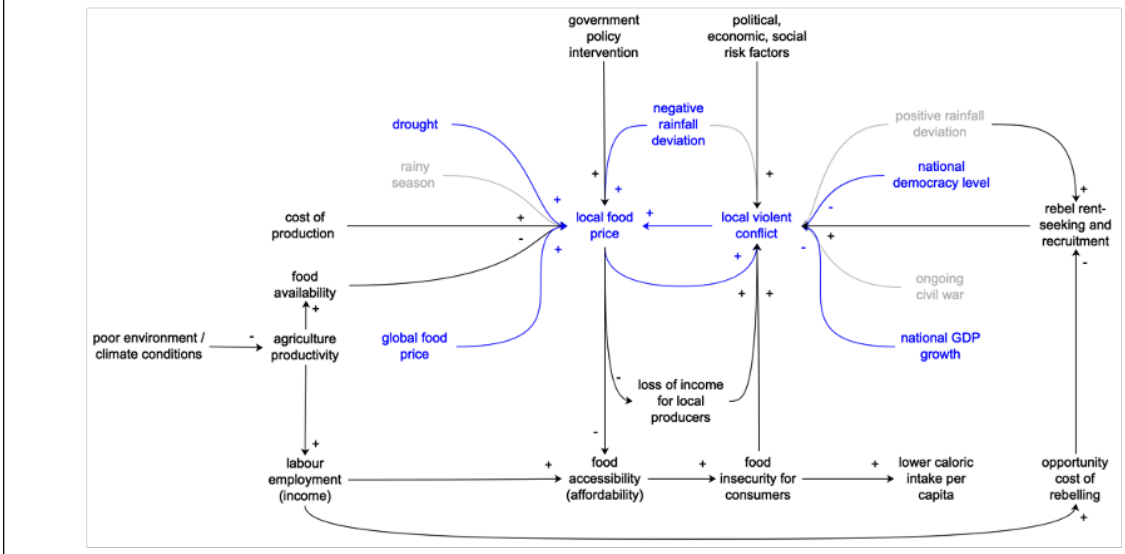
i-CLD C12: Pinstrup-Andersen & Shimokawa (2008), *Do poverty and poor health and nutrition increase the risk of armed conflict onset?*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.21: i-CLD for evidence point C12

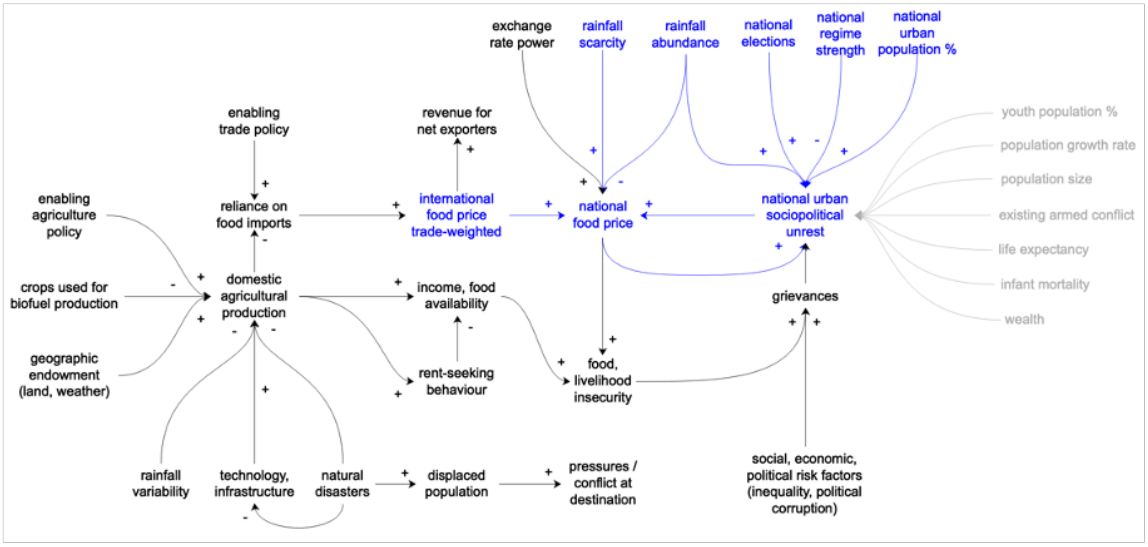
i-CLD C13: Raleigh et al (2015), *The devil is in the details: An investigation of the relationships between conflict, food price and climate across Africa*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.22: i-CLD for evidence point C13

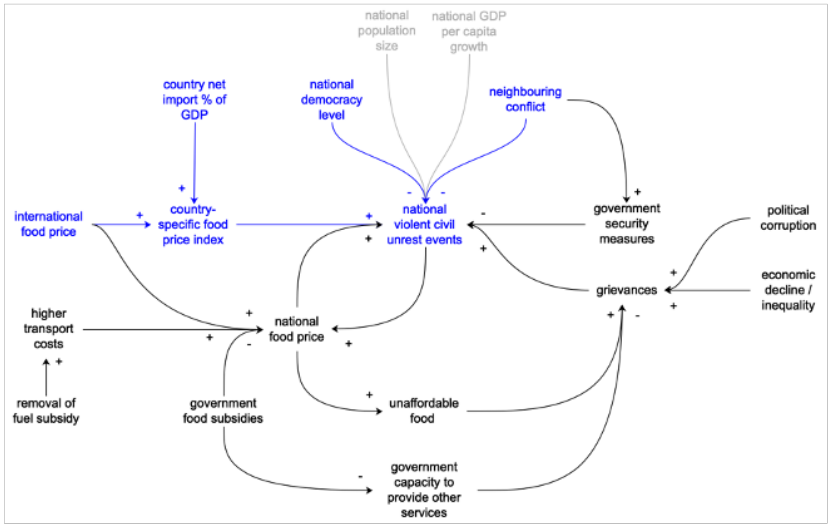
i-CLD C14: Smith (2014), *Feeding unrest: Disentangling the causal relationship between food price shocks and sociopolitical conflict in urban Africa*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.23: i-CLD for evidence point C14

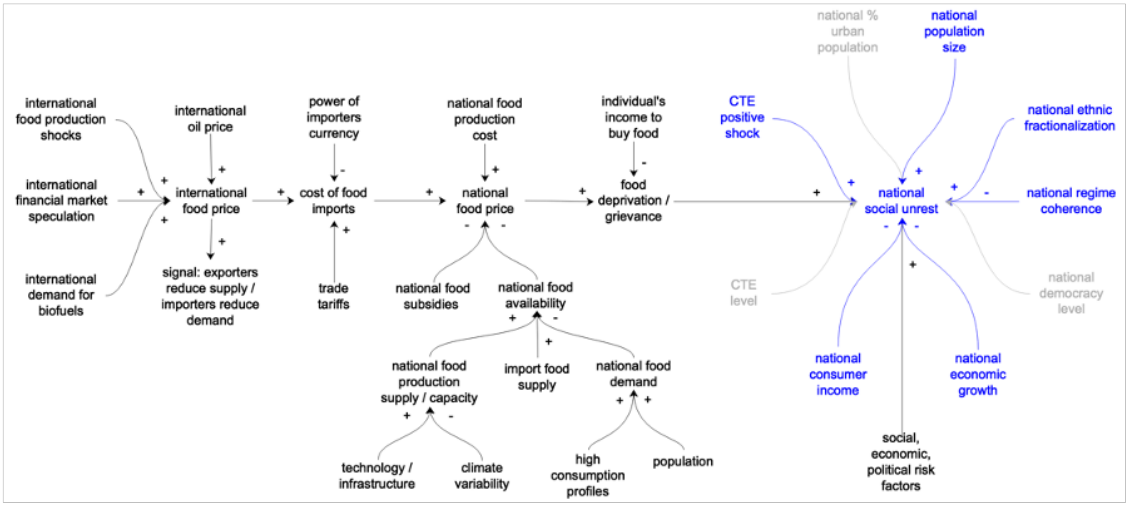
i-CLD C15: van Weezel (2016), *Food imports, international prices, and violence in Africa*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.24: i-CLD for evidence point C15

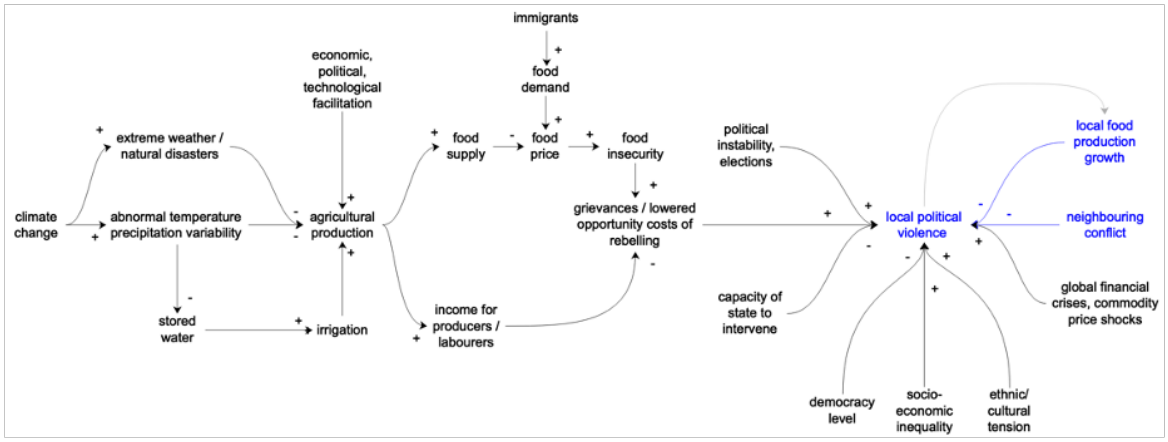
i-CLD C16: Weinberg & Bakker (2015), *Let them eat cake: Food prices, domestic policy and social unrest*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.25: i-CLD for evidence point C16

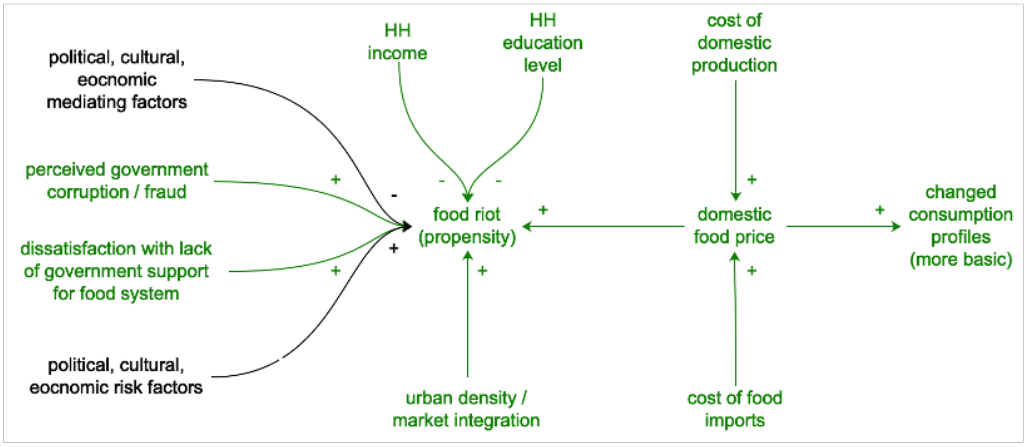
i-CLD C17: Wischnath & Buhaug (2014), *Rice or riots: On food production and conflict severity across India*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.26: i-CLD for evidence point C17

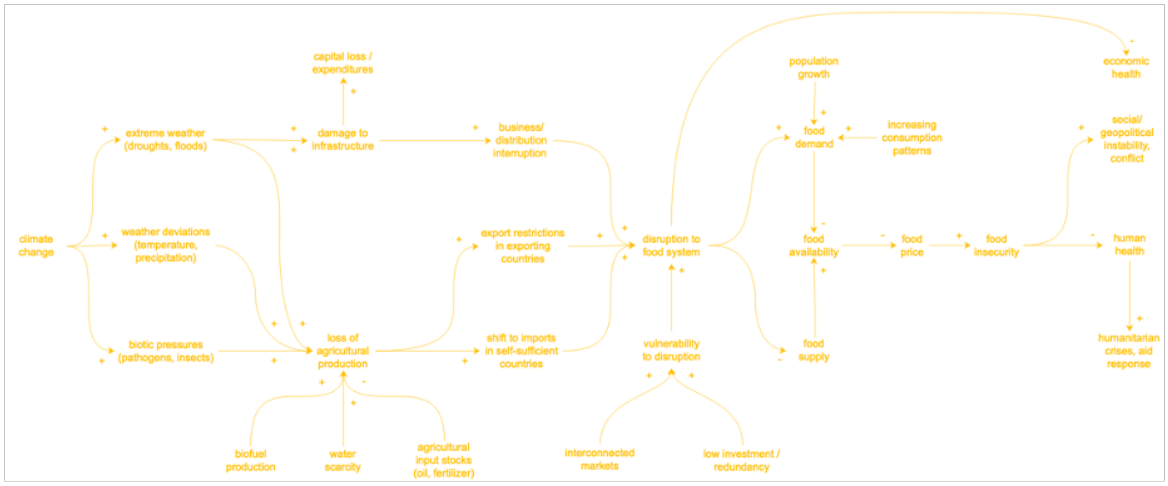
i-CLD C18: Legwegoh et al (2015), *Do Dietary Changes Increase the Propensity of Food Riots? An Exploratory Study of Changing Consumption Patterns and the Inclination to Engage in Food-Related Protests*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.27: i-CLD for evidence point C18

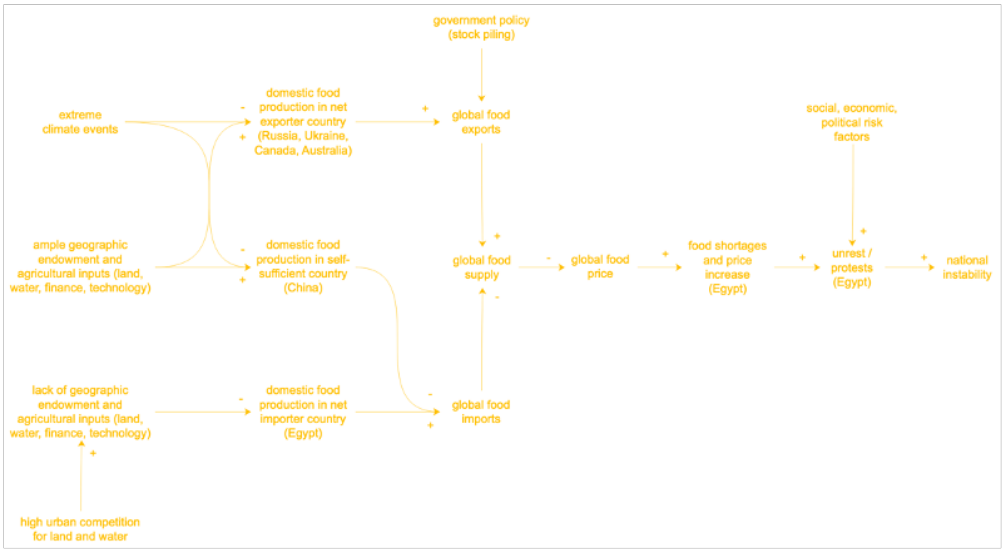
i-CLD C19: Lunt et al (2016), *Vulnerabilities to agricultural production shocks: An extreme, plausible scenario for assessment of risk for the insurance sector*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.28: i-CLD for evidence point C19

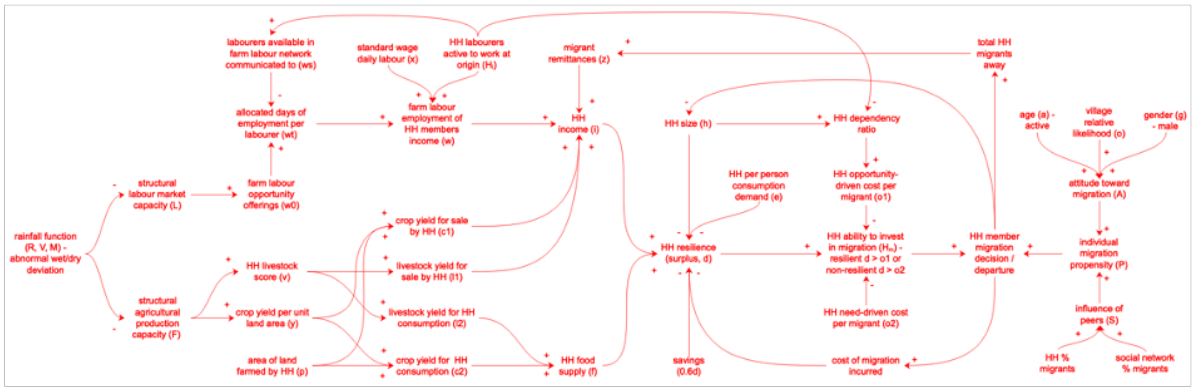
i-CLD C20: Sternberg (2012), *Chinese drought, bread and the Arab Spring*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.29: i-CLD for evidence point C20

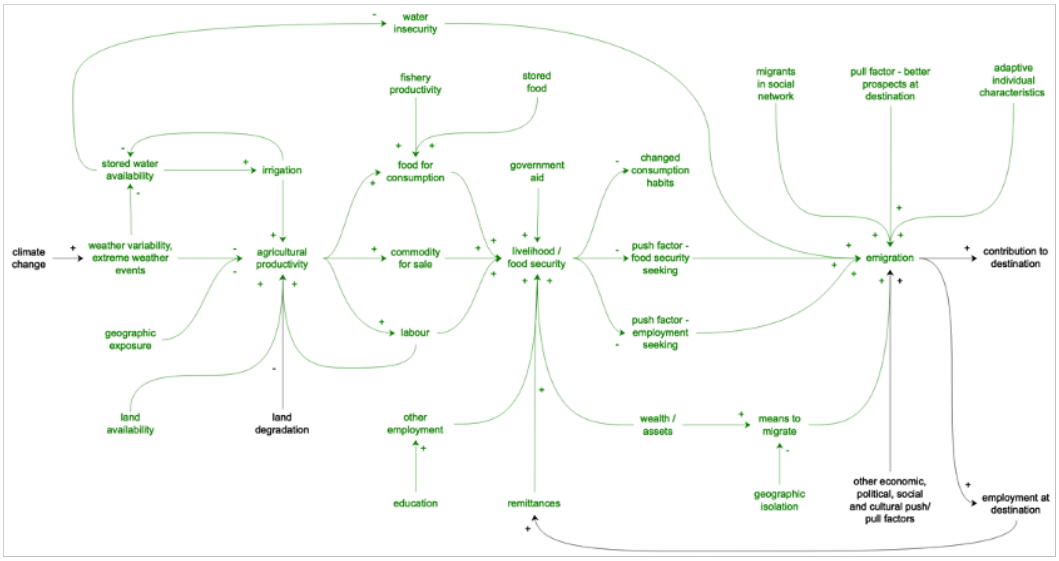
i-CLD E1: Smith (2014), *Modelling migration futures: development and testing of the Rainfalls Agent-Based Migration Model – Tanzania*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.30: i-CLD for evidence point E1

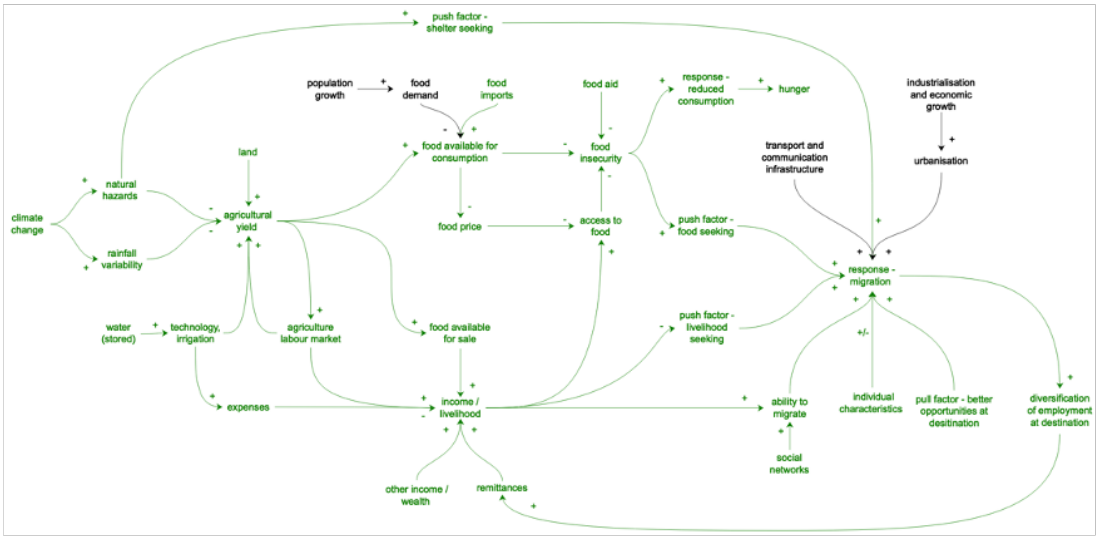
i-CLD E2: Afifi et al (2014), *Rainfall-induced crop failure, food insecurity and out-migration in Same-Kilimanjaro, Tanzania*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.31: i-CLD for evidence point E2

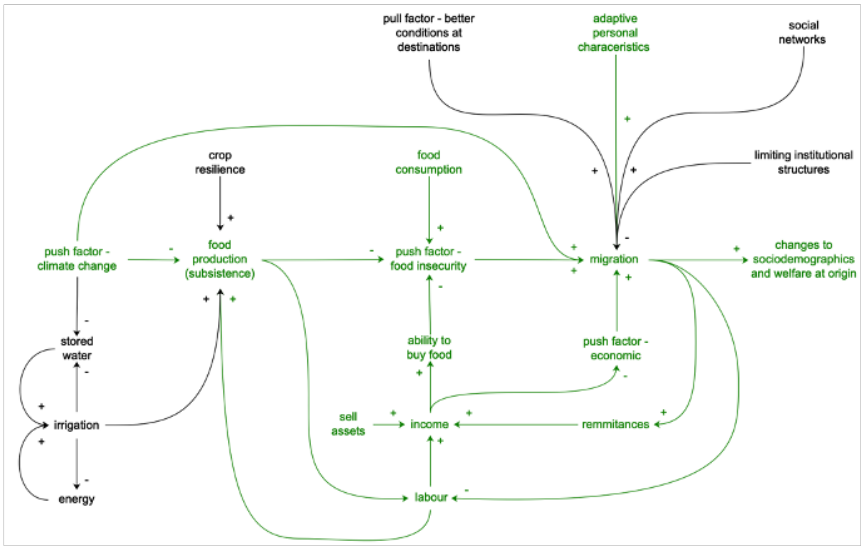
i-CLD E3: Etzold et al (2014), *Clouds gather in the sky, but no rain falls. Vulnerability to rainfall variability and food insecurity in Northern Bangladesh and its effects on migration*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.32: i-CLD for evidence point E3

i-CLD E4: Jacobson et al (2019), *When is migration a maladaptive response to climate change?*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.33: i-CLD for evidence point E4

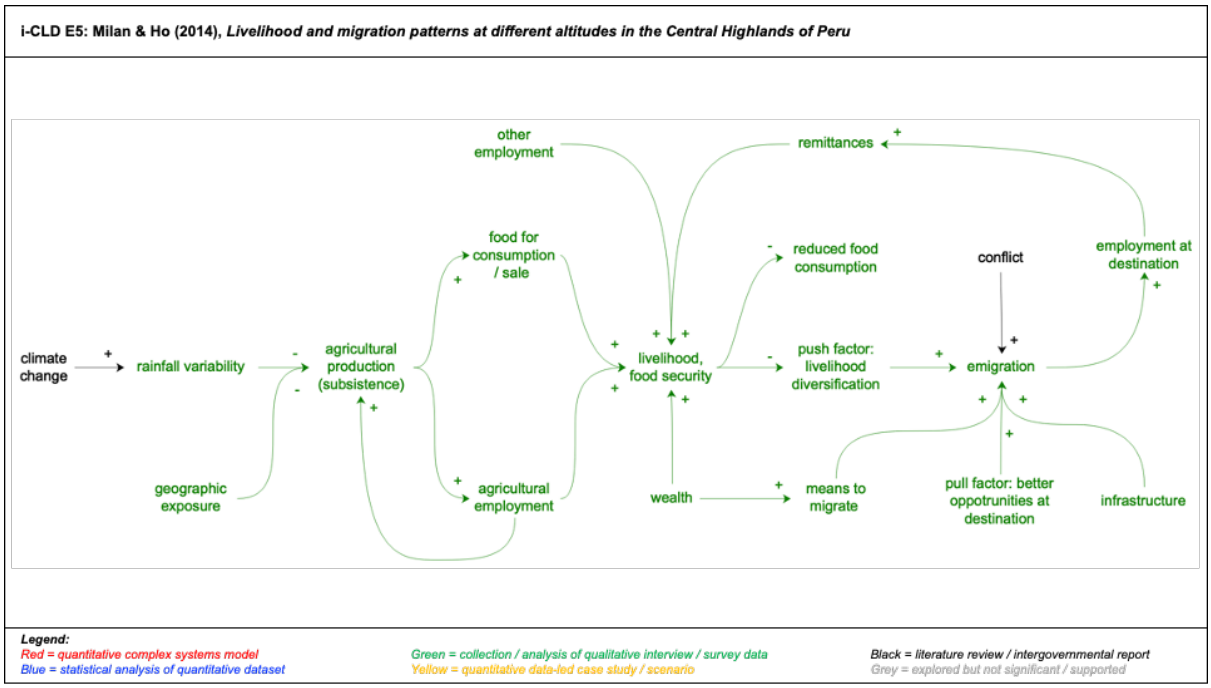


Figure A.34: i-CLD for evidence point E5

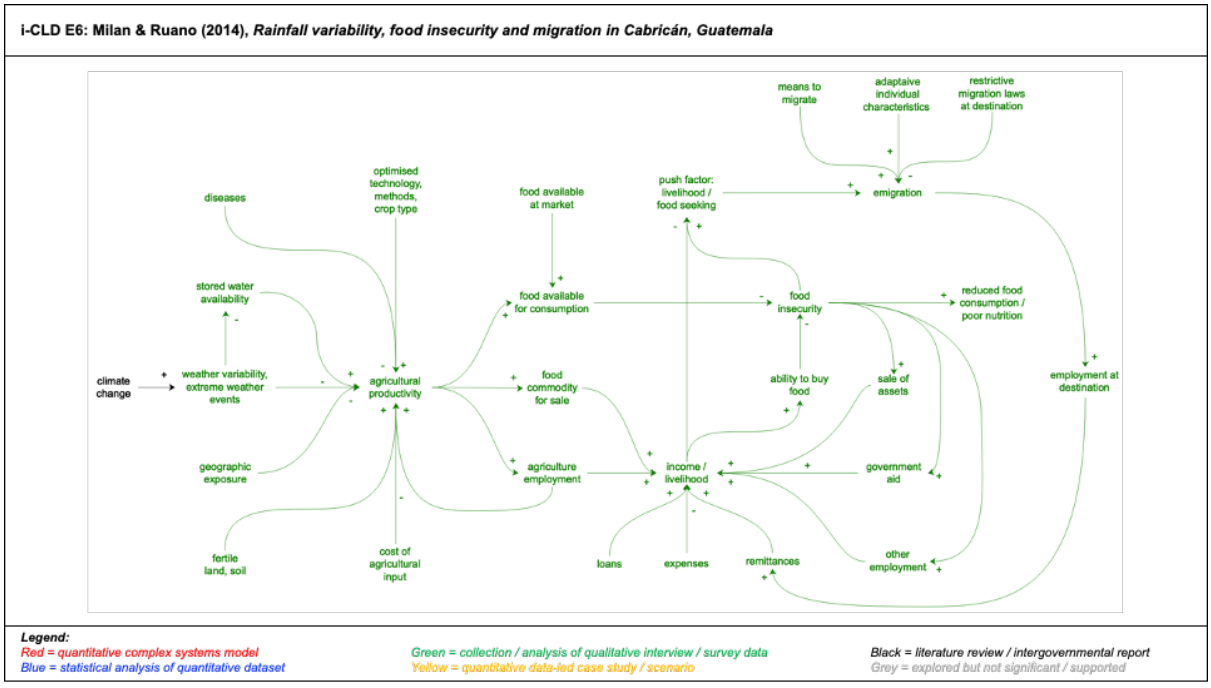
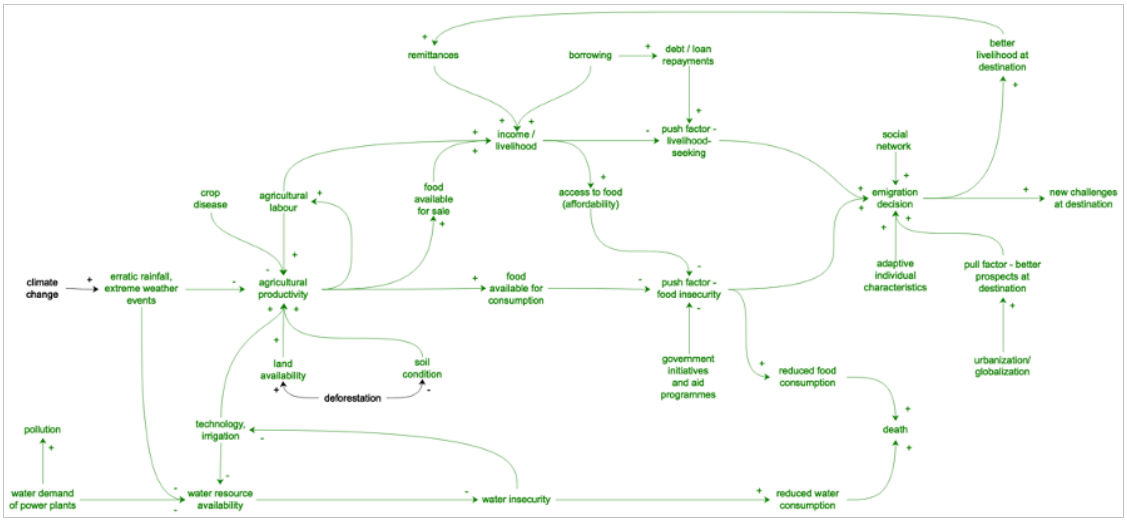


Figure A.35: i-CLD for evidence point E6

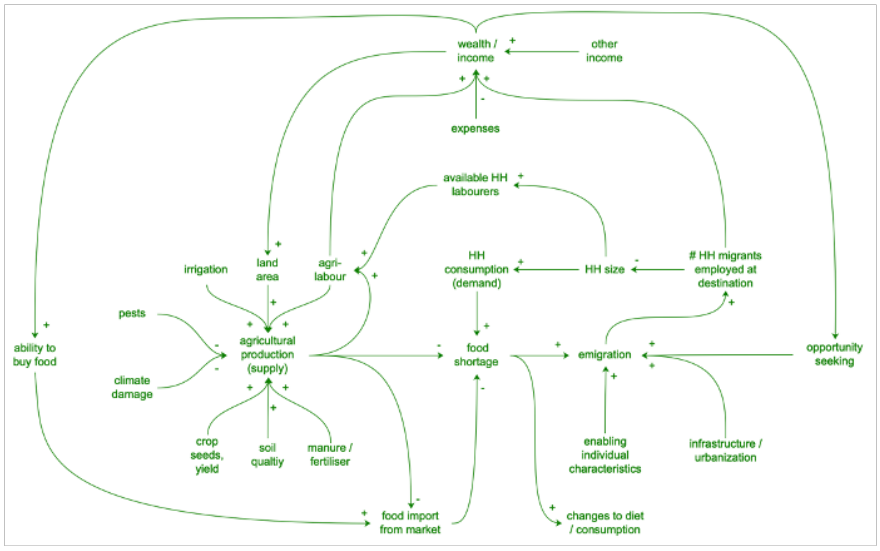
i-CLD E7: Murali & Afifi (2014), *Rainfall variability, food security and human mobility in the Janjgir-Champa district of Chhattisgarh state, India*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.36: i-CLD for evidence point E7

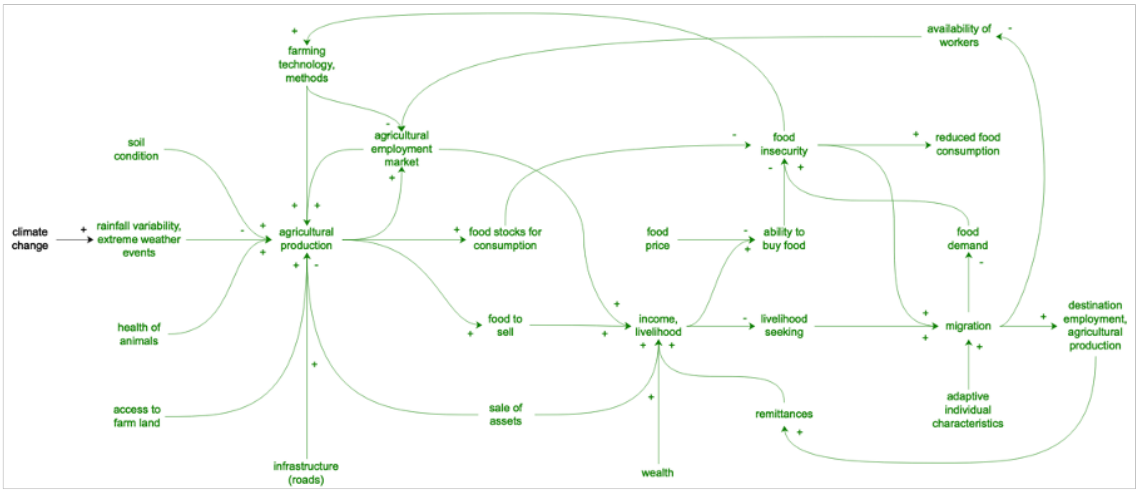
i-CLD E8: Panter-Brick & Eggerman (1997), *Household Responses to Food Shortages in Western Nepal*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.37: i-CLD for evidence point E8

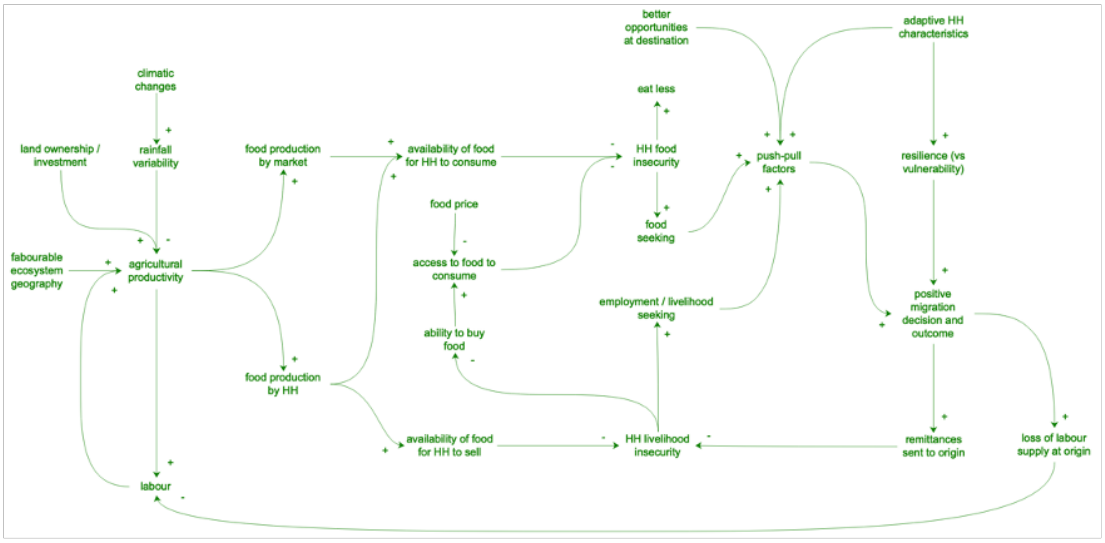
i-CLD E9: Rademacher-Schulz et al (2014), *Time matters: shifting seasonal migration in Northern Ghana in response to rainfall variability and food insecurity*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.38: i-CLD for evidence point E9

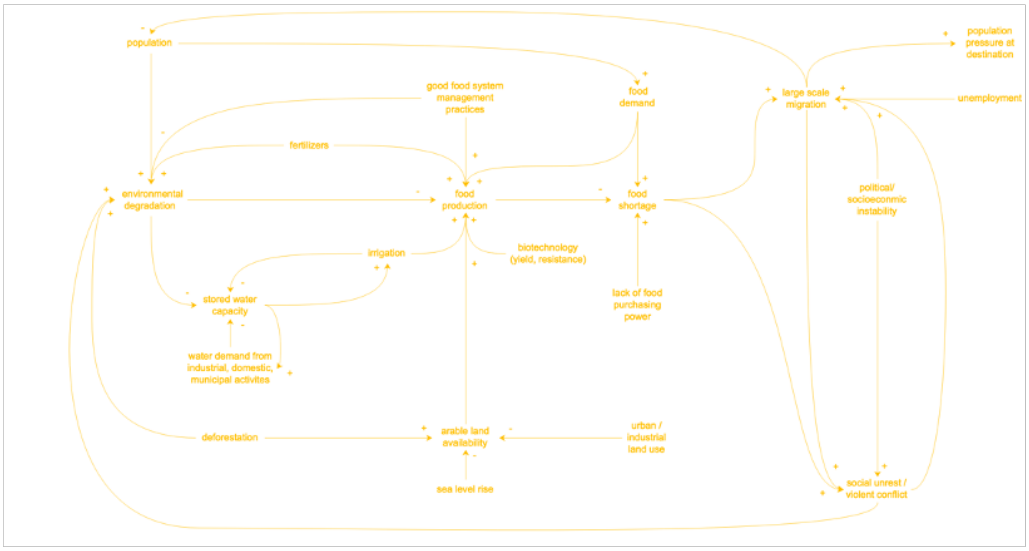
i-CLD E10: Warner & Afifi (2014), *Where the rain falls: Evidence from 8 countries on how vulnerable households use migration to manage the risk of rainfall variability and food insecurity*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.39: i-CLD for evidence point E10

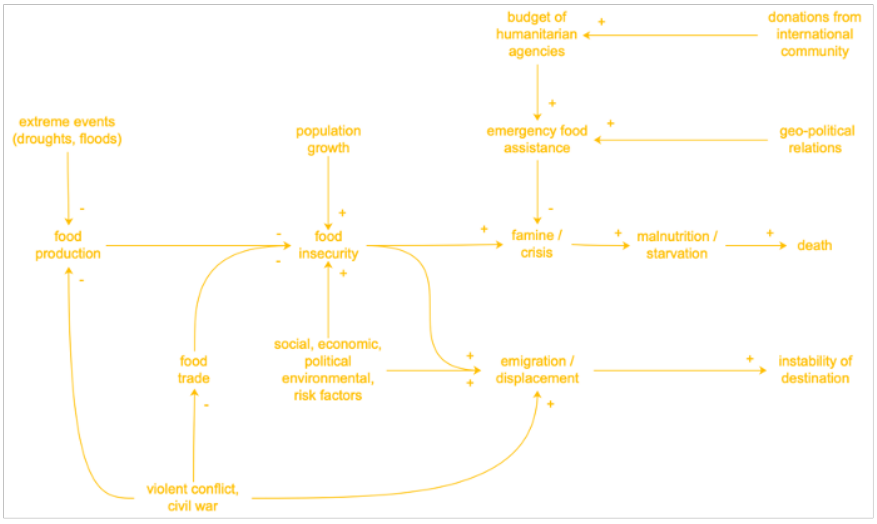
i-CLD E11: Doos (1994), *Environmental Degradation, Global Food Production, and Risk for Large-Scale Migrations*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.40: i-CLD for evidence point E11

i-CLD E12: Puma et al (2018), *A developing food crisis and potential refugee movements*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.41: i-CLD for evidence point E12

A.3 Standard f-CLD

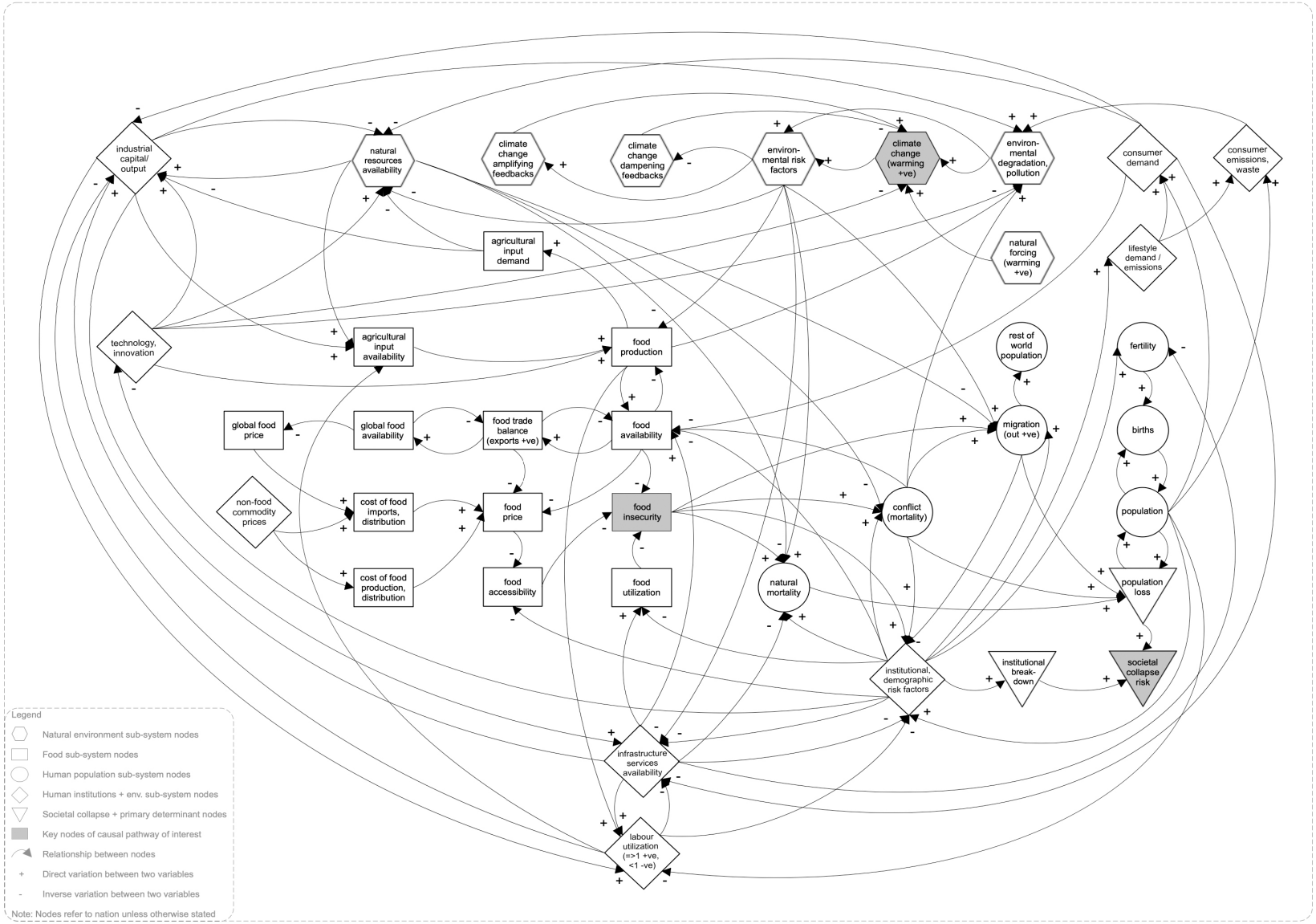


Figure A.42: Standard format f-CLD

A.4 Mapping i-CLDs to construct novel format f-CLD

For each i-CLD, yellow highlighting with Hindu-Arabic numerals is used to identify/reference the variables and purple highlighting along with English alphabet letters is used to identify/reference the links. Mapping documentation for the variables and links analysed by the data-driven method of each evidence point only is shown for clarity (i.e. the red, blue, green and yellow classifications from the custom typology, used to produce the novel form f-CLD with colour-coded weighting). The black coloured variables and links (i.e. those not analysed by the data-driven method but discussed in the introduction/literature review/discussion sections of an evidence point) were similarly mapped. While some of this mapping was straightforward, some required interpretation or multiple routing. This was done in a consistent manner, and the main interpretations adopted are summarised below.

Effects of climate change and environmental risk factors on food system

(1) For conditions / event effecting natural resource agricultural inputs, e,g, natural disaster (flood) contaminating water supply or change in precipitation/temperature leading to water shortage:

[climate change] > [environmental risk factors] > [natural resource availability] > [agricultural input availability] > [food production] …

(2) For conditions / events effecting production process / yields, e.g. temperature effecting crop growth rates, natural disaster (disease) killing livestock:

[climate change] > [environmental risk factors] > [natural resource availability] > [agricultural input availability] > [food production] …

(3) For events effecting storage / distribution infrastructure, e.g. a storm destroying a warehouse containing produced food supplies:

[climate change] > [environmental risk factors] > [infrastructure services] > [food availability] …

Effects of institutional / demographic risk factors on food system and societal collapse proxies

In reality, institutional and demographic factors influence nearly all components of the human and natural world systems and how they interact. As such, the links shown in the f-CLD are simplified to focus on the key relationships of interest. For instance, rather than explicitly routing institutional / demographic risk factors to all aspects of the food system that it can effect, three key routes are used which implicitly show the relationships in a clear manner, namely: food availability, food accessibility, and food utilization as these are the final nodes contributing to food insecurity.

(1) For economic/policy factors, e.g. food price subsidies, related to food access:

[institutional /demographic risk factors] > [food accessibility] …

(2) For economic/policy factors, e.g. international trade relations, related to food availability:

[institutional /demographic risk factors] > [food availability] …

(3) For demographic risk factors, e.g. lifestyle (smoking), related to food sub-system:

[institutional /demographic risk factors] > [food utilization] …

(4) For general political/social factors, e.g. political instability, not related to food sub-system:

[institutional /demographic risk factors] > [conflict]…

(5) For demographic factors, e.g. gender, not related to food sub-system:

[institutional /demographic risk factors] > [natural mortality] …

(6) For institutional and demographic factors, e.g. civil rights and age, not related to food sub-system:

[institutional /demographic risk factors] > [emigration] …

Effects of infrastructure services on food system and societal collapse proxies

(1) For infrastructure service factors, e.g. education, related to human food choice and hygiene:

[infrastructure services] > [institutional /demographic risk factors] > [food utilization] …

(2) For infrastructure service factors, e.g. sanitation, related to:

[infrastructure services] > [food utilization] …

(3) For infrastructure service factors, e.g. healthcare, related to human health:

[infrastructure services] > [natural mortality] …

Effects of food availability

(1) If the link between food availability and food insecurity or a societal collapse proxy is analysed by an evidence point but food price discussed:

[food production] > [food availability] > [food insecurity] …

&

[food production] > [food availability] > [food price] > [food accessibility] > [food insecurity] …

Effects of trade balance weighted food price index

(1) For international trade influencing food priece:

[international food price] > [price of food imports] > [food price] …

&

[cost of food production] > [food price] …

&

[food trade balance] > [food price] …

Effects of population growth

(1) For population concentration contributing to institutional pressures, e.g. social unrest:

[population] > [institutional/demographic risk factors] …

(2) For population growth contributing to total consumption increase:

[population] > [consumer demand] > [food availability] > [food insecurity] …

&

[population] > [consumer demand] > [food price] > [food accessibility] > [food insecurity] …

Effects of technology / innovation on food system

(1) For technology / innovation, e.g. fertilizers, increasing industrial agricultural inputs:

[technology/innovation] > [industrial capital/output] > [agricultural input availability] > …

(2) For technology / innovation, e.g. water storage, increasing natural resource agricultural inputs:

[technology/innovation] > [natural resources availability] > [agricultural input availability] > …

(3) For technology / innovation, e.g. crop yield enhancement, increasing food production:

[technology/innovation] > [food production] > …

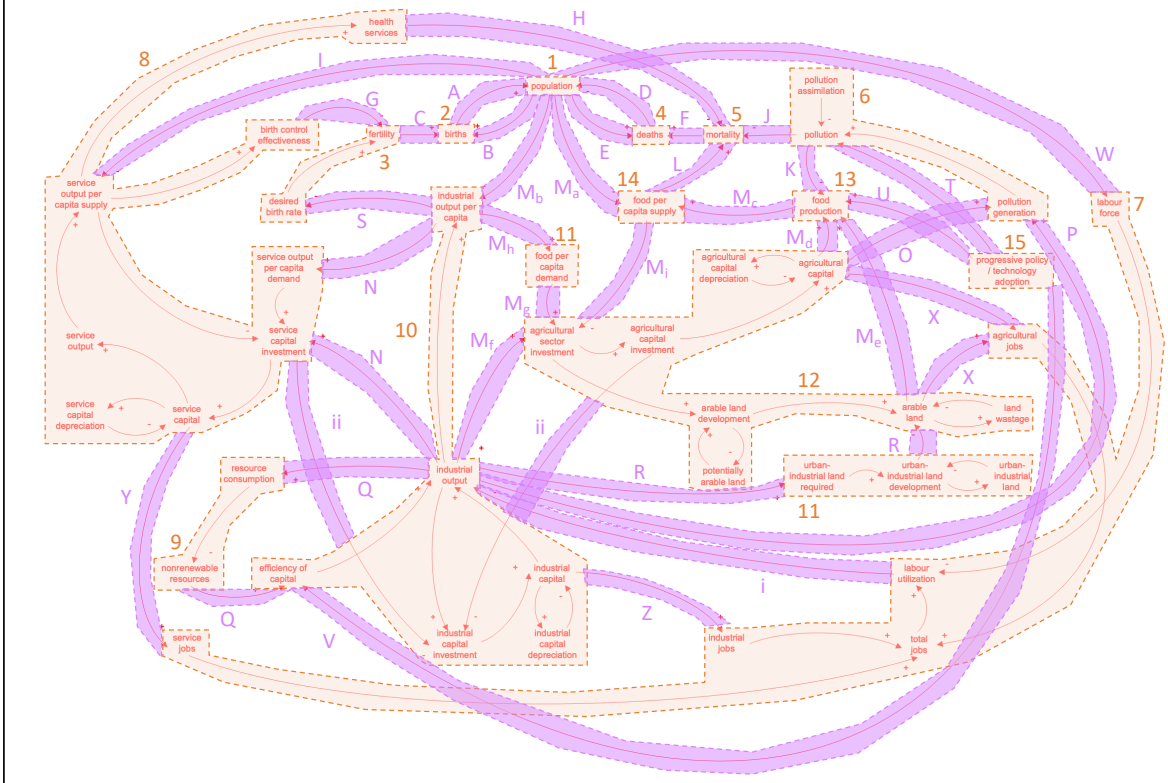
Mapping i-CLD N1: Meadows et al (2004), *The Limits to Growth: The 30 Year Update;* extended version from examination of model

Variables

1. ***population***
2. ***births***
3. ***fertility***
4. ***population loss***
5. ***natural mortality***
6. ***environmental degradation / pollution***
7. ***labour utilization***
8. ***infrastructure services***
9. ***natural resource***
10. ***industrial capital/output*** and ***institutional/demographic risk factors***
11. ***consumer demand***
12. ***agricultural input availability*** and ***natural resources*** and ***agricultural input demand***
13. ***food production***
14. ***food availability***
15. ***technology/innovation*** and ***institutional / demographic risk factors***

Links

A. ***[births] > [population]***
B. ***[population] > [births]***
C. ***[fertility] > [births]***
D. ***[population loss] > [population]***
E. ***[population] > [population loss]***
F. ***[natural mortality] > [population loss]***
G. ***[infrastructure services] > [fertility]***
H. ***[infrastructure services] > [natural mortality]***
I. ***[population] > [consumer demand] > [infrastructure services]***
J. ***[environmental degradation / pollution] > [environmental risk factors] > [natural mortality]***
K. ***[environmental degradation/pollution] > [environmental risk factors] > [natural resources availability] > [agricultural input availability] > [food production] & [environmental degradation/pollution] > [environmental risk factors] > [food production]***
L. ***[food availability] > [food insecurity] > [natural mortality]***
M. a) ***[population] > [consumer demand] > [food availability]***
b) ***[population] > [consumer demand] > [industrial capital/output]***
c) ***[food production] > [food availability]***
d) ***[agricultural input availability] > [food production]***
e) ***[natural resources] > [agricultural input availability] > [food production]***
f) ***[industrial capital / output] > [agricultural input availability] > [food production]***
g) ***[consumer demand] > [food availability] > [food production] > [agricultural input demand]***
h) ***[institutional / demographic risk factors] > [lifestyle demand/emissions] > [consumer demand]***
i) ***[food availability] > [food production] > [agricultural input demand]***
N. ***[industrial capital / output] > [infrastructure services]***
O. ***[food production] > [environmental degradation/pollution]***
P. ***[industrial capital / output] > [environmental degradation/pollution]***
Q. ***[industrial capital / output] > [natural resources] > [industrial capital / output]***
R. ***[industrial capital / output] > [natural resources] & [consumer demand] > [natural resources]***
S. ***[institutional/demographic risk factors] > [fertility]***
T. ***[institutional/demographic risk factors] > [technology/innovation] > [environmental degradation / pollution]***
U. ***[institutional/demographic risk factors] > [technology/innovation] > [food production]***
V. ***[institutional/demographic risk factors] > [technology/innovation] > [industrial capital / output]***
W. ***[population] > [labour utilization]***
X. ***[agricultural input availability] > [food production] > [labour utilization]***
Y. ***[infrastructure services] > [labour utilization]***
Z. ***[industrial capital / output] > [labour utilization]***
i. ***[labour utilization] > [industrial capital / output]***
ii. ***[infrastructure service] > [industrial capital / output] & [agricultural input demand] > [industrial capital / output]***



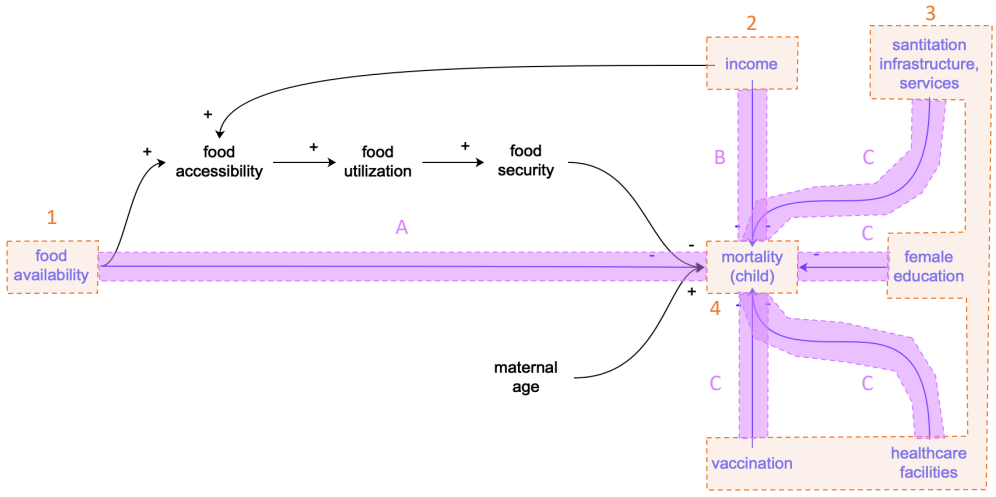
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.43: Mapping the i-CLD for evidence point N1

Mapping i-CLD N2: Agboola (2017), *Impact of food availability on child mortality: a cross country comparative analysis*

Variables
1. *food availability*
2. *institutional/demographic risk factors*
3. *infrastructure services*
4. *natural mortality*

Links
A. *[food availability] > [food insecurity] > [natural mortality]*
& [food availability] > [food price] > [food accessibility] > [food insecurity] > [natural mortality]
B. *[institutional/demographic risk factors] > [natural mortality]*
& [institutional/demographic risk factors] > [food accessibility] > [food insecurity] > [natural mortality]
C. *[infrastructure services] > [natural mortality]*
& [infrastructure services] > [food utilization] > [food insecurity] > [natural mortality]
& [infrastructure services] > [institutional/demographic risk factors] > [food utilization] > [food insecurity] > [natural mortality]



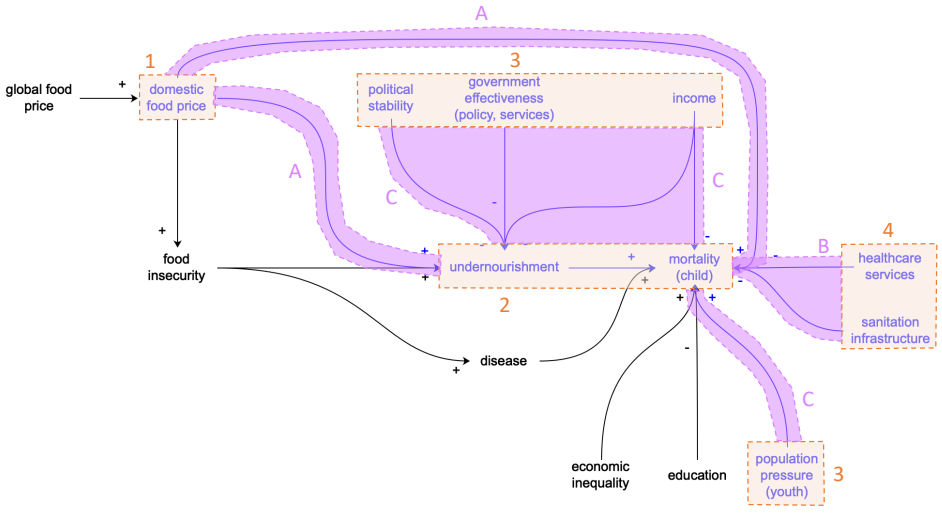
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.44: Mapping the i-CLD for evidence point N2

Mapping i-CLD N3: Lee et al (2016), *Effects of food price inflation on infant and child mortality in developing countries*

Variables
1. *food price*
2. *natural mortality*
3. *institutional/demographic risk factors*
4. *infrastructure services*

Links
A. *[food price] > [food accessibility] > [food insecurity] > [natural mortality]*
B. *[infrastructure services] > [natural mortality]*
& [infrastructure services] > [food utilization] > [food insecurity] > [natural mortality]
C. *[institutional/demographic risk factors] > [natural mortality]*
& [institutional/demographic risk factors] > [food accessibility] > [food insecurity] > [natural mortality]



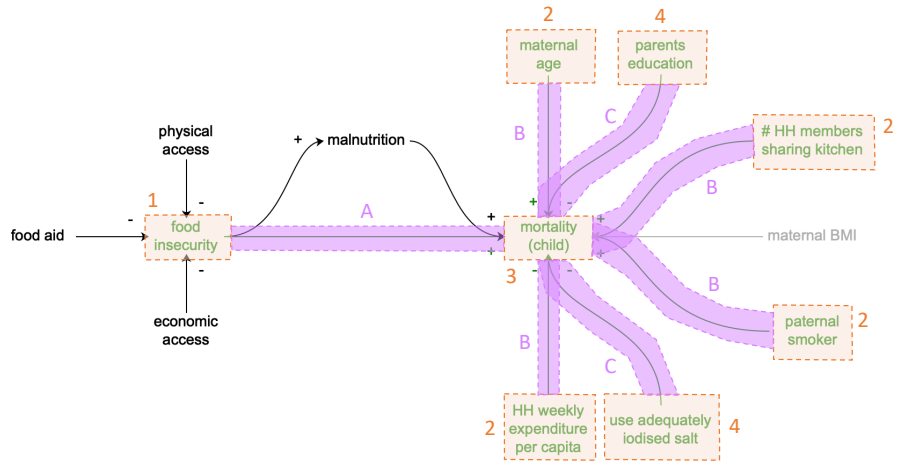
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.45: Mapping the i-CLD for evidence point N3

Mapping i-CLD N4: Campbell et al (2009), *Relationship of household food insecurity to neonatal, infant, and under-five child mortality among families in rural Indonesia*

Variables
1. *food insecurity*
2. *institutional / demographic risk factors*
3. *natural mortality*
4. *infrastructure services*

Links
A. *[food insecurity] > [natural mortality]*
B. *[institutional / demographic risk factors] > [food accessibility] > [food insecurity] > [natural mortality] & [institutional / demographic risk factors] > [food utilization] > [food insecurity] > [natural mortality] & [institutional / demographic risk factors] > [natural mortality]*
C. *[infrastructure services] > [institutional / demographic risk factors] > [food utilization] > [food insecurity] > [natural mortality]*



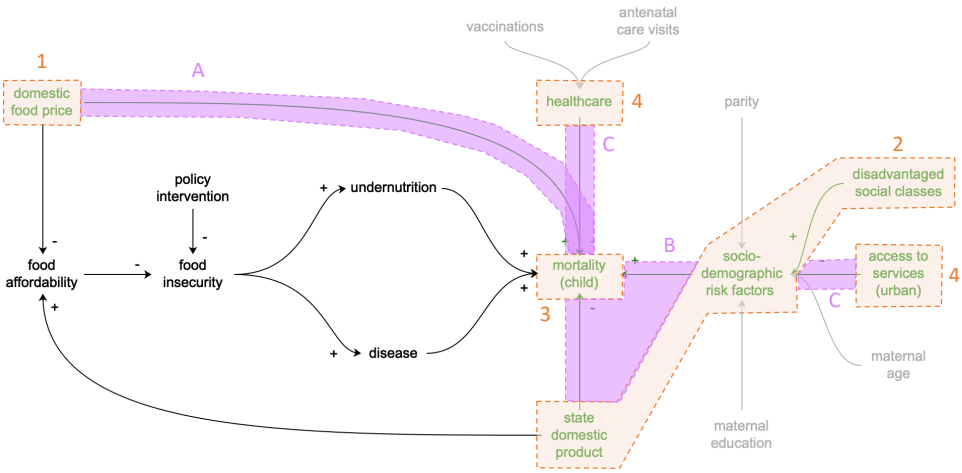
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.46: Mapping the i-CLD for evidence point N4

Mapping i-CLD N5: Fledderjohann et al (2016), *Quantifying the impact of rising food prices on child mortality in India: a cross-district statistical analysis of the District Level Household Survey*

Variables
1. *food price*
2. *institutional / demographic risk factors*
3. *natural mortality*
4. *infrastructure services*

Links
A. *[food price] > [food accessibility] > [food insecurity] > [natural mortality]*
B. *[institutional / demographic risk factors] > [food accessibility] > [food insecurity] > [natural mortality] & [institutional / demographic risk factors] > [natural mortality]*
C. *[infrastructure services] > [institutional / demographic risk factors] > [food utilization] > [food insecurity] > [natural mortality] & [infrastructure services]> [food utilization] > [food insecurity] > [natural mortality] & [infrastructure services] > [natural mortality]*



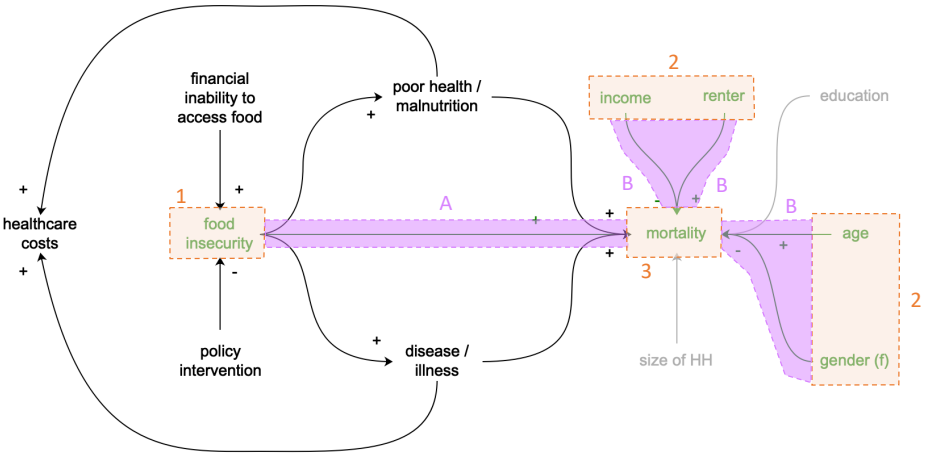
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.47: Mapping the i-CLD for evidence point N5

Mapping i-CLD N6: Gundersen et al (2018), *Food insecurity status and mortality among adults in Ontario, Canada*

Variables
1. *food insecurity*
2. *institutional / demographic risk factors*
3. *natural mortality*

Links
A. *[food insecurity] > [natural mortality]*
B. *[institutional / demographic risk factors] > [food accessibility] > [food insecurity] > [natural mortality] & [institutional / demographic risk factors] > [natural mortality]*



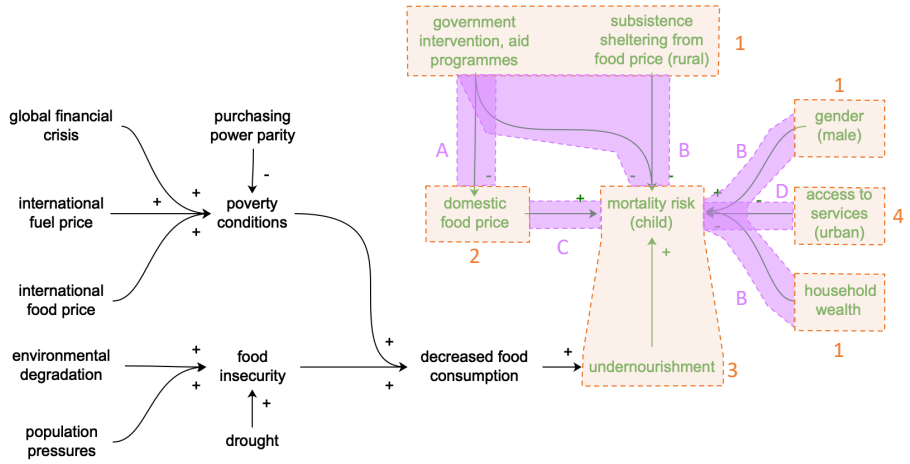
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.48: Mapping the i-CLD for evidence point N6

Mapping i-CLD N7: Nandy et al (2016), *Examining the changing profile of undernutrition in the context of food price rises and greater inequality*

Variables
1. *institutional / demographic risk factors*
2. *food price* and *food accessibility*
3. *natural mortality*
4. *infrastructure services*

Links
A. *[institutional / demographic risk factors] > [food accessibility]*
B. *[institutional / demographic risk factors] > [food accessibility] > [food insecurity] > [natural mortality]*
[institutional / demographic risk factors] > [food availability] > [food insecurity] > [natural mortality]
& [institutional / demographic risk factors] > [natural mortality]
C. *[food price] > [food accessibility] > [food insecurity] > [natural mortality]*
D. *[infrastructure services] > [institutional / demographic risk factors] > [food utilization] > [food insecurity] > [natural mortality]*
& [infrastructure services] > [food utilization] > [food insecurity] > [natural mortality]
& [infrastructure services] > [natural mortality]



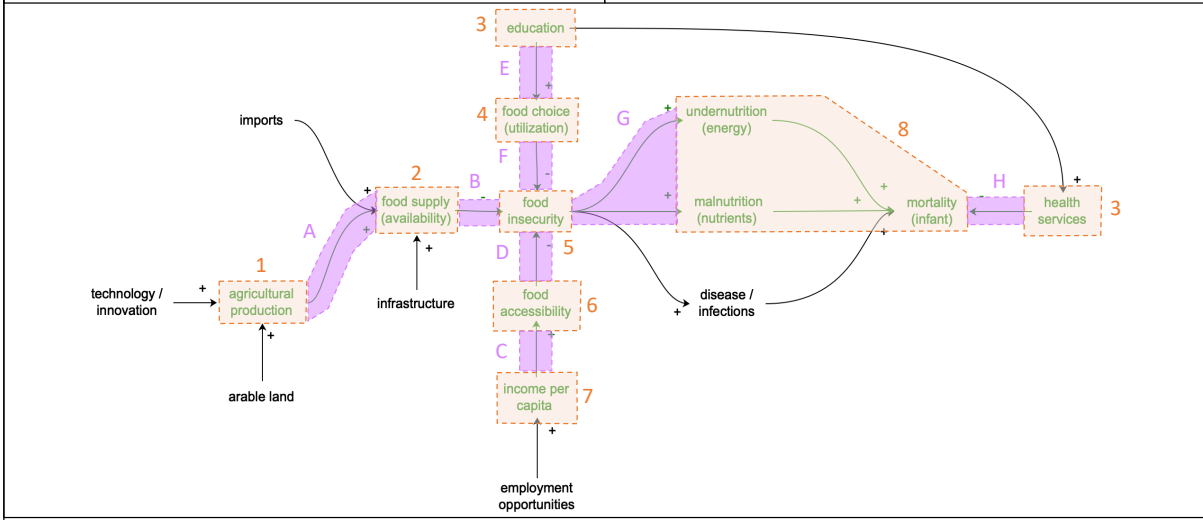
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.49: Mapping the i-CLD for evidence point N7

Mapping i-CLD N8: Sati & Vangchhia (2016), *Nutritional status and infant mortality rate in Saiha district, Mizoram, India*

Variables
1. *food production*
2. *food availability*
3. *infrastructure services*
4. *food utilization*
5. *food insecurity*
6. *food accessibility*
7. *institutional / demographic risk factors*
8. *natural mortality*

Links
A. *[food production] > [food availability]*
B. *[food availability] > [food insecurity]*
& [food availability] > [food price] > [food accessibility] > [food insecurity]
C. *[institutional / demographic risk factors] > [food accessibility]*
D. *[food accessibility] > [food insecurity]*
E. *[infrastructure services] > [institutional / demographic risk factors] > [food utilization]*
F. *[food utilization] > [food insecurity]*
G. *[food insecurity] > [natural mortality]*
H. *[infrastructure services] > [natural mortality]*



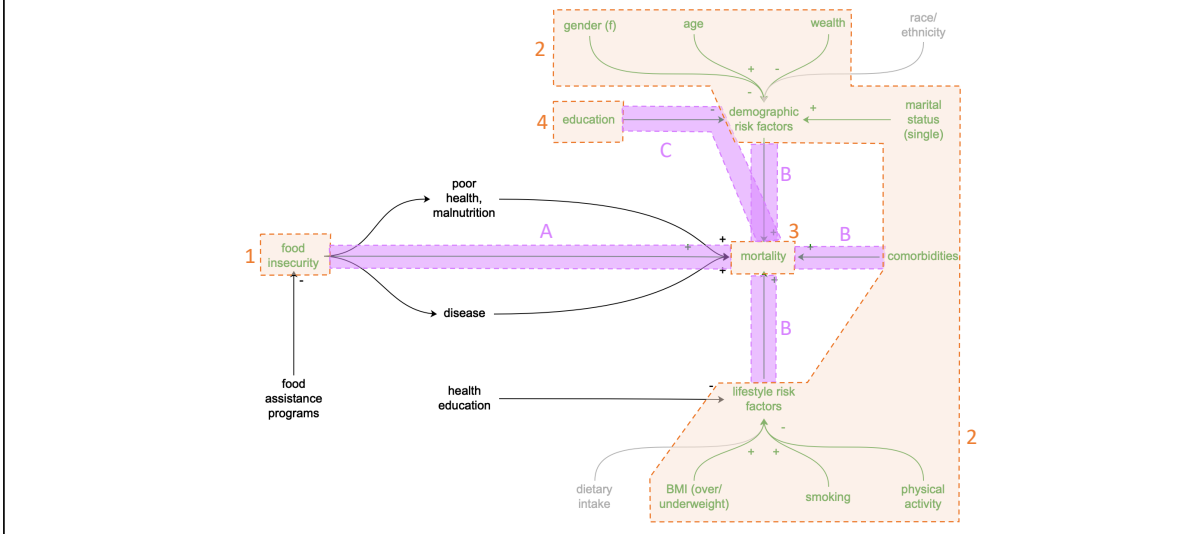
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.50: Mapping the i-CLD for evidence point N8

Mapping i-CLD N9: Walker et al (2019), *Assessing the relationship between food insecurity and mortality among U.S. adults*

Variables
1. *food insecurity*
2. *institutional / demographic risk factors*
3. *natural mortality*
4. *infrastructure services*

Links
A. *[food insecurity] > [natural mortality]*
B. *[institutional / demographic risk factors] > [food accessibility] > [food insecurity] > [natural mortality]*
& [institutional / demographic risk factors] > [food utilization] > [food insecurity] > [natural mortality]
& [institutional / demographic risk factors] > [natural mortality]
C. *[infrastructure services] > [institutional / demographic risk factors] > [food utilization] > [food insecurity] > [natural mortality]*



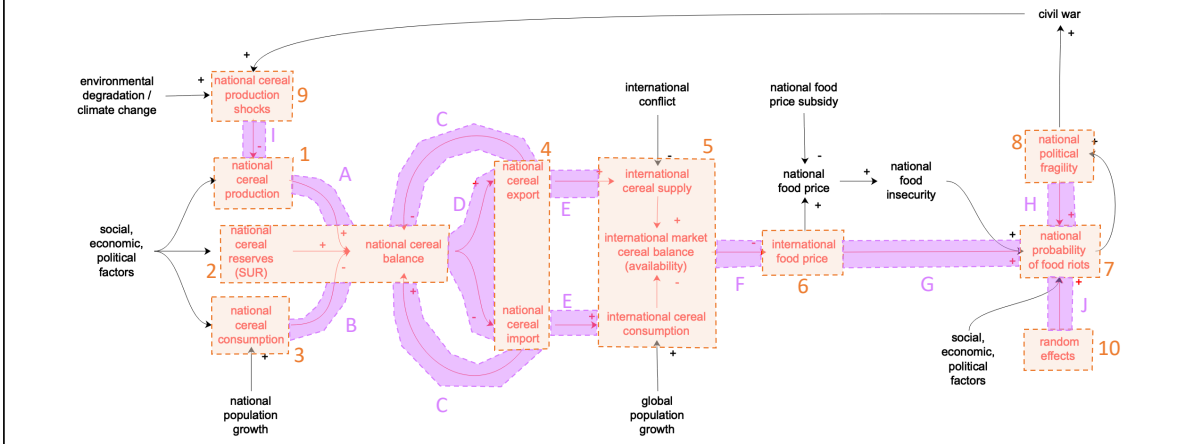
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.51: Mapping the i-CLD for evidence point N9

Mapping i-CLD C1: Natalini, Bravo & Jones (2017), *Global food security and food riots – an agent-based modelling approach*

Variables
1. ***food production***
2. ***food availability***
3. ***consumer demand***
4. ***food trade balance***
5. ***international food availability***
6. ***international food price***
7. ***conflict***
8. ***institutional/demographic risk factors***
9. ***climate change*** and ***environmental risk factors***
   The production shocks are used a proxy of the impact of climate change.
10. Not captured; aspect of modelling.

Links
A. ***[food production] > [food availability]***
B. ***[consumer demand] > [food availability]***
C. ***[food trade balance] > [food availability]***
D. ***[food availability] > [food trade balance]***
E. ***[food trade balance] > [international food availability]***
F. ***[international food availability] > [international food price]***
G. ***[international food price] > [cost of food imports / distribution] > [food price] > [food accessibility] > [food insecurity] > [conflict]***
H. ***[institutional/demographic risk factors] > [conflict]***
I. ***[climate change] > [environmental risk factors] > [natural resources] > [agricultural input availability] > [food production]***
& [climate change] > [environmental risk factors] > [food production]
J. Not captured; aspect of modelling.



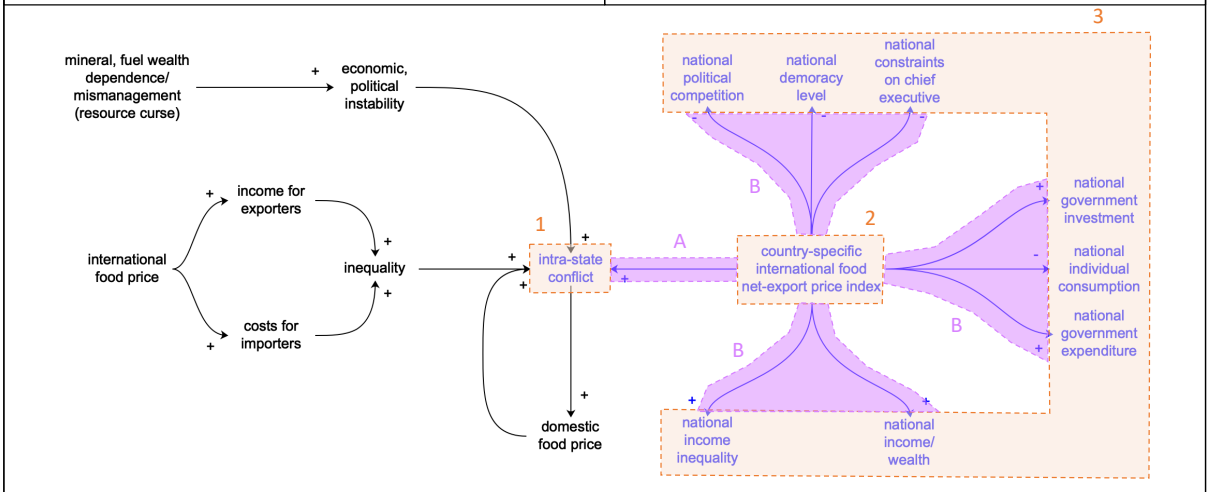
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.52: Mapping the i-CLD for evidence point C1

Mapping i-CLD C2: Arezki & Brueckner (2014), *Effects of International Food Price Shocks on Political Institutions in Low-Income Countries: Evidence from an International Food Net-Export Price Index*

Variables
1. ***conflict***
2. ***international food price*** and ***cost of food production*** and ***food trade balance***
   This index accounts for positive trade effect for net exporters and negative trade effect for net importers.
3. ***institutional / demographic risk factors***

Links
A. ***[international food price] > [cost of food imports] > [food price] > [food accessibility] > [food insecurity] > [conflict]***
& [cost of food production] > [food price] > [food accessibility] > [food insecurity] > [conflict]
& [food trade balance] > [food price] > [food accessibility] > [food insecurity] > [conflict]
B. ***[international food price] > [cost of food imports] > [food price] > [food accessibility] > [food insecurity] > [institutional / demographic risk factors]***
& [cost of food production] > [food price] > [food accessibility] > [food insecurity] > [institutional / demographic risk factors]
& [food trade balance] > [food price] > [food accessibility] > [food insecurity] > [institutional / demographic risk factors]



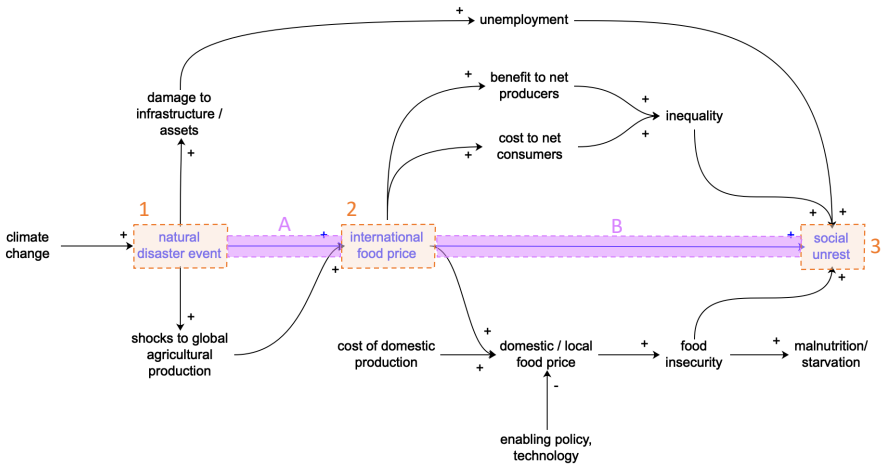
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.53: Mapping the i-CLD for evidence point C2

Mapping i-CLD C3: Bellemare (2014), *Rising food prices, food price volatility and social unrest*

Variables
1. ***environmental risk factors*** and ***climate change***
   The natural disasters are used as a proxy of the impact of climate change.
2. ***international food price***
3. ***conflict***

Links
A. ***[climate change] > [environmental risk factors] > [natural resources] > [agricultural input availability] > [food production] > [food availability] > [food trade balance] > [international food availability] > [international food price]***
& [climate change] > [environmental risk factors] > [food production] > [food availability] > [food trade balance] > [international food availability] > [international food price]
& [climate change] > [environmental risk factors] > [infrastructure services] > [food availability] > [food trade balance] > [international food availability] > [international food price]
B. ***[international food price] > [cost of food imports] > [food price] > [food accessibility] > [food insecurity] > [conflict]***



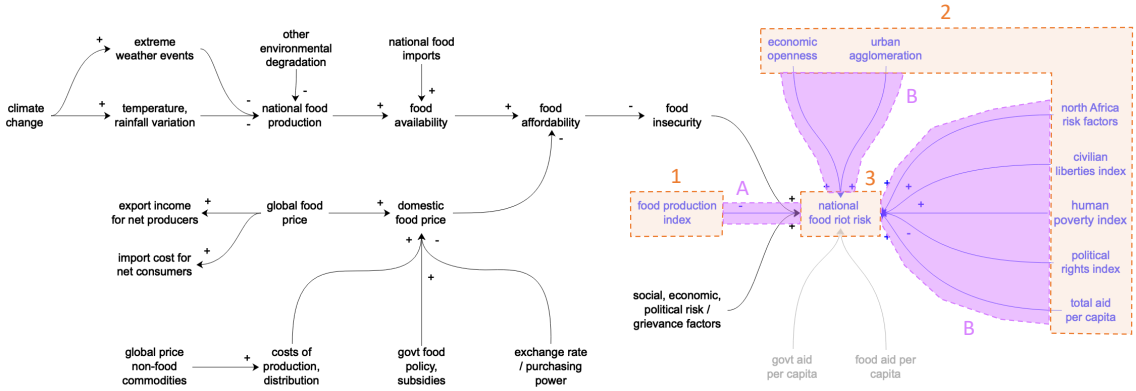
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.54: Mapping the i-CLD for evidence point C3

Mapping i-CLD C4: Berazneva & Lee (2013), *Explaining the African food riots of 2007–2008: An empirical analysis*

Variables
1. ***food production***
2. ***conflict***
3. ***institutional / demographic risk factors***

Links
A. ***[food production] > [food availability] > [food insecurity] > [conflict]***
& [food production] > [food availability] > [food price] > [food accessibility] > [food insecurity] > [conflict]
B. ***[institutional/demographic risk factors] > [conflict]***
& [institutional/demographic risk factors] > [food accessibility] > [food insecurity] > [conflict]
& [institutional/demographic risk factors] > [food availability] > [food insecurity] > [conflict]



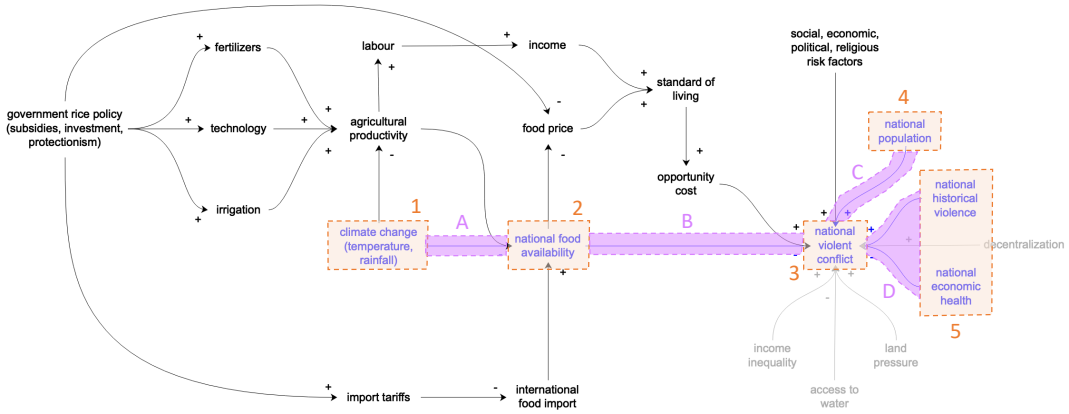
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.55: Mapping the i-CLD for evidence point C4

Mapping i-CLD C5: Caruso et al (2016), *Climate change, rice crops, and violence: Evidence from Indonesia*

Variables
1. ***climate change*** and ***environmental risk factors***
   The change in rainfall and temperature are used as a proxy of the impact of climate change.
2. ***food availability***
3. ***conflict***
4. ***population***
5. ***institutional / demographic risk factors***

Links
A. *[climate change] > [environmental risk factors] > [natural resources] > [agricultural input availability] > [food production] > [food availability]*
   & [climate change] > [environmental risk factors] > [food production] > [food availability]
B. *[food availability] > [food insecurity] > [conflict]*
   & [food availability] > [food price] > [food accessibility] > [food insecurity] > [conflict]
C. *[population] > [institutional/demographic risk factors] > [conflict]*
   & [population] > [consumer demand] > [food availability] > [food insecurity] > [conflict]
   & [population] > [consumer demand] > [food availability] > [food price] > [food accessibility] > [food insecurity] > [conflict]
D. *[institutional/demographic risk factors] > [conflict]*
   & [institutional/demographic risk factors] > [food accessibility] > [food insecurity] > [conflict]



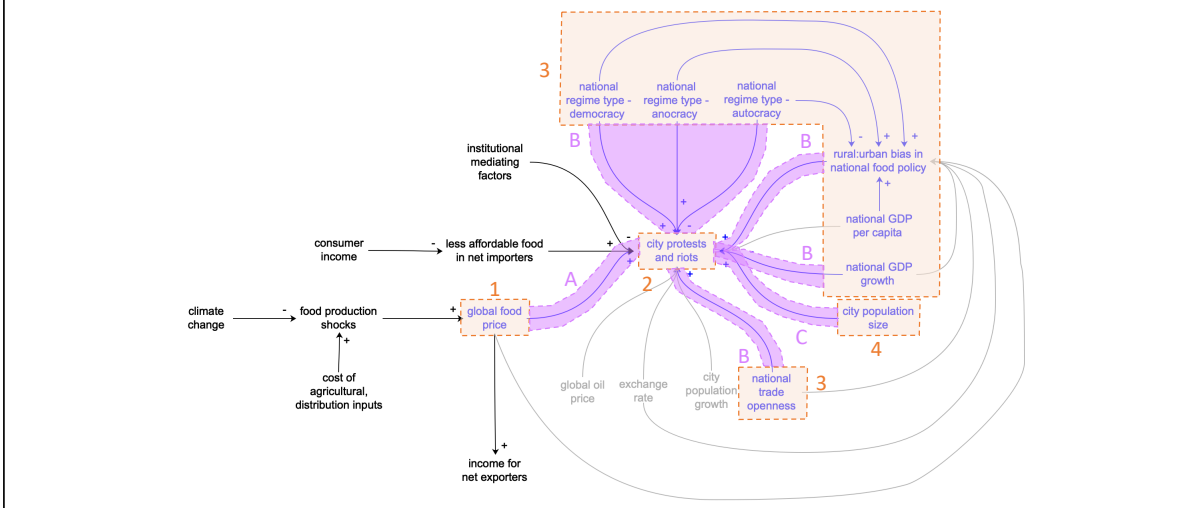
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.56: Mapping the i-CLD for evidence point C5

Mapping i-CLD C6: Hendrix & Haggard (2015), *Global food prices, regime type, and urban unrest in the developing world*

Variables
1. ***international food price***
2. ***conflict***
3. ***institutional/demographic risk factors***
4. ***population***

Links
A. *[international food price] > [cost of imports] > [food price] > [food accessibility] > [food insecurity] > [conflict]*
B. *[institutional/demographic risk factors] > [conflict]*
   & [institutional/demographic risk factors] > [food accessibility] > [food insecurity] > [conflict]
   & [institutional/demographic risk factors] > [food availability] > [food insecurity] > [conflict]
C. *[population] > [institutional/demographic risk factors] > [conflict]*
   & [population] > [consumer demand] > [food availability] > [food insecurity] > [conflict]
   & [population] > [consumer demand] > [food availability] > [food price] > [food accessibility] > [food insecurity] > [conflict]



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.57: Mapping the i-CLD for evidence point C6

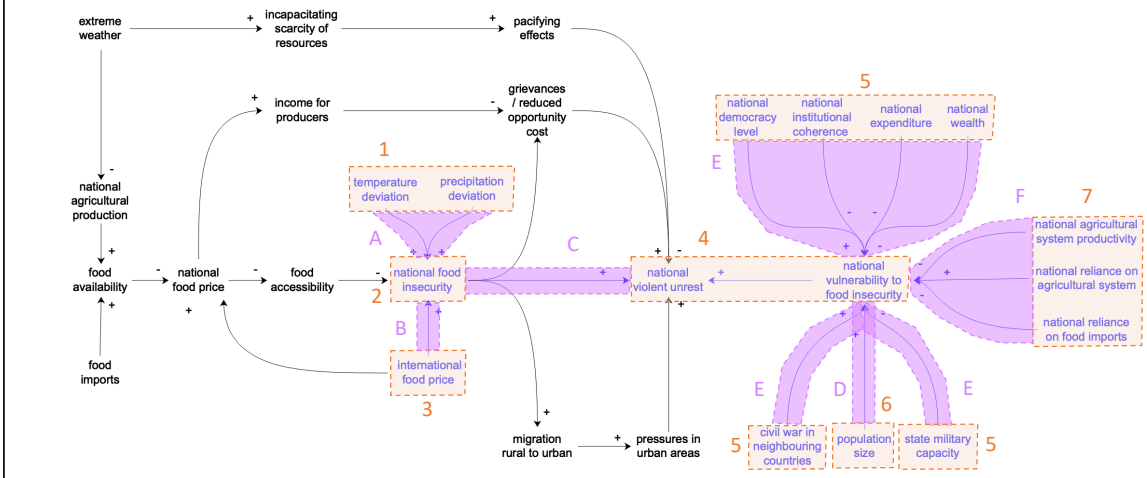
Mapping i-CLD C7: Jones et al (2017), *Food scarcity and state vulnerability: Unpacking the link between climate variability and violent unrest*

Variables

1. ***climate change*** and ***environmental risk factors***
   The change in rainfall and temperature are used as a proxy of the impact of climate change.
2. ***food insecurity***
3. ***international food price***
4. ***conflict***
5. ***institutional/demographic risk factors***
6. ***population***
7. ***institutional/demographic risk factors*** and ***food production*** and ***natural resources*** and ***food trade balance***
   Variables collectively account for food availability system and institutional influence over this measured by agriculture % of GDP (agricultural system productivity), % land dedicated to agriculture (reliance on agricultural system), imports % of GDP (reliance on food imports).

Links

A. ***[climate change] > [environmental risk factors] > [natural resources] > [agricultural input availability] > [food production] > [food availability] > [food insecurity]***
   & [climate change] > [environmental risk factors] > [food production] > [food availability] > [food insecurity]
   & [climate change] > [environmental risk factors] > [natural resources] > [agricultural input availability] > [food production] > [food availability] > [food price] > [food accessibility] > [food insecurity]
   & [climate change] > [environmental risk factors] > [food production] > [food availability] > [food price] > [food accessibility] > [food insecurity]
B. ***[international food price] > [cost of imports] > [food price] > [food accessibility] > [food insecurity]***
C. ***[food insecurity] > [conflict]***
D. ***[population] > [institutional/demographic risk factors] > [conflict]***
   & [population] > [consumer demand] > [food availability] > [food insecurity] > [conflict]
   & [population] > [consumer demand] > [food availability] > [food price] > [food accessibility] > [food insecurity] > [conflict]
E. ***[institutional/demographic risk factors] > [conflict]***
   & [institutional/demographic risk factors] > [food accessibility] > [food insecurity] > [conflict]
F. ***[institutional/demographic risk factors] > [food availability] > [food production] > [agricultural input demand] > [natural resources] > [food input availability] > [food production] > [food availability] > [food trade balance] > [food availability] > [food insecurity] > [conflict]***



Legend:

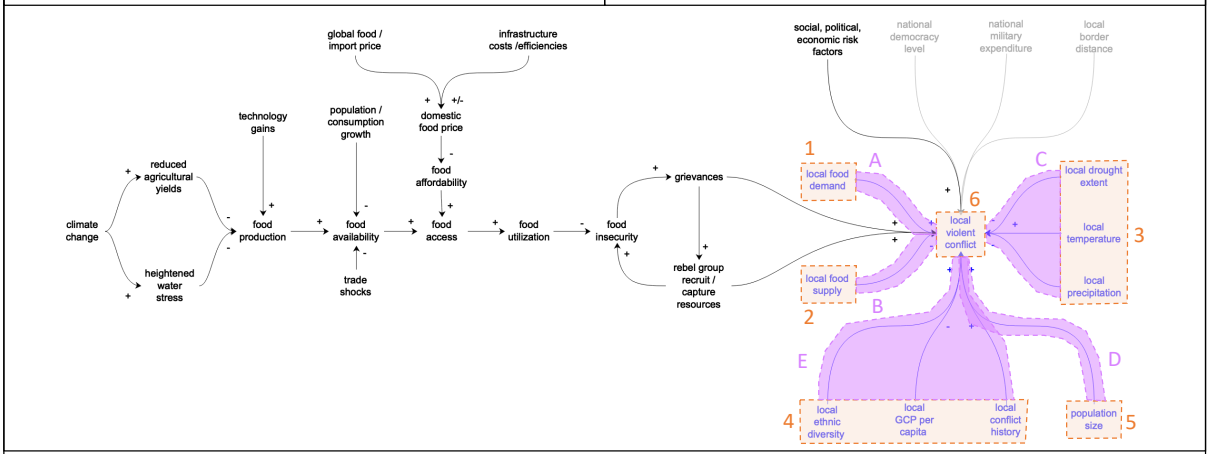
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.58: Mapping the i-CLD for evidence point C7

Mapping i-CLD C8: Koren & Bagozzi (2016), *From global to local, food insecurity is associated with contemporary armed conflicts*

Variables
1. ***consumer demand***
2. ***food availability*** and ***food production*** and ***food trade balance***
3. ***environmental risk factors*** and ***climate change***
   The change in rainfall and temperature and drought are used as a proxy of the impact of climate change.
4. ***institutional/demographic risk factors***
5. ***population***
6. ***conflict***

Links
A. ***[consumer demand] > [food availability] > [food insecurity] > [conflict]***
   & [consumer demand] > [food availability] > [food price] > [food accessibility] > [food insecurity] > [conflict]
B. ***[food availability] > [food production] > [agricultural input demand] > [natural resources] > [agricultural input availability] > [food production] > [food availability] > [food trade balance] > [food availability] > [food insecurity] > [conflict]***
C. ***[climate change] > [environmental risk factors] > [natural resources] > [agricultural input availability] > [food production] > [food availability] > [food insecurity] > [conflict]***
   & [climate change] > [environmental risk factors] > [food production] > [food availability] > [food insecurity] > [conflict]
   & [climate change] > [environmental risk factors] > [natural resources] > [agricultural input availability] > [food production] > [food availability] > [food price] > [food accessibility] > [food insecurity] > [conflict]
   & [climate change] > [environmental risk factors] > [food production] > [food availability] > [food price] > [food accessibility] > [food insecurity] > [conflict]
D. ***[population] > [institutional/demographic risk factors] > [conflict]***
   & [population] > [consumer demand] > [food availability] > [food insecurity] > [conflict]
   & [population] > [consumer demand] > [food availability] > [food price] > [food accessibility] > [food insecurity] > [conflict]
E. ***[institutional/demographic risk factors] > [conflict]***
   & [institutional/demographic risk factors] > [food accessibility] > [food insecurity] > [conflict]



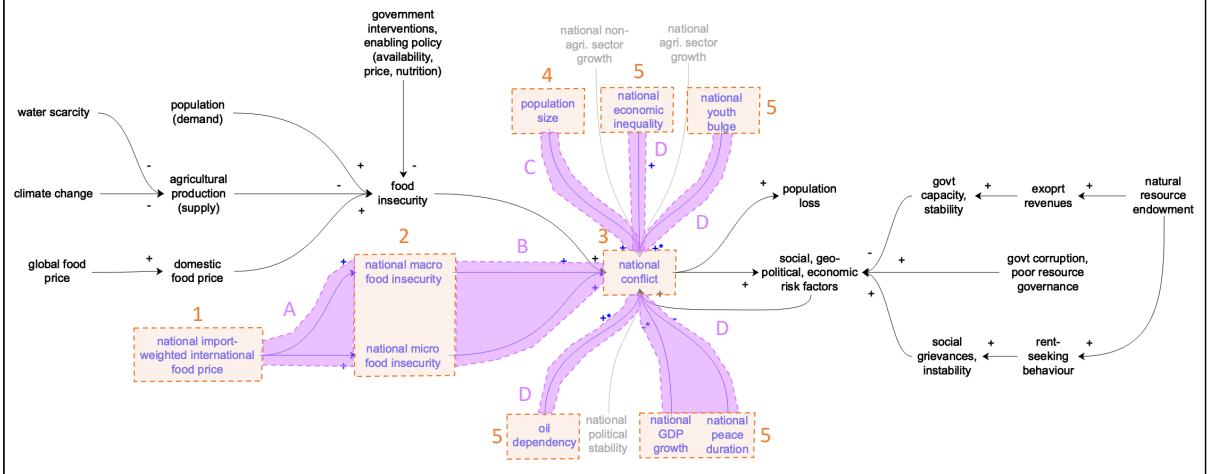
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.59: Mapping the i-CLD for evidence point C8

Mapping i-CLD C9: Maystadt et al (2014), *Does food security matter for transition in Arab countries?*

Variables
1. ***international food price*** and ***cost of food production*** and ***food trade balance***
   Index accounts for price and import/export weight of commodity.
2. ***food insecurity***
   Macro measured by food imports:exports ratio. Micro measured by child stinting and mortality.
3. ***conflict***
4. ***population***
5. ***institutional/demographic risk factors***

Links
A. ***[international food price] > [cost of food imports] > [food price] > [food accessibility] > [food insecurity]***
   & [cost of food production] > [food price] > [food accessibility] > [food insecurity]
   & [food trade balance] > [food price] > [food accessibility] > [food insecurity]
B. ***[food insecurity] > [conflict]***
C. ***[population] > [institutional/demographic risk factors] > [conflict]***
   & [population] > [consumer demand] > [food availability] > [food insecurity] > [conflict]
   & [population] > [consumer demand] > [food availability] > [food price] > [food accessibility] > [food insecurity] > [conflict]
D. ***[institutional/demographic risk factors] > [conflict]***
   & [institutional/demographic risk factors] > [food accessibility] > [food insecurity] > [conflict]



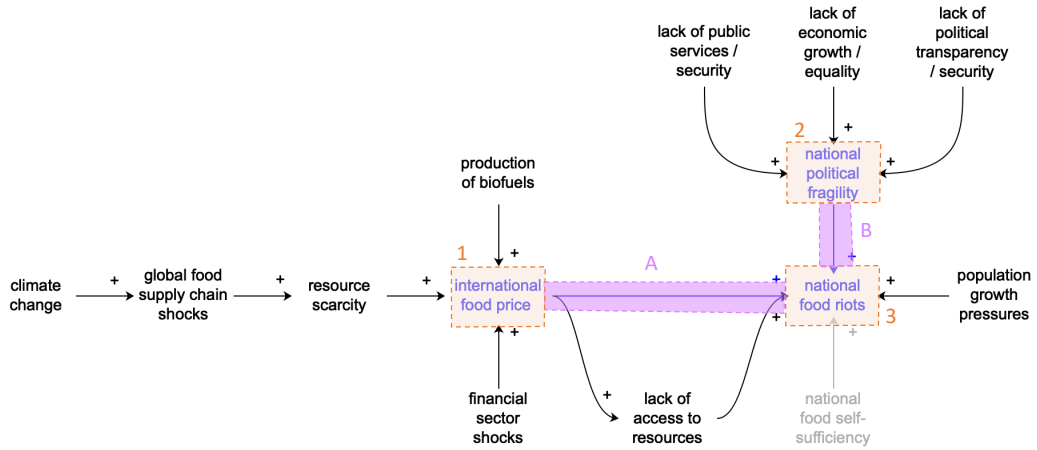
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.60: Mapping the i-CLD for evidence point C9

Mapping i-CLD C10: Natalini et al (2015), *Quantitative Assessment of Political Fragility Indices and Food Prices as Indicators of Food Riots in Countries*

Variables
1. ***international food price***
2. ***Institutional / demographic risk factors***
3. ***conflict***

Links
A. ***[international food price] > [cost of food imports] > [food price] > [food accessibility] > [food insecurity] > [conflict]***
B. ***[institutional/demographic risk factors] > [conflict]***



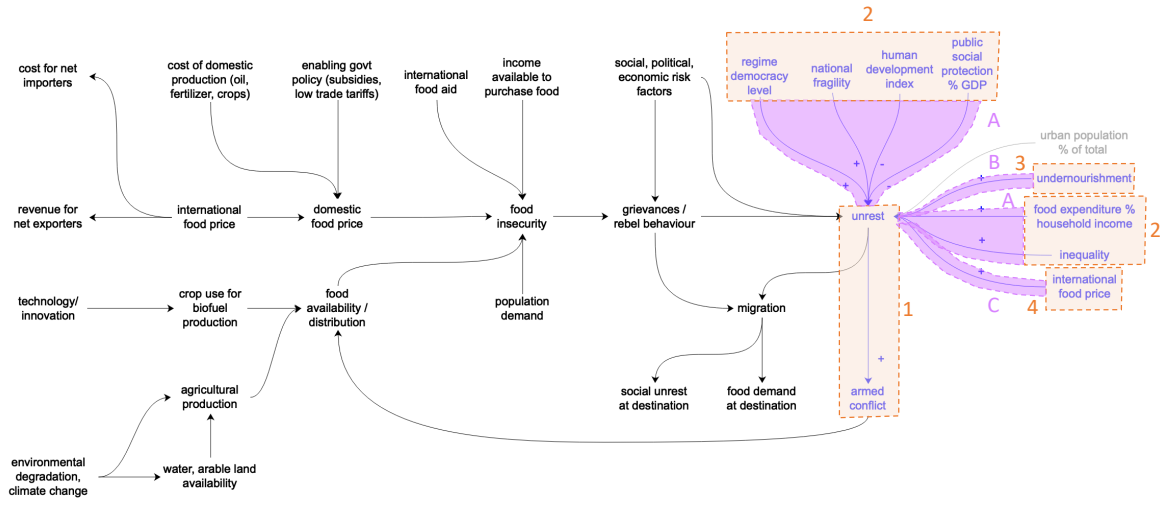
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.61: Mapping the i-CLD for evidence point C10

Mapping i-CLD C11: Newman (2018), *Hungry, or Hungry for Change? Food Riots and Political Conflict, 2005–2015*

Variables
1. ***conflict***
2. ***institutional/demographic risk factors***
3. ***food insecurity***
   Undernourishment is used as a proxy for food insecurity.
4. ***international food price***

Links
A. ***[institutional/demographic risk factors] > [conflict]***
   & [institutional/demographic risk factors] > [food accessibility] > [food insecurity] > [conflict]
B. ***[food insecurity] > [conflict]***
C. ***[international food price] > [cost of food imports] > [food price] > [food accessibility] > [food insecurity] > [conflict]***



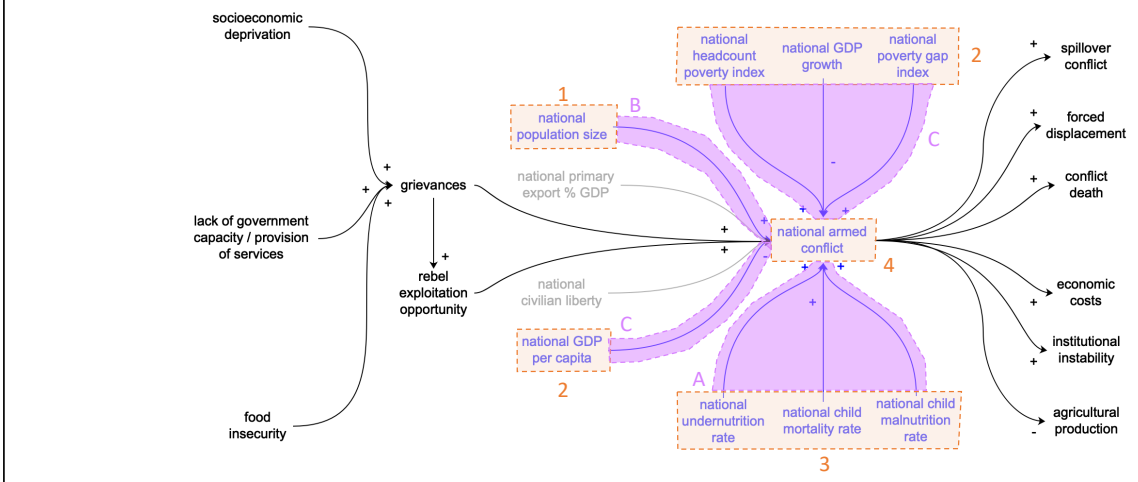
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.62: Mapping the i-CLD for evidence point C11

i-CLD C12: Pinstrup-Andersen & Shimokawa (2008), *Do poverty and poor health and nutrition increase the risk of armed conflict onset?*

Variables
1. ***population***
2. ***institutional/demographic risk factors***
3. ***food insecurity***
   Undernutrition, child mortality and malnutrition are used as a proxy for food insecurity.
4. ***conflict***

Links
A. *[food insecurity] > [conflict]*
B. *[population] > [institutional/demographic risk factors] > [conflict]*
& [population] > [consumer demand] > [food availability] > [food insecurity] > [conflict]
& [population] > [consumer demand] > [food availability] > [food price] > [food accessibility] > [food insecurity] > [conflict]
C. *[institutional/demographic risk factors] > [conflict]*
& [institutional/demographic risk factors] > [food accessibility] > [food insecurity] > [conflict]



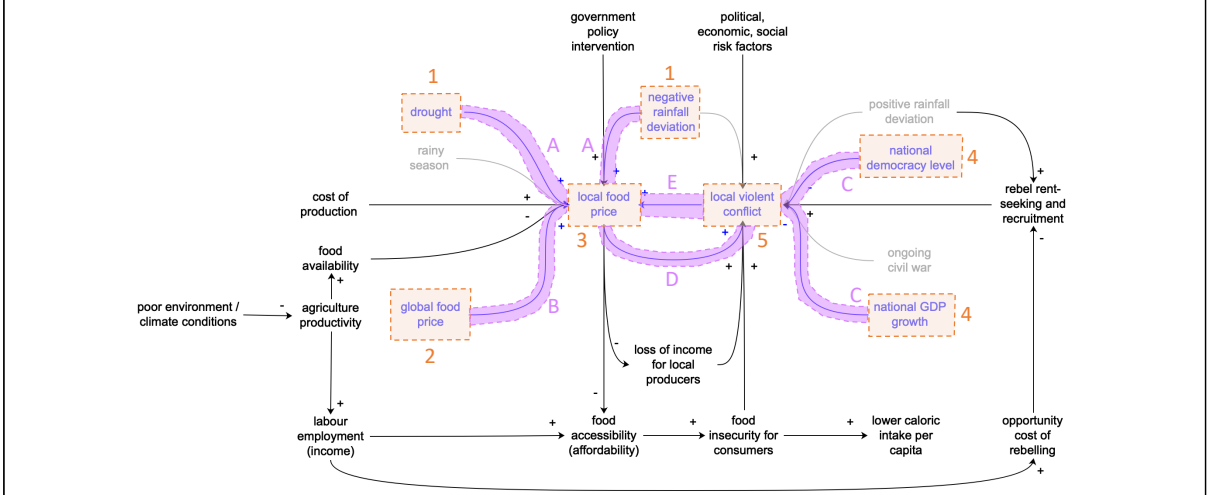
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.63: Mapping the i-CLD for evidence point C12

Mapping i-CLD C13: Raleigh et al (2015), *The devil is in the details: An investigation of the relationships between conflict, food price and climate across Africa*

Variables
1. ***climate change*** and ***environmental risk factors***
   The change in rainfall and drought are used as a proxy of the impact of climate change.
2. ***international food price***
3. ***food price***
4. ***institutional/demographic risk factors***
5. ***conflict***

Links
A. *[climate change] > [environmental risk factors] > [natural resources] > [agricultural input availability] > [food production] > [food availability] > [food price]*
& [climate change] > [environmental risk factors] > [food production] > [food availability] > [food price]
B. *[international food price] > [cost of food imports] > [food price]*
C. *[institutional/demographic risk factors] > [conflict]*
& [institutional/demographic risk factors] > [food accessibility] > [food insecurity] > [conflict]
D. *[food price] > [food accessibility] > [food insecurity] > [conflict]*
E. *[conflict] > [food availability] > [food price]*
& [conflict] > [environmental degradation/pollution] > [environmental risk factors] > [natural resources] > [agricultural input availability] > [food production] > [food availability] > [food price]
& [conflict] > [environmental degradation/pollution] > [environmental risk factors] > [food production] > [food availability] > [food price]



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.64: Mapping the i-CLD for evidence point C13

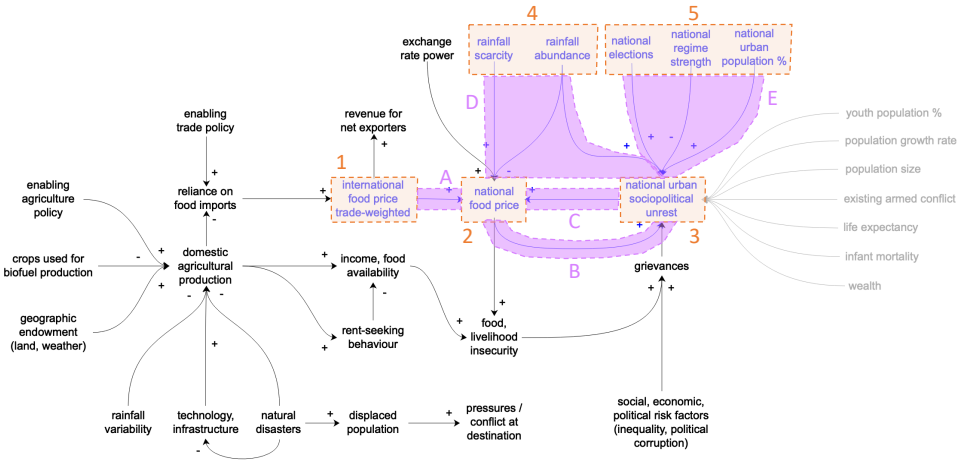
Mapping i-CLD C14: Smith (2014), *Feeding unrest: Disentangling the causal relationship between food price shocks and sociopolitical conflict in urban Africa*

Variables

1. ***international food price*** and ***cost of food production*** and ***food trade balance***
   Standardized grain instrument used to account for price and import/export weight of commodity.
2. ***food price***
3. ***conflict***
4. ***environmental risk factors*** and ***climate change***
   The change in rainfall is used as a proxy of the impact of climate change.
5. ***institutional/demographic risk factors***

Links

A. ***[international food price] > [cost of food imports] > [food price]***
   & [cost of food production] > [food price]
   & [food trade balance] > [food price]
B. ***[food price] > [food accessibility] > [food insecurity] > [conflict]***
C. ***[conflict] > [food availability] > [food price]***
   & [conflict] > [environmental degradation/pollution] > [environmental risk factors] > [natural resources] > [agricultural input availability] > [food production] > [food availability] > [food price]
   & [conflict] > [environmental degradation/pollution] > [environmental risk factors] > [food production] > [food availability] > [food price]
D. ***[climate change] > [environmental risk factors] > [natural resources] > [agricultural input availability] > [food production] > [food availability] > [food price]***
   & [climate change] > [environmental risk factors] > [food production] > [food availability] > [food price]
E. ***[institutional/demographic risk factors] > [conflict]***



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.65: Mapping the i-CLD for evidence point C14

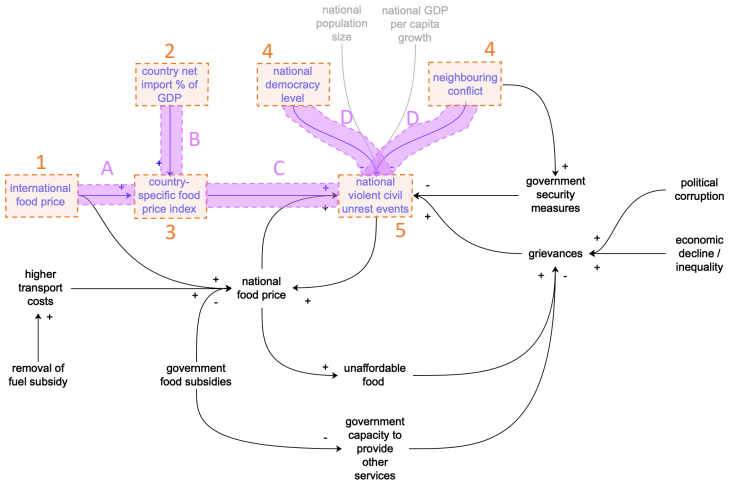
Mapping i-CLD C15: van Weezel (2016), *Food imports, international prices, and violence in Africa*

Variables

1. ***international food price***
   See (3) comment – contributor.
2. ***institutional / demographic risk factors***
   See (3) comment – contributor.
3. ***food price*** and ***food accessibility*** and ***cost of food production*** and ***food trade balance***
   Index accounts for different food commodities, net import to proxy vulnerability to trade shocks and international food price, and imports % GDP to proxy impact of income on accessibility.
4. ***institutional/demographic risk factors***
5. ***conflict***

Links

A. ***[international food price] > [cost of food imports] > [food price]***
   & [cost of food production] > [food price]
   & [food trade balance] > [food price]
B. ***[institutional/demographic risk factors] > [food accessibility]***
C. ***[food price] > [food accessibility] > [food insecurity] > [conflict]***
D. ***[institutional/demographic risk factors] > [conflict]***



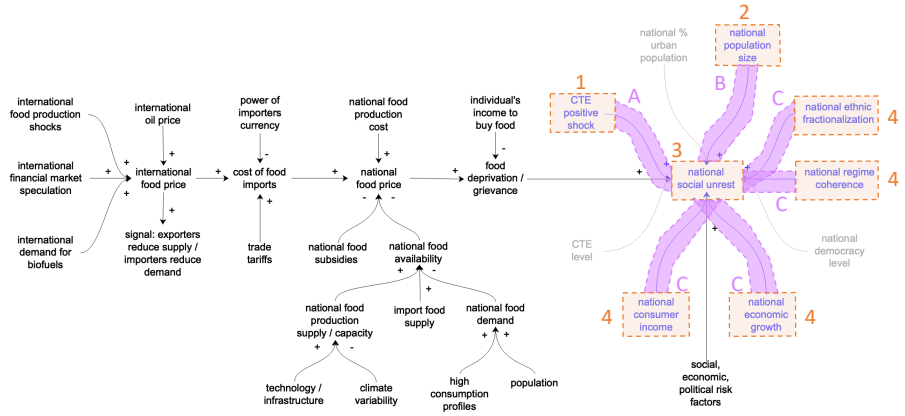
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.66: Mapping the i-CLD for evidence point C15

Mapping i-CLD C16: Weinberg & Bakker (2015), *Let them eat cake: Food prices, domestic policy and social unrest*

Variables
1. ***international food price*** and ***cost of food production*** and ***food trade balance*** and ***institutional risk factors***
   CTE measures the gap between international and domestic prices, and accounts for domestic policy influence on what the consumer pays.
2. ***population***
3. ***conflict***
4. ***institutional/demographic risk factors***

Links
A. ***[international food price] > [cost of food imports] > [food price] > [food accessibility] > [food insecurity] > [conflict]***
   & [cost of food production] > [food price] > [food accessibility] > [food insecurity] > [conflict]
   & [food trade balance] > [food price] > [food accessibility] > [food insecurity] > [conflict]
   & [institutional / demographic risk factors] > [food accessibility] > [food insecurity] > [conflict]
B. ***[population] > [institutional/demographic risk factors] > [conflict]***
   & [population] > [consumer demand] > [food availability] > [food insecurity] > [conflict]
   & [population] > [consumer demand] > [food availability] > [food price] > [food accessibility] > [food insecurity] > [conflict]
C. ***[institutional/demographic risk factors] > [conflict]***
   & [institutional/demographic risk factors] > [food accessibility] > [food insecurity] > [conflict]



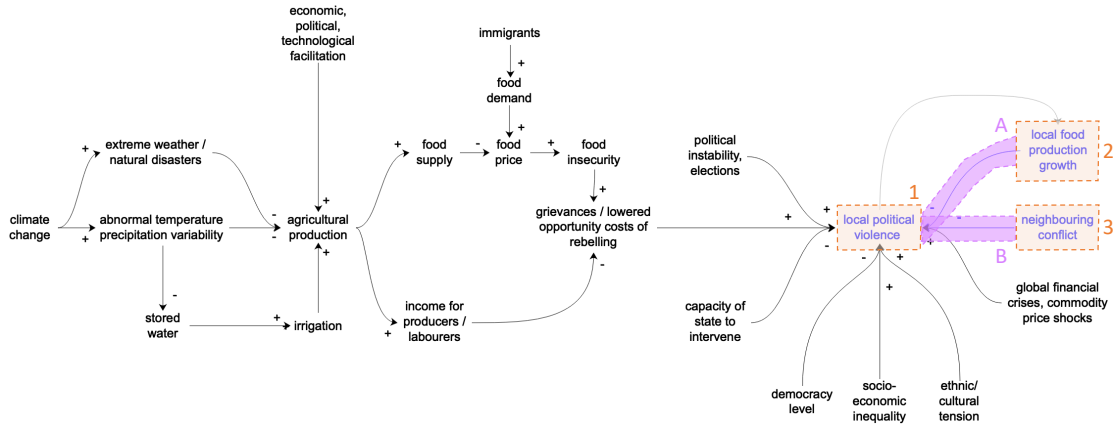
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.67: Mapping the i-CLD for evidence point C16

Mapping i-CLD C17: Wischnath & Buhaug (2014), *Rice or riots: On food production and conflict severity across India*

Variables
1. ***conflict***
2. ***food production***
3. ***institutional/demographic risk factors***

Links
A. ***[food production] > [food availability] > [food insecurity] > [conflict]***
   & [food production] > [food availability] > [food price] > [food accessibility] > [food insecurity] > [conflict]
B. ***[institutional/demographic risk factors] > [conflict]***



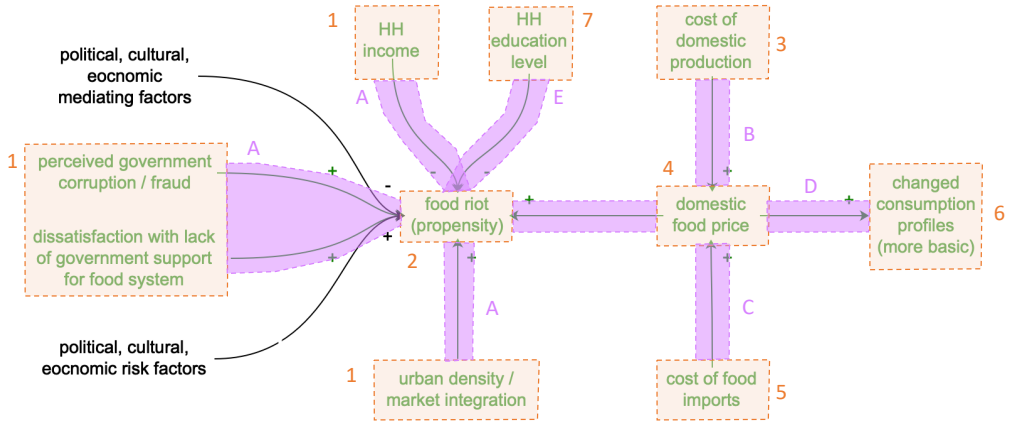
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.68: Mapping the i-CLD for evidence point C17

Mapping i-CLD C18: Legwegoh et al (2015), *Do Dietary Changes Increase the Propensity of Food Riots? An Exploratory Study of Changing Consumption Patterns and the Inclination to Engage in Food-Related Protests*

Variables
1. ***institutional/demographic risk factors***
2. ***conflict***
3. ***cost of production***
4. ***food price***
5. ***cost of imports***
6. ***food insecurity*** (proxy in this evidence point)
7. ***infrastructure services***

Links
A. ***[institutional/demographic risk factors] > [conflict]***
& [institutional/demographic risk factors] > [food accessibility] > [food insecurity] > [conflict]
B. ***[cost of food production] > [food price]***
C. ***[price of imports] > [food price]***
D. ***[food price] > [food accessibility] > [food insecurity] > [natural mortality]***
E. ***[infrastructure services] > [institutional/demographic risk factors] > [food utilization] > [food insecurity] > [conflict]***



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.69: Mapping the i-CLD for evidence point C18

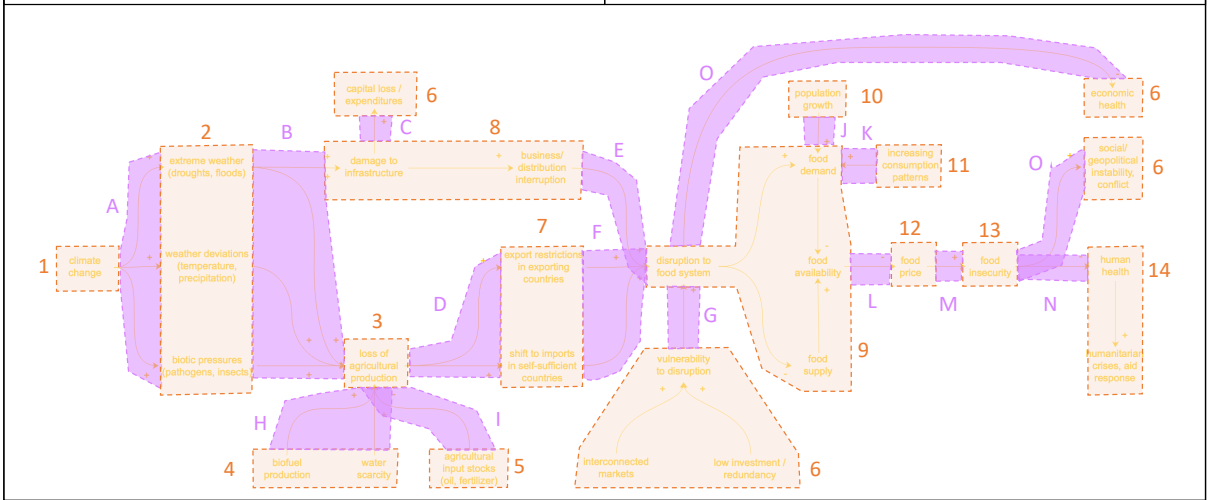
Mapping i-CLD C19: Lunt et al (2016), *Vulnerabilities to agricultural production shocks: An extreme, plausible scenario for assessment of risk for the insurance sector*

Variables

1. *climate change*
2. *environmental risk factors*
3. *food production*
4. *natural resources*
5. *industrial capital/output*
6. *institutional / demographic risk factors*
7. *food trade balance*
8. *infrastructure services*
9. *food availability*
10. *population*
11. *lifestyle demand/emissions*
12. *food price*
13. *food insecurity*
14. *natural mortality*

Links

A. *[climate change] > [environmental risk factors]*
B. *[environmental risk factors] > [natural resources] > [agricultural input availability] > [food production]*
& [environmental risk factors] > [food production]
& [environmental risk factors] > [infrastructure services]
C. *[infrastructure services] > [institutional/demographic risk factors]*
D. *[food production] > [food availability] > [food trade balance]*
E. *[infrastructure services] > [food availability]*
F. *[food trade balance] > [food availability]*
& [food trade balance] > [international food availability] > [food trade balance] > [food availability]
G. *[institutional/demographic risk factors] > [food availability]*
H. *[natural resources] > [agricultural input availability] > [food production]*
I. *[industrial capital/output] > [agricultural input availability] > [food production]*
J. *[population] > [consumer demand] > [food availability]*
K. *[lifestyle demand / emissions] > [consumer demand] > [food availability]*
L. *[food availability] > [food price]*
M. *[food price] > [food accessibility] > [food insecurity]*
N. *[food insecurity] > [natural mortality]*
O. *[food insecurity] > [institutional/demographic risk factors]*



Legend:

Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.70: Mapping the i-CLD for evidence point C19

Mapping i-CLD C20: Sternberg (2012), *Chinese drought, bread and the Arab Spring*

Variables

1. ***climate change***
2. ***natural resources*** and ***industrial capital/output*** and ***technology/innovation***
3. ***consumer demand***
4. ***food production***
5. ***institutional / demographic risk factors***
6. ***food trade balance***
7. ***international food availability***
8. ***international food price***
9. ***domestic food price***
10. ***conflict***

Links

A. *[climate change] > [environmental risk factors] > [natural resources] > [agricultural input availability] > [food production]*
& [climate change] > [environmental risk factors] > [food production]

B. *[natural resources] > [agricultural input availability] > [food production]*
& [industrial capital/output] > [agricultural input availability] > [food production]
& [technology/innovation] > [food production]

C. *[food production] > [food availability] > [food trade balance]*

D. *[institutional / demographic risk factors] > [food availability] > [food trade balance]*

E. *[food trade balance] > [international food availability]*

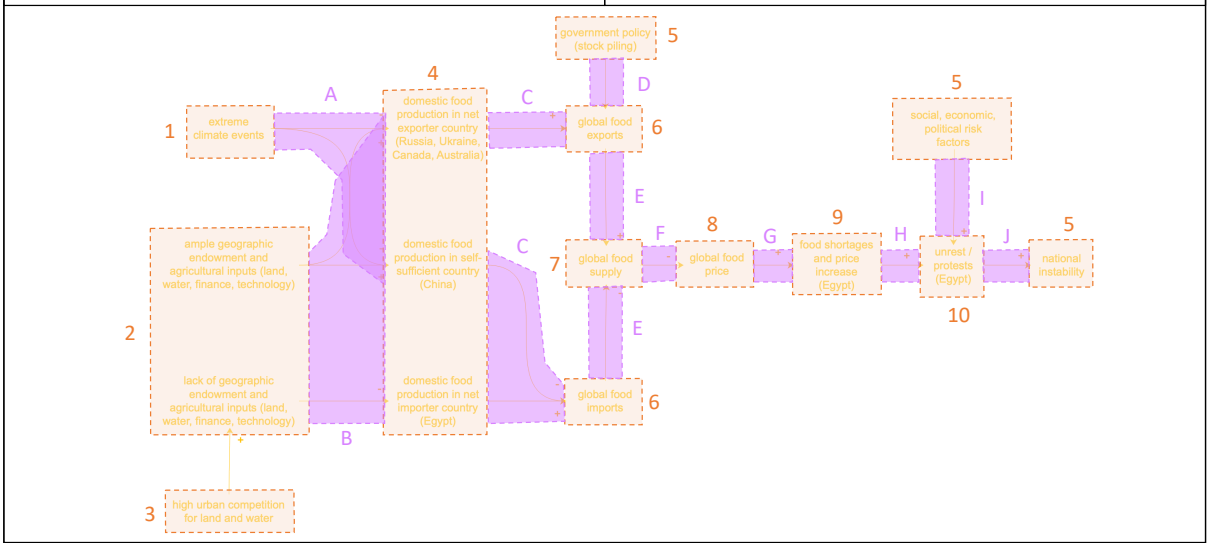
F. *[international food availability] > [international food price]*

G. *[international food price] > [cost of food imports] > [food price] > [food accessibility] > [food insecurity]*

H. *[food insecurity] > [conflict]*

I. *[institutional/demographic risk factors] > [conflict]*
& [institutional/demographic risk factors] > [food accessibility] > [food insecurity] > [conflict]
& [institutional/demographic risk factors] > [food availability] > [food insecurity] > [conflict]
& [institutional/demographic risk factors] > [food utilization] > [food insecurity] > [conflict]

J. *[conflict] > [institutional/demographic risk factors]*



Legend:

Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.71: Mapping the i-CLD for evidence point C20

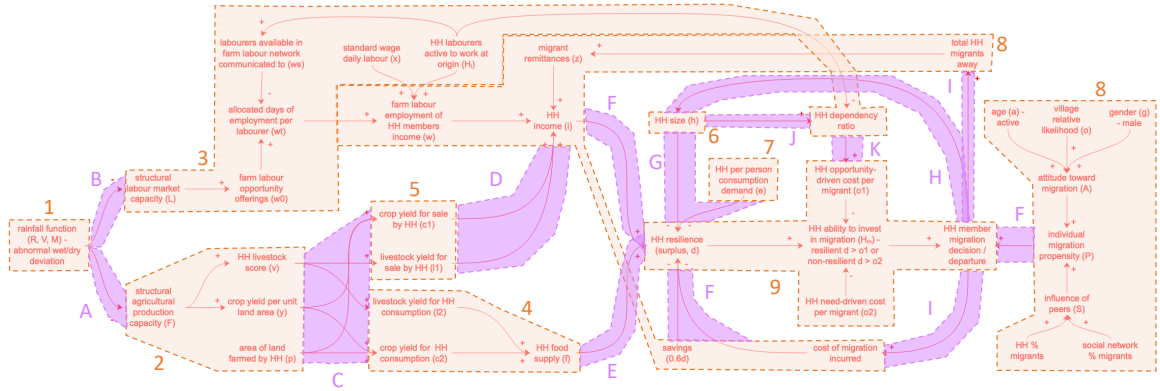
Mapping i-CLD E1: Smith (2014), *Modelling migration futures: development and testing of the Rainfalls Agent-Based Migration Model – Tanzania*

Variables

1. ***climate change*** and ***environmental risk factors***
   The change in rainfall is used as a proxy of the impact of climate change.
2. ***food production***
3. ***labour utilization***
4. ***food availability***
5. ***food trade balance***
6. ***population***
7. ***lifestyle demand/emissions***
8. ***institutional/demographic risk factors***
9. ***emigration***

Links

A. ***[climate change] > [environmental risk factors] > [food production]***
   & [climate change] > [environmental risk factors] > [natural resources] > [agricultural Input availability] > [food production]
B. ***[climate change] > [environmental risk factors] > [food production] > [food production] > [labour utilization]***
   & [climate change] > [environmental risk factors] > [natural resources] > [agricultural Input availability] > [food production] > [labour utilization]
C. ***[food production] > [food availability] > [food trade balance]***
D. Not shown explicitly; financial income and expenses accounted for implicitly in institutional risk factors. W.r.t food system; exports increase income for producers, but not consumers within a country.
E. ***[food availability] > [food insecurity] > [emigration]***
F. ***[institutional/demographic risk factors] > [migration]***
G. ***[population] > [consumer demand] > [food availability] > [food insecurity] > [emigration]***
   & [lifestyle demand/emissions] > [consumer demand] > [food availability] > [food insecurity] > [emigration]
H. ***[emigration] > [population loss] > [population]***
I. ***[emigration] > [institutional/demographic risk factors]***
J. ***[population] > [labour utilization]***
K. ***[labour utilization] > [institutional/demographic risk factors] > [migration]***



Legend:

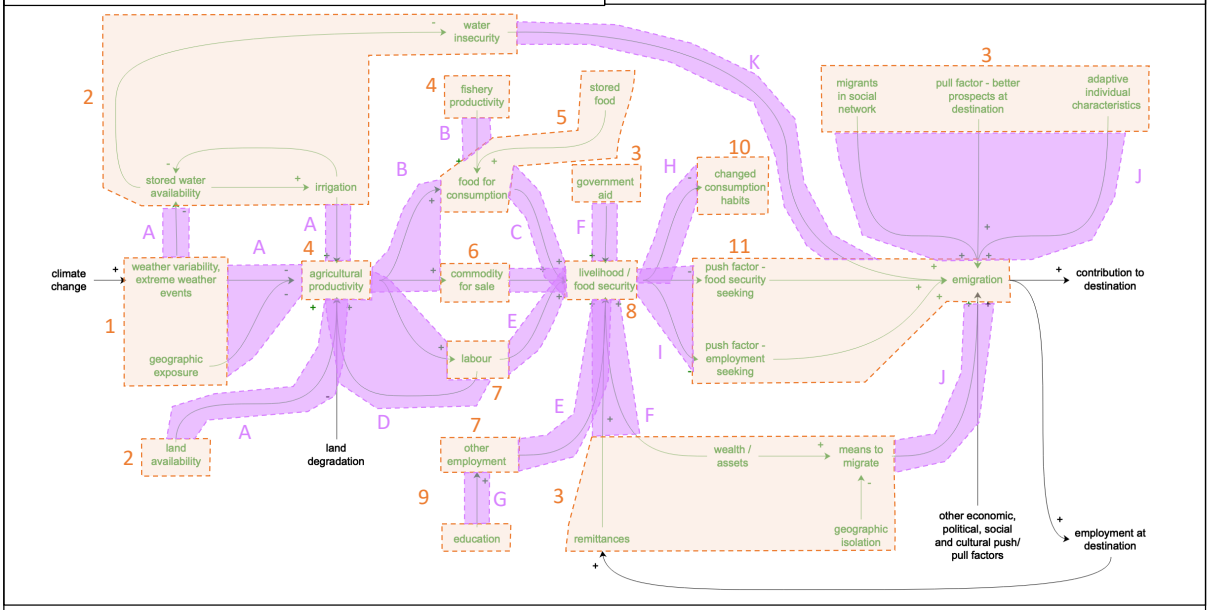
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.72: Mapping the i-CLD for evidence point E1

Mapping i-CLD E2: Afifi et al (2014), *Rainfall-induced crop failure, food insecurity and out-migration in Same-Kilimanjaro, Tanzania*

Variables
1. ***climate change*** and ***environmental risk factors***
2. ***natural resources***
3. ***institutional /demographic risk factors***
4. ***food production***
5. ***food availability***
6. ***food trade balance***
7. ***labour utilization***
8. ***food insecurity***
9. ***infrastructure services***
10. ***natural mortality***
11. ***emigration***

Links
A. *[climate change] > [environmental risk factors] > [natural resources] > [agricultural input availability] > [food production]*
& [climate change] > [environmental risk factors] > [food production]
B. *[food production] > [food availability]*
& [food production] > [food availability] > [food trade balance]
C. *[food availability] > [food insecurity]*
& [food availability] [food price] > [food accessibility] > [food insecurity]
D. *[food production] > [labour utilization] > [agricultural input availability] > [food production]*
E. *[labour utilization] > [institutional/demographic risk factors] > [food accessibility] > [food insecurity]*
F. *[institutional/demographic risk factors] > [food accessibility] > [food insecurity]*
& [institutional/demographic risk factors] > [food availability] > [food insecurity]
& [institutional/demographic risk factors] > [food availability] > [food price] > [food insecurity]
G. *[infrastructure services] > [labour utilization]*
H. *[food insecurity] > [natural mortality]*
I. *[food insecurity] > [emigration]*
J. *[institutional/demographic risk factors] > [emigration]*
K. *[natural resources] > [emigration]*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.73: Mapping the i-CLD for evidence point E2

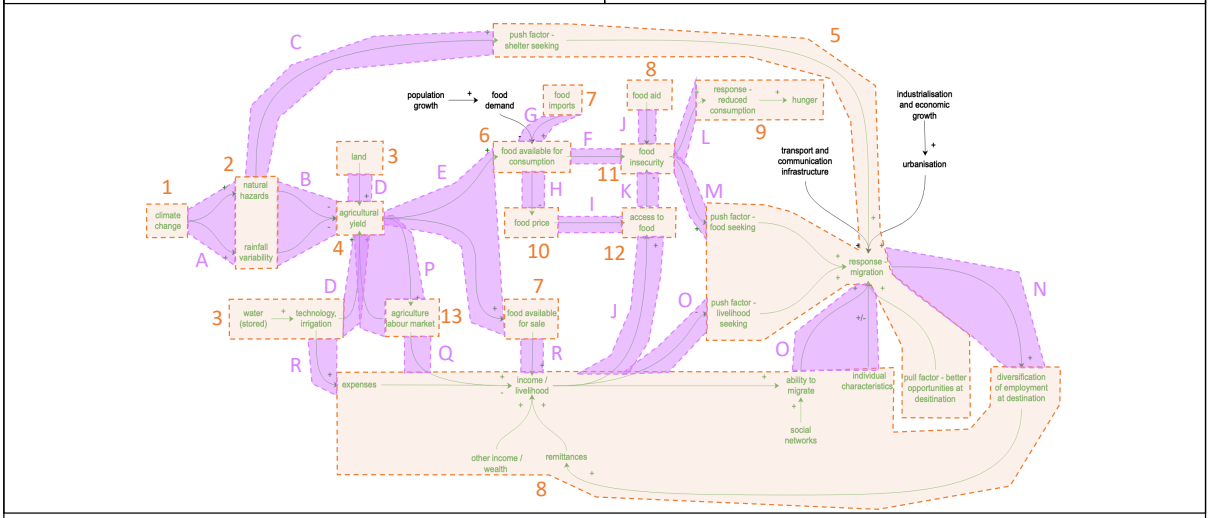
Mapping i-CLD E3: Etzold et al (2014), *Clouds gather in the sky, but no rain falls. Vulnerability to rainfall variability and food insecurity in Northern Bangladesh and its effects on migration*

Variables

1. ***climate change***
2. ***environmental risk factors***
3. ***technology/innovation*** and ***natural resources***
4. ***food production***
5. ***emigration***
6. ***food availability***
7. ***food trade balance***
8. ***institutional/demographic risk factors***
9. ***natural mortality***
10. ***food price***
11. ***food insecurity***
12. ***food accessibility***
13. ***labour utilization***

Links

A. ***[climate change] > [environmental risk factors]***
B. ***[environmental risk factors] > [natural resources] > [agricultural input availability] > [food production]***
& [environmental risk factors] > [food production]
C. ***[environmental risk factor] > [emigration]***
D. ***[technology/innovation] > [natural resources] > [agricultural input availability] > [food production]***
& [technology/innovation] > [food production]
E. ***[food production] > [food availability]***
& [food production] > [food availability] > [food trade balance]
F. ***[food availability] > [food insecurity]***
G. ***[food trade balance] > [food availability]***
H. ***[food availability] > [food price]***
I. ***[food price] > [food accessibility]***
J. ***[institutional/demographic risk factors] > [food accessibility] > [food insecurity]***
K. ***[food accessibility] > [food insecurity]***
L. ***[food insecurity] > [natural mortality]***
M. ***[food insecurity] > [emigration]***
N. ***[emigration] > [institutional/demographic risk factors]***
O. ***[institutional/demographic risk factors] > [emigration]***
P. ***[food production] > [labour utilization] > [agricultural input availability] > [food production]***
Q. ***[labour utilization] > [institutional/demographic risk factors]***
R. Not shown explicitly; financial income and expenses accounted for implicitly in institutional risk factors. W.r.t food system; exports increase income for producers, but not consumers within a country.



Legend:

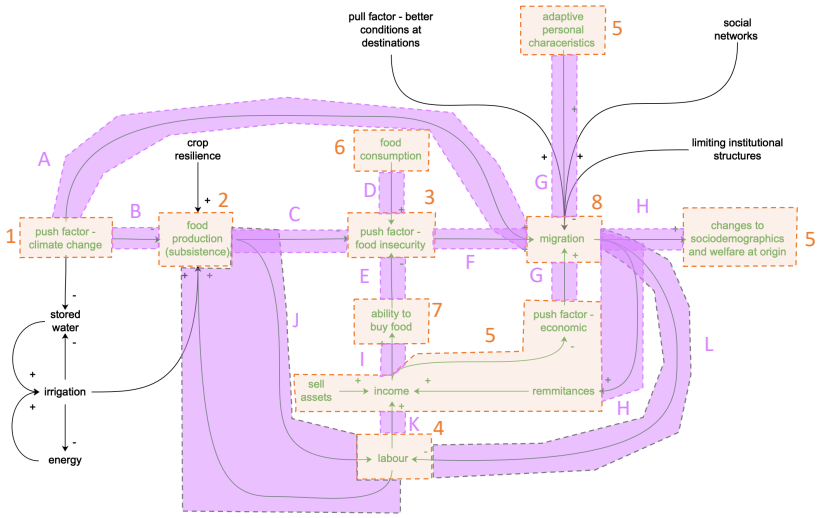
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.74: Mapping the i-CLD for evidence point E3

Mapping i-CLD E4: Jacobson et al (2019), *When is migration a maladaptive response to climate change?*

Variables
1. *climate change*
2. *food production*
3. *food insecurity*
4. *labour utilization*
5. *institutional /demographic risk factors*
6. *consumer demand*
7. *food accessibility*
8. *emigration*

Links
A. *[climate change] > [environmental risk factors] > [emigration]*
B. *[climate change] > [environmental risk factors] > [natural resources] > [agricultural input availability] > [food production]*
& [climate change] > [environmental risk factors] > [food production]
C. *[food production] > [food availability] > [food insecurity]*
& *[food production] > [food availability] > [food price] > [food accessibility] > [food insecurity]*
D. *[consumer demand] > [food availability] > [food insecurity]*
E. *[food accessibility] > [food insecurity]*
F. *[food insecurity] > [emigration]*
G. *[institutional/demographic risk factors] > [emigration]*
H. *[emigration] > [institutional /demographic risk factors]*
I. *[institutional/demographic risk factors] > [food accessibility] > [food insecurity]*
J. *[food production] > [labour utilization] > [agricultural input availability] > [food production]*
K. *[labour utilization] > [institutional/demographic risk factors]*
L. *[emigration] > [population loss] > [population] > [labour utilization]*



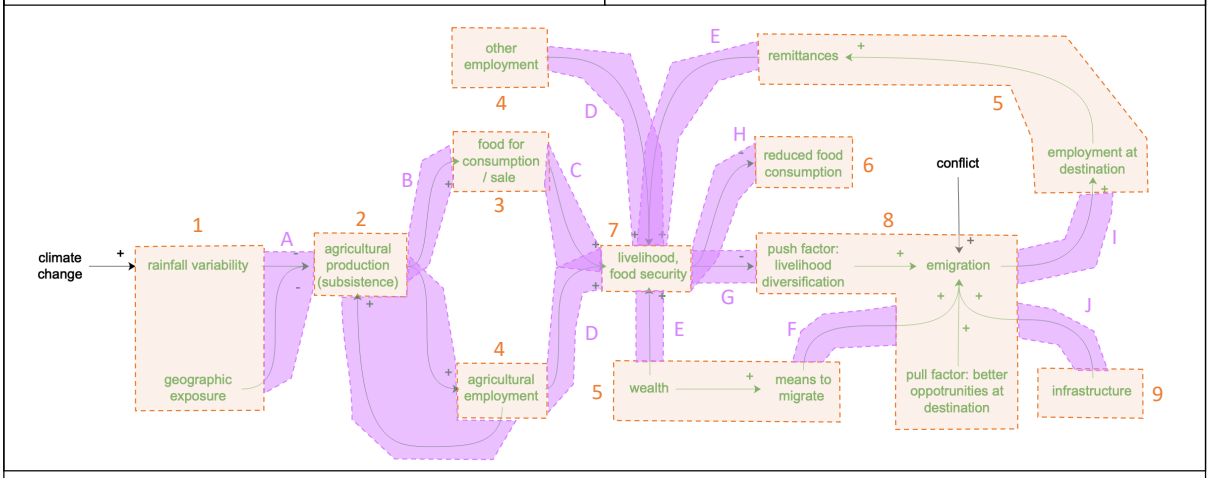
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.75: Mapping the i-CLD for evidence point E4

Mapping i-CLD E5: Milan & Ho (2014), *Livelihood and migration patterns at different altitudes in the Central Highlands of Peru*

Variables
1. ***climate change*** and ***environmental risk factors***
2. ***food production***
3. ***food availability*** and ***food trade balance***
4. ***labour utilization***
5. ***institutional / demographic risk factors***
6. ***natural mortality***
7. ***food insecurity***
8. ***emigration***
9. ***infrastructure services***

Links
A. ***[climate change] > [environmental risk factors] > [natural resources] > [agricultural input availability] > [food production]***
& [climate change] > [environmental risk factors] > [food production]
B. ***[food production] > [food availability] > [food trade balance]***
C. ***[food availability] > [food insecurity]***
& [food availability] > [food price] > [food accessibility] > [food insecurity]
D. ***[labour utilization] > [institutional / demographic risk factors] > [food accessibility] > [food insecurity]***
E. ***[institutional / demographic risk factors] > [food accessibility] > [food insecurity]***
F. ***[institutional / demographic risk factors] > [emigration]***
G. ***[food insecurity] > [emigration]***
H. ***[food insecurity] > [natural mortality]***
I. ***[emigration] > [institutional/demographic risk factors]***
J. ***[infrastructure services] > [institutional/demographic risk factors] > [emigration]***



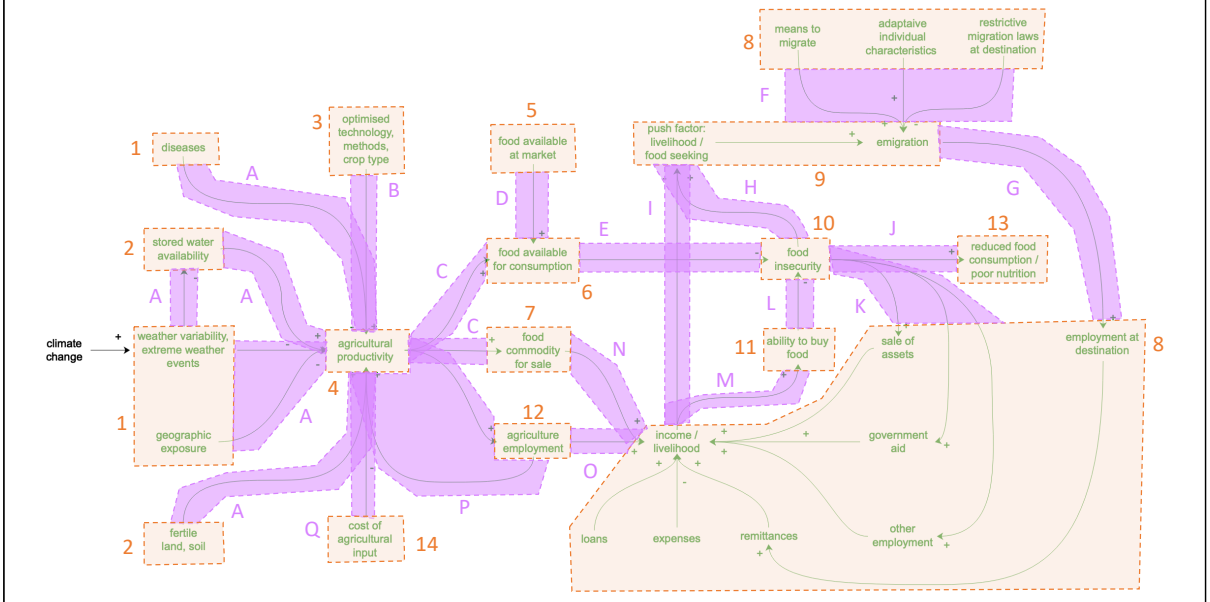
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.76: Mapping the i-CLD for evidence point E5

Mapping i-CLD E6: Milan & Ruano (2014), *Rainfall variability, food insecurity and migration in Cabricán, Guatemala*

Variables
1. ***environmental degradation/pollution***
2. ***natural resources***
3. ***technology/innovation***
4. ***food production***
5. ***international food availability***
6. ***food availability***
7. ***food trade balance***
8. ***institutional/demographic risk factors***
9. ***emigration***
10. ***food insecurity***
11. ***food accessibility***
12. ***labour utilization***
13. ***natural mortality***
14. ***cost of food production***

Links
A. ***[climate change] > [environmental risk factors] > [food production]***
& [climate change] > [environmental risk factors] > [natural resources] > [agricultural input availability] > [food production]
B. ***[technology/innovation] > [food production]***
C. ***[food production] > [food availability] > [food trade balance]***
D. ***[international food availability] > [food trade balance] > [food availability]***
E. ***[food availability] > [food insecurity]***
& [food availability] > [food price] > [food accessibility] > [food insecurity]
F. ***[institutional/demographic risk factors] > [emigration]***
G. ***[emigration] > [institutional/demographic risk factors]***
H. ***[food insecurity] > [emigration]***
I. ***[institutional/demographic risk factors] > [emigration]***
J. ***[food insecurity] > [natural mortality]***
K. ***[food insecurity] > [institutional/demographic risk factors]***
L. ***[food accessibility] > [food insecurity]***
M. ***[institutional/demographic risk factors] > [food accessibility]***
N. Not shown explicitly; financial income and expenses accounted for implicitly in institutional risk factors. W.r.t food system; exports increase income for producers, but not consumers within a country.
O. ***[labour utilization] > [institutional/demographic risk factors]***
P. ***[food production] > [labour utilization] > [agricultural input availability] > [food production]***
Q. Not shown explicitly; role of costs in productivity is implicit to food production (self-contained sub-system)



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.77: Mapping the i-CLD for evidence point E6

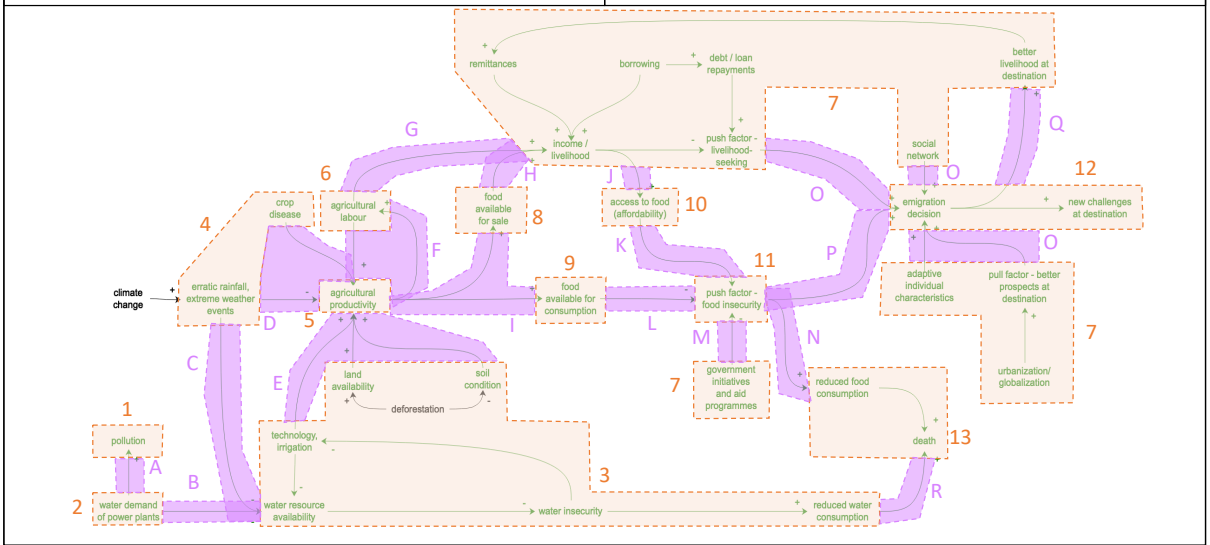
Mapping i-CLD E7: Murali & Afifi (2014), *Rainfall variability, food security and human mobility in the Janjgir-Champa district of Chhattisgarh state, India*

Variables

1. ***environmental degradation/pollution***
2. ***industrial capital / output***
3. ***technology/innovation*** and ***natural resources***
4. ***climate change*** and ***environmental risk factors***
5. ***food production***
6. ***labour utilization***
7. ***institutional / demographic risk factors***
8. ***food trade balance***
9. ***food availability***
10. ***food accessibility***
11. ***food insecurity***
12. ***emigration***
13. ***natural mortality***

Links

A. ***[industrial capital / output] > [environmental degradation/pollution]***
B. ***[industrial capital / output] > [natural resources]***
C. ***[climate change] > [environmental risk factors] > [natural resources]***
D. ***[climate change] > [environmental risk factors] > [food production]***
E. ***[natural resources] > [agricultural input availability] > [food production]***
F. ***[food production] > [labour utilization] > [agricultural input availability] > [food production]***
G. ***[labour utilization] > [institutional/demographic risk factors]***
H. Not shown explicitly; financial income and expenses accounted for implicitly in institutional risk factors. W.r.t food system; exports increase income for producers, but not consumers within a country
I. ***[food production] > [food availability]***
& [food production] > [food availability] > [food trade balance]
J. ***[institutional/demographic risk factors] > [food accessibility]***
K. ***[food accessibility] > [food insecurity]***
L. ***[food availability] > [food insecurity]***
& [food availability] > [food price] > [food accessibility] > [food insecurity]
M. ***[institutional/demographic risk factors] > {[food accessibility] & [food availability]}***
N. ***[food insecurity] > [natural mortality]***
O. ***[institutional/demographic risk factors] > [emigration]***
P. ***[food insecurity] > [emigration]***
Q. ***[emigration] > [institutional/demographic risk factors]***
R. ***[natural resources] > [natural mortality]***



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.78: Mapping the i-CLD for evidence point E7

Mapping i-CLD E8: Panter-Brick & Eggerman (1997), *Household Responses to Food Shortages in Western Nepal*

Variables

1. ***climate change*** and ***environmental risk factors***
2. ***natural resources*** and ***industrial capital/output*** and ***technology/innovation***
3. ***food production***
4. ***labour utilization***
5. ***food insecurity*** and ***food availability*** and ***food accessibility*** and ***food trade balance***
6. ***consumer demand***
7. ***institutional / demographic risk factors*** and ***population***
8. ***natural mortality***
9. ***emigration***

Links

A. ***[climate change] > [environmental risk factors] > [natural resources] > [agricultural input availability] > [food production]***
& [climate change] > [environmental risk factors] > [food production]

B. ***[technology/innovation] > [natural resources] > [agricultural input availability] > [food production]***
& [industrial input/output] > [agricultural input availability] > [food production]
& [technology/innovation] > [food production]

C. ***[food production] > [labour utilization] > [agricultural input availability] > [food production]***

D. ***[food production] > [food availability] > [food insecurity]***
& [food availability] > [food price] > [food accessibility] > [food insecurity]
& [food availability] > [food trade balance] > [international food availability] > [food trade balance] > [food availability]
& [food accessibility] > [food insecurity]

E. ***[institutional/demographic risk factors] > [food accessibility]***

F. ***[institutional/demographic risk factors] > [migration]***

G. ***[food insecurity] > [natural mortality]***

H. ***[food insecurity] > [emigration]***

I. ***[emigration] > [institutional/demographic risk factors]***
& [emigration] > [population loss] > [population]

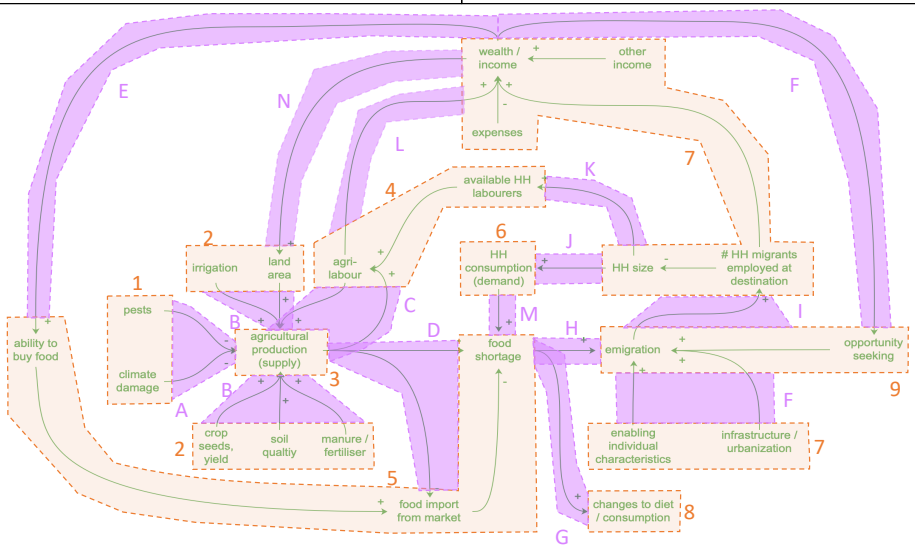
J. ***[population] > [consumer demand]***

K. ***[population] > [labour utilization]***

L. ***[labour utilization] > [institutional/demographic risk factors]***

M. ***[consumer demand] > [food availability]***

N. Not shown explicitly; assets and expenses accounted for implicitly in institutional risk factors. W.r.t food system; land ownership is part of country's geographic endowment.



Legend:

Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.79: Mapping the i-CLD for evidence point E8

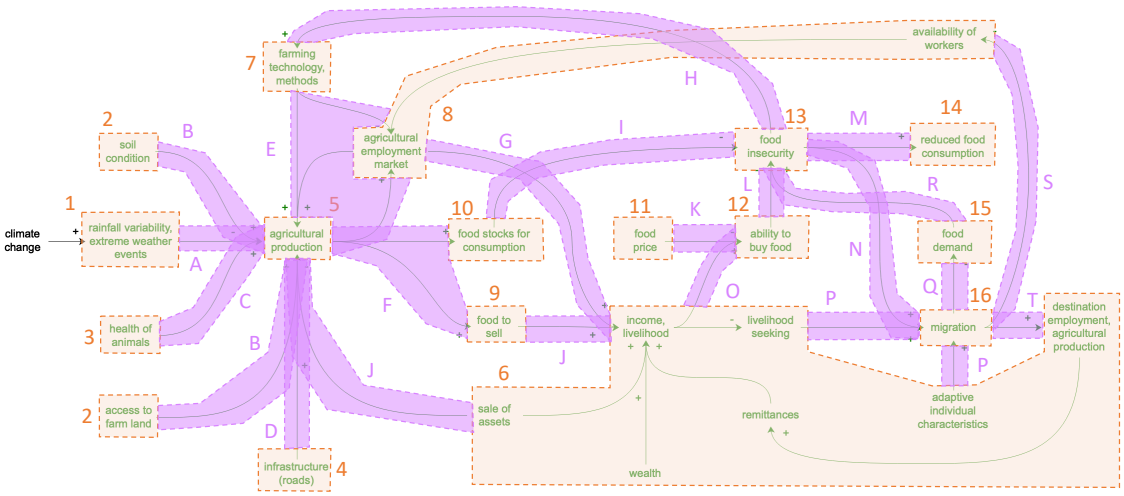
Mapping i-CLD E9: Rademacher-Schulz et al (2014), *Time matters: shifting seasonal migration in Northern Ghana in response to rainfall variability and food insecurity*

Variables

1. ***climate change*** and ***environmental risk factors***
2. ***natural resources*** and ***agricultural input availability***
3. ***agricultural input availability***
4. ***industrial capital / output***
5. ***food production***
6. ***institutional / demographic risk factors***
7. ***technology/innovation***
8. **labour utilization**
9. ***food availability***
10. ***food trade balance***
11. ***food price***
12. ***food accessibility***
13. ***food insecurity***
14. ***natural mortality***
15. ***consumer demand***
16. ***emigration***

Links

A. ***[climate change] > [environmental risk factors] > [natural resources] > [agricultural input availability] > [food production]***
& [climate change] > [environmental risk factors] > [food production]
B. ***[natural resources] > [agricultural input availability] > [food production]***
C. ***[agricultural input availability] > [food production]***
D. ***[industrial capital / output] > [agricultural input availability] > [food production]***
E. ***[technology/innovation] > [food production] > [labour utilization] > [agricultural input availability] > [food production]***
F. ***[food production] > [food availability]***
& [food production] > [food availability] > [food trade balance]
G. ***[labour utilization] > [institutional/demographic risk factors]***
H. ***[food insecurity] > [institutional/demographic risk factors] > [technology/innovation]***
I. ***[food availability] > [food insecurity]***
J. Not shown explicitly; financial income and expenses accounted for implicitly in institutional risk factors. W.r.t food system; exports increase income for producers, but not consumers within a country.
K. ***[food price] > [food accessibility]***
L. ***[food accessibility] > [food insecurity]***
M. ***[food insecurity] > [natural mortality]***
N. ***[food insecurity] > [emigration]***
O. ***[institutional/demographic risk factors] > [food accessibility]***
P. ***[institutional/demographic risk factors] > [emigration]***
Q. ***[emigration] > [population loss] > [population] > [consumer demand]***
R. ***[consumer demand] > [food availability] > [food insecurity]***
S. ***[emigration] > [population loss] > [population] > [labour utlization]***
T. ***[emigration] > [institutional/demographic risk factors]***



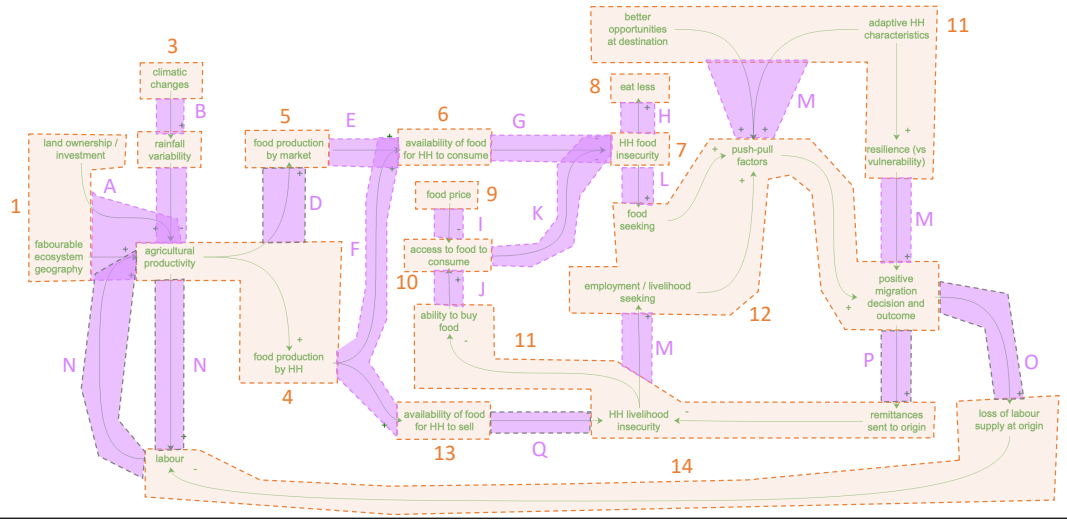
Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.80: Mapping the i-CLD for evidence point E9

Mapping i-CLD E10: Warner & Afifi (2014), *Where the rain falls: Evidence from 8 countries on how vulnerable households use migration to manage the risk of rainfall variability and food insecurity*

Variables
1. ***natural resources***
2. ***climate change***
3. ***environmental risk factors***
4. ***food production***
5. ***international food availability***
6. ***food availability***
7. ***food insecurity***
8. ***natural mortality***
9. ***food price***
10. ***food accessibility***
11. ***institutional/demographic risk factors***
12. ***emigration***
13. ***food trade balance***
14. ***labour utilization***

Links
A. ***[natural resources] > [agricultural input availability] > [food production]***
B. ***[climate change] > [environmental risk factors]***
C. ***[environmental risk factors] > [natural resource] > [agricultural input availability] > [food production]***
D. ***[food production] > [food availability] > [food trade balance] > [international food availability]***
E. ***[international food availability] > [food trade balance] > [food availability]***
F. ***[food production] > [food availability]***
& [food production] > [food availability] > [food trade balance]
G. ***[food availability] > [food insecurity]***
H. ***[food insecurity] > [natural mortality]***
I. ***[food price] > [food accessibility]***
J. ***[institutional/demographic risk factors] > [food accessibility]***
K. ***[food accessibility] > [food insecurity]***
L. ***[food insecurity] > [emigration]***
M. ***[institutional/demographic risk factors] > [migration]***
N. ***[food production] > [labour utilization] > [agricultural input availability] > [food production]***
O. ***[emigration] > [population loss] > [population] > [labour utilization]***
P. ***[emigration] > [institutional/demographic risk factors]***
Q. Not shown explicitly; remittances and financial livelihood accounted for as a type of income in institutional risk factors. Exports increase income for producers, but not consumers within a country.



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.81: Mapping the i-CLD for evidence point E10

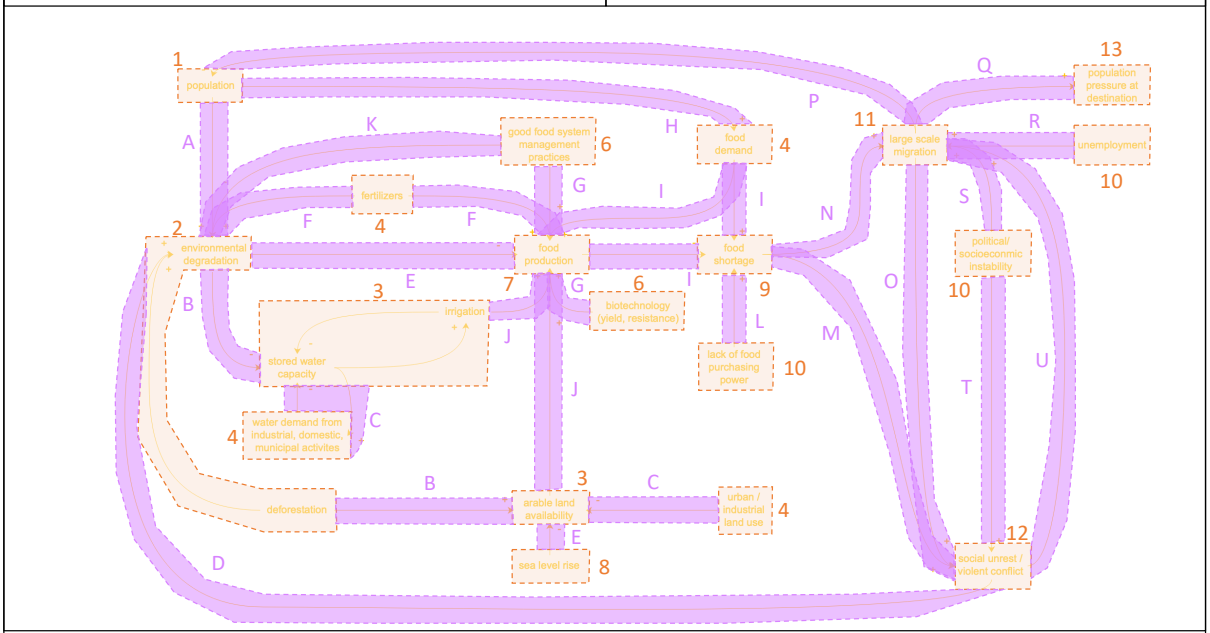
Mapping i-CLD E11: Doos (1994), *Environmental Degradation, Global Food Production, and Risk for Large-Scale Migrations*

Variables

1. ***population***
2. ***environmental degradation / pollution***
3. ***natural resources***
4. ***consumer demand*** and ***industrial capital / output***
5. ***industrial capital / output***
6. ***technology/innovation***
7. ***food production***
8. ***climate change*** and ***environmental risk factors***
9. ***food availability*** and ***food insecurity***
10. ***institutional /demographic risk factors***
11. ***emigration***
12. ***conflict***
13. ***rest of world population / pressure***

Links

A. *[population] > [consumer emissions / waste] > [environmental degradation / pollution]*
B. *[environmental degradation / pollution] > [environmental risk factors] > [natural resources] & [environmental degradation / pollution] > [climate change] > [environmental risk factors] > [natural resources]*
C. *[industrial capital / output] > [infrastructure services] > [industrial capital / output] > [natural resources] & [consumer demand] > [natural resources]*
D. *[conflict] > [environmental degradation / pollution]*
E. *[environmental degradation / pollution] > [environmental risk factors] > [natural resources] > [agricultural input availability] > [food production] & [environmental risk factors] > [food production] & [environmental degradation / pollution] > [climate change] > [environmental risk factors] > [natural resources] > [agricultural input availability] > [food production] & [environmental risk factors] > [climate change] > [food production]*
F. *[industrial capital / output] > [agricultural input availability] > [food production] > [environmental degradation / pollution]*
G. *[technology/innovation] > [food production]*
H. *[population] > [consumer demand]*
I. *[consumer demand] > [food availability] > [food insecurity] & [consumer demand] > [food availability] > [food price] > [food accessibility] > [food insecurity] & [consumer demand] > [food availability] > [food production]*
J. *[natural resources] > [agricultural input availability] > [food production]*
K. *[technology/innovation] > [environmental degradation / pollution]*
L. *[institutional/demographic risk factors] > [food accessibility] > [food insecurity]*
M. *[food insecurity] > [conflict]*
N. *[food insecurity] > [emigration]*
O. *[emigration] > [institutional/demographic risk factors] > [conflict]*
P. *[emigration] > [population loss] > [population]*
Q. *[emigration] > [rest of world population/pressure]*
R. *[institutional/demographic risk factors] > [emigration]*
S. *[emigration] > [institutional/demographic risk factors]*
T. *[institutional/demographic risk factors] > [conflict]*
U. *[conflict] > [emigration]*



Legend:
Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.82: Mapping the i-CLD for evidence point E11

Mapping i-CLD E12: Puma et al (2018), *A developing food crisis and potential refugee movements*

Variables

1. ***climate change*** and ***environmental risk factors***
2. ***food production*** (and ***food availability***)
3. ***population***
4. ***food insecurity***
5. ***food trade balance*** and ***international food availability***
6. ***conflict***
7. ***institutional / demographic risk factors***
8. ***emigration***
9. ***natural mortality***
10. ***rest of world population / pressure***

Links

A. *[climate change] > [environmental risk factors] > [natural resource] > [agricultural input availability] > [food production]*
& [climate change] > [environmental risk factors] > [food production]

B. *[food production] > [food availability] > [food insecurity]*
& [food production] > [food availability] > [food price] > [food accessibility] > [food insecurity]

C. *[population] > [consumer demand] > [food availability] > [food insecurity]*
& [population] > [consumer demand] > [food availability] > [food price] > [food insecurity]

D. *[institutional / demographic risk factors] > [food availability] > [food insecurity]*
& [institutional / demographic risk factors] > [food accessibility] > [food insecurity]

E. *[food insecurity] > [natural mortality]*

F. *[emigration] > [rest of world population/pressures]*

G. *[food trade balance] > [food availability] > [food insecurity]*

H. *[international food availability] > [food trade balance] > [food availability] > [food insecurity]*

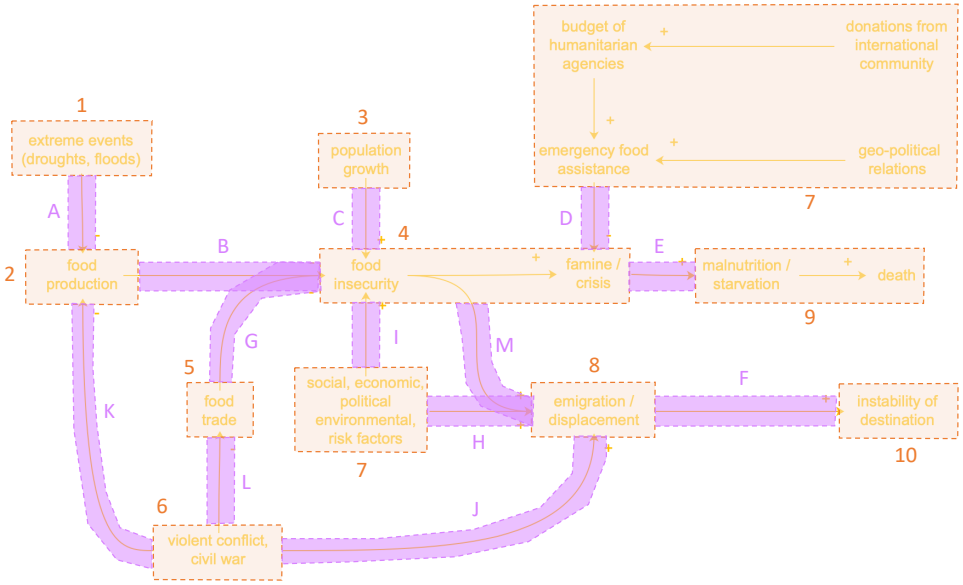
I. *[institutional / demographic risk factors] > [food availability] > [food insecurity]*
& [institutional / demographic risk factors] > [food accessibility] > [food insecurity]
& [institutional / demographic risk factors] > [food utilization] > [food insecurity]

J. *[conflict] > [emigration]*

K. *[conflict] > [environmental degradation / pollution] > [environmental risk factors] > [food production]*
& [conflict] > [environmental risk factors] > [natural resource] > [agricultural input availability] > [food production]

L. *[conflict] > [environmental degradation / pollution] > [environmental risk factors] > [food production] > [food availability] > [food trade balance] > [international food availability]*
& [conflict] > [environmental degradation / pollution] > [environmental risk factors] > [natural resource availability] > [agricultural input availability] > [food production] > [food availability] > [food trade balance] > [international food availability]

M. *[food insecurity] > [emigration]*



Legend:

Red = quantitative complex systems model
Blue = statistical analysis of quantitative dataset
Green = collection / analysis of qualitative interview / survey data
Yellow = quantitative data-led case study / scenario
Black = literature review / intergovernmental report
Grey = explored but not significant / supported

Figure A.83: Mapping the i-CLD for evidence point E12

Appendix B

Supplementary information for Chapter 4 and 5

This appendix provides supporting information, regarding data preparation and simulation verification, for the second and third investigation of the three-part research framework presented in Chapter 4 and 5 respectively. A table of contents of this appendix is provided below.

Appendix B: table of contents

B.1 Chapter 4 & 5: Country list 243

B.2 Chapter 4 & 5: *population_historical* 254

B.3 Chapter 4 & 5: *gdp_pc_historical* 256

B.4 Chapter 4 & 5: *food_production_historical* 259

B.5 Chapter 4 & 5: *food_demand_pc_historical* 264

B.6 Chapter 4 & 5: *trade_distance* 268

B.7 Chapter 4 & 5: Land area values used in *food_production_historical* data preparation 270

B.8 Chapter 4 & 5: Derivation of energy-equivalent-grain-weight conversion factors used in *food_production_historical* data preparation 272

B.9 Chapter 4 & 5: MLFD constant used in *food_demand_pc_historical* data preparation 279

B.10 Chapter 4 & 5: *population_growth* 280

B.11 Chapter 4 & 5: *gdp_pc_growth* 282

B.12 Chapter 4 & 5: *food_production_growth_cropland* 284

B.13 Chapter 4 & 5: *food_production_growth_cropyield* 286

B.14 Chapter 4 & 5: *food_demand_pc_growth* 292

B.15 Chapter 4: *RCP85_climate_forcing* 294

B.16 Chapter 4: *W3_climate_forcing, W3_population, W3_gdp, W3_food_production, W3_food_demand* 295

B.17 Chapter 4: Verification of results 298

B.18 Chapter 5: Verification of results 302

B.1 Chapter 4 & 5: Country list

The model includes 242 of the 249 countries defined as per the ISO (2021) 3166 standard, as presented in Table B.1. The seven other ISO 3166 defined countries, presented in Table B.2, were not explicitly included as they do not have a permanent civilian population. Each country was assigned a geographic continent, within which there may be first- or second-order regions.

The 'geo-units' shape file from Natural Earth (2021) was used to spatially define each country. The 'geo-units' are defined at a granularity greater than or equal to the countries in the model. Any 'geo-units' designated disputed territories or demilitarized zones were excluded on the basis that they have no obvious 'sovereign' country to which to be mapped, while all other 'geo-units' are mapped to the respective 'sovereign' country, as presented in Table B.3.

Chapter 4 only: Each country was assigned a classification of either 'landlocked developing country' (LLDG), 'small island developing country' (SIDG), 'other developing country' (ODG) or 'developed country' (DVD) based on the UNSD (2021) M49 standard. DVD, LLDG and SIDG countries are as defined by UNSD (2021), while ODG includes countries listed under developing but not included in the LLDG and SIGD categories in UNDS (2021). Each country was assigned a vulnerability and resilience rank and score based on the Fragile States Index (FSI) (The Fund for Peace 2020) and Resilience Index (RI) (FM Global 2021), respectively, noting that only 178 countries are included in the latter and only 128 countries are included in the former. The FSI was last updated in 2020, while RI was last updated in 2021, but both are presented as 2020 for simplicity.

Table B.1: List of countries in the model

ISO 3166 English short name	ISO 3166 alpha-3 code	UNSD M49 geographic region	UNSD M49 based classification	FSI vulnerability rank / score		RI resilience rank / score	
Algeria	DZA	Africa: Northern Africa	ODG	71	74.6	104	31.2
Egypt	EGY			36	86	71	46.9
Libya	LBY			20	95.2	-	-
Morocco	MAR			80	71.2	119	24.3
Sudan (the)	SDN			8	104.8	-	-
Tunisia	TUN			95	68.1	81	42.8
Western Sahara*	ESH			-	-	-	-
Burundi	BDI	Africa: Sub-Saharan Africa: Eastern Africa	LLDG	11	97.9	-	-
Ethiopia	ETH			21	94.6	122	19.2
Malawi	MWI			43	84	43	64.7
Rwanda	RWA			35	86	66	50
South Sudan	SSD			3	110.8	-	-
Uganda	UGA			24	92.8	107	29.6
Zambia	ZMB			41	84.5	101	32.5
Zimbabwe	ZWE			10	99.2	99	34
Djibouti	DJI		ODG	47	82.7	-	-

Eritrea	ERI			18	95.8	-	-
Kenya	KEN			29	90.3	89	39.9
Madagascar	MDG			57	79.5	-	-
Mayotte	MYT			-	-	-	-
Mozambique	MOZ			27	91.7	117	25.4
Réunion	REU			-	-	-	-
Somalia	SOM			2	110.9	-	-
Tanzania, the United Republic of	TZA			61	78.1	95	35.8
Comoros (the)	COM		SIDG	53	81.2	-	-
Mauritius	MUS			153	37.2	73	46.7
Seychelles	SYC			126	54.7	-	-
Central African Republic (the)	CAF	Africa: Sub-Saharan Africa: Middle Africa	LLDG	6	107.5	-	-
Chad	TCD			7	106.4	123	18.9
Angola	AGO		ODG	34	87.3	-	-
Cameroon	CMR			12	97.9	112	26.7
Congo (the Democratic Republic of the)	COD			5	109.4	-	-
Congo (the)	COG			26	92.1	-	-
Equatorial Guinea	GNQ			45	83	-	-
Gabon	GAB			90	69.1	-	-
Sao Tome and Principe	STP		SIDG	83	70.3	-	-
Botswana	BWA	Africa: Sub-Saharan Africa: Southern Africa	LLDG	121	57.1	52	56.9
Eswatini	SWZ			46	83	-	-
Lesotho	LSO			60	78.3	-	-
Namibia	NAM		ODG	105	65.1	-	-
South Africa	ZAF			85	70.1	47	62
Burkina Faso	BFA	Africa: Sub-Saharan Africa: Western Africa	LLDG	37	85.9	-	-
Mali	MLI			16	96	45	62.8
Niger (the)	NER			19	95.3	-	-
Benin	BEN		ODG	77	72.5	102	31.5
Côte d'Ivoire	CIV			32	89.7	92	38.5
Gambia (the)	GMB			51	82.2	-	-
Ghana	GHA			109	64.2	90	39.6
Guinea	GIN			15	97.2	103	31.4
Liberia	LBR			31	90	-	-
Mauritania	MRT			33	88.7	-	-
Nigeria	NGA			14	97.3	74	46.3
Saint Helena, Ascension and Tristan da Cunha	SHN			-	-	-	-
Senegal	SEN			72	74.6	96	35.5
Sierra Leone	SLE			42	84.4	-	-
Togo	TGO			38	85.8	-	-
Cabo Verde	CPV		SIDG	106	64.8	-	-
Guinea-Bissau	GNB			23	92.9	-	-
Cayman Islands (the)	CYM	Americas: Latin America & the Caribbean: Caribbean	ODG	-	-	-	-
Guadeloupe	GLP			-	-	-	-
Martinique	MTQ			-	-	-	-
Saint Barthélemy	BLM			-	-	-	-
Saint Martin (French part)	MAF			-	-	-	-
Turks and Caicos Islands (the)	TCA			-	-	-	-
Anguilla	AIA		SIDG	-	-	-	-
Antigua and Barbuda	ATG			128	52.1	-	-
Aruba	ABW			-	-	-	-
Bahamas (the)	BHS			132	49.9	-	-
Barbados	BRB			137	46.4	-	-

Bonaire, Sint Eustatius and Saba	BES			-	-	-	-
Cuba	CUB			118	59.2	-	-
Curaçao	CUW			-	-	-	-
Dominica	DMA			-	-	-	-
Dominican Republic (the)	DOM			107	64.4	87	41.3
Grenada	GRD			125	55.2		
Haiti	HTI			13	97.7	126	**0**
Jamaica	JAM			116	60	100	33.5
Montserrat	MSR			-	-	-	-
Puerto Rico	PRI			-	-	-	-
Saint Kitts and Nevis	KNA			-	-	-	-
Saint Lucia	LCA			-	-	-	-
Saint Vincent and the Grenadines	VCT			-	-	-	-
Sint Maarten (Dutch part)	SXM			-	-	-	-
Trinidad and Tobago	TTO			129	51.9	84	41.8
Virgin Islands (British)	VGB			-	-	-	-
Virgin Islands (U.S.)	VIR			-	-	-	-
Costa Rica	CRI	Americas: Latin America & the Caribbean: Central America	ODG	147	40.2	58	52.9
El Salvador	SLV			93	68.9	109	28.4
Guatemala	GTM			58	79.2	114	26.1
Honduras	HND			64	76.8	116	25.4
Mexico	MEX			98	67.2	78	43.5
Nicaragua	NIC			62	77.1	111	27.9
Panama	PAN			140	46	59	52.6
Belize	BLZ		SIDG	114	60.8	-	-
Bolivia (Plurinational State of)	BOL	Americas: Latin America & the Caribbean: South America	LLDG	70	75	48	60.7
Paraguay	PRY			104	65.2	85	41.7
Argentina	ARG		ODG	139	46.1	57	53.7
Brazil	BRA			75	73	61	52.1
Chile	CHL			142	42.5	50	58.5
Colombia	COL			65	76.6	67	49.5
Ecuador	ECU			89	69.4	94	35.9
Falkland Islands (the) [Malvinas]	FLK			-	-	-	-
French Guiana	GUF			-	-	-	-
Peru	PER			97	67.6	80	43
Uruguay	URY			157	33.4	46	62.3
Venezuela (Bolivarian Republic of)	VEN			28	91.2	125	1.5
Guyana	GUY		SIDG	102	66	-	-
Suriname	SUR			115	60.1	-	-
Bermuda	BMU	Americas: North America	DVD	-	-	-	-
Canada	CAN			171	18.7	12	90.4
Greenland	GRL			-	-	-	-
Saint Pierre and Miquelon	SPM			-	-	-	-
United States of America (the)	USA			149	38.3	18	89
Kazakhstan	KAZ	Asia: Central Asia	LLDG	117	59.8	56	54.5
Kyrgyzstan	KGZ			73	73.9	110	28.2
Tajikistan	TJK			66	75.5	106	30.3
Turkmenistan	TKM			91	69.1	-	-
Uzbekistan	UZB			74	73.1	-	-
Japan	JPN	Asia: Eastern Asia	DVD	158	32.3	23	82
Mongolia	MNG		LLDG	130	51.9	76	43.9
China	CHN		ODG	86	69.9	75	46.1
Hong Kong	HKG			-	-	24	81.9

Korea (the Democratic People's Republic of)	PRK			30	90.2	-	-
Korea (the Republic of)	KOR			159	32	34	71.3
Macao	MAC			-	-	-	-
Taiwan (Province of China)	TWN			-	-	27	76.4
Lao People's Democratic Republic (the)	LAO	Asia: South-Eastern Asia	LLDG	63	76.9	105	31
Brunei Darussalam	BRN		ODG	122	56.6	41	65.6
Cambodia	KHM			55	80.3	113	26.4
Indonesia	IDN			96	67.8	79	43.4
Malaysia	MYS			120	57.6	120	22.6
Myanmar	MMR			22	94	-	-
Philippines (the)	PHL			54	81	86	41.5
Thailand	THA			82	70.8	69	47.2
Viet Nam	VNM			111	63.9	93	37.9
Singapore	SGP		SIDG	162	26.3	11	91.3
Timor-Leste	TLS			48	82.7	-	-
Afghanistan	AFG	Asia: Southern Asia	LLDG	9	102.9	-	-
Bhutan	BTN			88	69.5	-	-
Nepal	NPL			49	82.6	15	90
Bangladesh	BGD		ODG	39	85.7	108	29.5
India	IND			68	75.3	62	52
Iran (Islamic Republic of)	IRN			44	83.4	124	16.1
Pakistan	PAK			25	92.1	115	25.8
Sri Lanka	LKA			52	81.8	77	43.6
Maldives	MDV		SIDG	99	66.2	-	-
Cyprus	CYP	Asia: Western Asia	DVD	123	56.1	42	64.7
Israel	ISR			69	75.1	35	70.5
Armenia	ARM		LLDG	108	64.2	70	46.9
Azerbaijan	AZE			78	71.3	88	40.6
Bahrain	BHR		ODG	110	63.9	49	60.7
Georgia	GEO			81	71.2	72	46.8
Iraq	IRQ			17	95.9	-	-
Jordan	JOR			67	75.4	91	38.7
Kuwait	KWT			131	50.9	83	42.1
Lebanon	LBN			40	84.7	121	19.4
Oman	OMN			134	48	68	47.8
Palestine, State of	PSE			-	-	-	-
Qatar	QAT			141	43.7	32	74
Saudi Arabia	SAU			94	68.8	55	56.1
Syrian Arab Republic (the)	SYR			4	110.7	-	-
Turkey	TUR			59	79.1	60	52.5
United Arab Emirates (the)	ARE			152	38.1	30	74.9
Yemen	YEM			1	112.4	-	-
Belarus	BLR	Europe: Eastern Europe	DVD	103	65.8	-	-
Bulgaria	BGR			133	49.2	44	64.6
Czechia	CZE			155	35.7	19	87.2
Hungary	HUN			135	47.6	33	72.8
Poland	POL			145	41	22	83.3
Romania	ROU			136	46.7	36	70.4
Russian Federation (the)	RUS			76	72.6	53	56.3
Slovakia	SVK			151	38.2	29	75.3
Ukraine	UKR			92	69	63	51.3
Moldova (the Republic of)	MDA		LLDG	101	66	65	50.5
Åland Islands	ALA	Europe: Northern Europe	DVD	-	-	-	-
Denmark	DNK			175	17.2	1	100
Estonia	EST			148	38.5	26	76.5

Faroe Islands (the)	FRO			-	-	-	-
Finland	FIN			178	14.6	6	95.3
Iceland	ISL			174	17.8	21	85.9
Ireland	IRL			168	19.9	10	91.4
Isle of Man	IMN			-	-	-	-
Latvia	LVA			144	42.3	37	68.5
Lithuania	LTU			154	36.5	28	76
Norway	NOR			177	16.2	2	98.1
Svalbard and Jan Mayen	SJM			-	-	-	-
Sweden	SWE			172	18.2	7	95
United Kingdom of Great Britain and Northern Ireland (the)	GBR			150	38.3	9	91.5
Guernsey	GGY	Europe: Northern Europe: Channel Islands	DVD	-	-	-	-
Jersey	JEY			-	-	-	-
Albania	ALB	Europe: Southern Europe	DVD	119	58.8	98	34.6
Andorra	AND			-	-	-	-
Bosnia and Herzegovina	BIH			84	70.2	40	65.6
Croatia	HRV			138	46.1	38	67.4
Gibraltar	GIB			-	-	-	-
Greece	GRC			127	52.1	51	57.2
Holy See (the)	VAT			-	-	-	-
Italy	ITA			143	42.4	31	74
Malta	MLT			156	33.6	54	56.3
Montenegro	MNE			124	55.5	82	42.1
Portugal	PRT			165	23.5	25	76.8
San Marino	SMR			-	-	-	-
Serbia	SRB			100	66.1	64	50.7
Slovenia	SVN			163	25.8	39	67.1
Spain	ESP			146	40.4	20	86.8
North Macedonia	MKD		LLDG	113	62.1	97	35.2
Austria	AUT	Europe: Western Europe	DVD	164	24.1	8	94.2
Belgium	BEL			161	27.1	14	90.1
France	FRA			160	30.5	17	89.3
Germany	DEU			166	23.2	4	96.2
Liechtenstein	LIE			-	-	-	-
Luxembourg	LUX			170	18.8	3	96.7
Monaco	MCO			-	-	-	-
Netherlands (the)	NLD			167	22.9	16	89.5
Switzerland	CHE			176	17.1	5	96.2
Australia	AUS	Oceania: Australia & New Zealand	DVD	169	19.7	13	90.3
Christmas Island	CXR			-	-	-	-
Cocos (Keeling) Islands (the)	CCK			-	-	-	-
New Zealand	NZL			173	17.9	118	24.7
Norfolk Island	NFK			-	-	-	-
Fiji	FJI	Oceania: Melanesia	SIDG	87	69.9	-	-
New Caledonia	NCL			-	-	-	-
Papua New Guinea	PNG			50	82.3	-	-
Solomon Islands	SLB			56	79.7	-	-
Vanuatu	VUT			-	-	-	-
Guam	GUM	Oceania: Micronesia	SIDG	-	-	-	-
Kiribati	KIR			-	-	-	-
Marshall Islands (the)	MHL			-	-	-	-
Micronesia (Federated States of)	FSM			79	71.2	-	-
Nauru	NRU			-	-	-	-

Northern Mariana Islands (the)	MNP			-	-	-	-
Palau	PLW			-	-	-	-
Pitcairn	PCN	Oceania: Polynesia	ODG	-	-	-	-
Tokelau	TKL			-	-	-	-
Wallis and Futuna	WLF			-	-	-	-
American Samoa	ASM		SIDG	-	-	-	-
Cook Islands (the)	COK			-	-	-	-
French Polynesia	PYF			-	-	-	-
Niue	NIU			-	-	-	-
Samoa	WSM			112	63.3	-	-
Tonga	TON			-	-	-	-
Tuvalu	TUV			-	-	-	-

Table B.2: List of countries excluded from the model

ISO 3166 English short name	ISO 3166 alpha-3 code	UNSD M49 geographic region	UNSD M49 based classification
Antarctica	ATA	Antarctica	-
Bouvet Island	BVT*	Americas: Latin America & the Caribbean: South America	-
British Indian Ocean Territory (the)	IOT*	Africa: Sub-Saharan Africa: Eastern Africa	-
French Southern Territories (the)	ATF*		-
Heard Island and McDonald Islands	HMD*	Oceania: Australia & New Zealand	-
South Georgia and the South Sandwich Islands	SGS*	Americas: Latin America & the Caribbean: South America	-
United States Minor Outlying Islands (the)	UMI*	Oceania: Micronesia	-

* Although not explicitly included due to not having a permanent civilian population, the landmass of this ISO 3166 defined country is implicitly included as an overseas territory of an explicitly included country in mapping the shapefile 'geo-units' to the model country list as presented in Table B.3.

Table B.3: Documentation of shape file 'geounits' mapped to the model countries

Model country	Geo-unit name	Geo-unit GU_A3 code	Geo-unit to model country mapping specifics
ABW	Aruba	ABW	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
AFG	Afghanistan	AFG	
AGO	Angola	AGO	
AIA	Anguilla	AIA	
ALA	Aland	ALD	
ALB	Albania	ALB	
AND	Andorra	AND	
ARE	United Arab Emirates	ARE	
ARG	Argentina	ARG	
ARM	Armenia	ARM	
ASM	American Samoa	ASM	
ATG	Antigua	ACA	Geounit is a component area of 1 of 242 ISO 3166 defined countries explicitly included in the model.
	Barbuda	ACB	
AUS	Ashmore and Cartier Islands	ATC	Geounit is an overseas territory of 1 of 242 ISO 3166 defined countries explicitly included in the model; landmass is mapped to sovereign country.
	Australia	AUS	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
	Coral Sea Islands	CSI	Geounit is an overseas territory of 1 of 242 ISO 3166 defined countries explicitly included in the model; landmass is mapped to sovereign country.
	Heard Island and McDonald Islands	HMD	Geounit is 1 of 7 ISO 3166 defined countries (coded HMD) not explicitly included in the model but that is an overseas territory of 1 of 242 ISO 3166 defined countries explicitly included in the model; landmass is mapped to sovereign country.
AUT	Austria	AUT	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
AZE	Azerbaijan	AZE	
BDI	Burundi	BDI	
BEL	Brussels Capital Region	BCR	Geounit is a component area of 1 of 242 ISO 3166 defined countries explicitly included in the model
	Flemish Region	BFR	
	Walloon Region	BWR	
BEN	Benin	BEN	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
BES	Caribbean Netherlands	NLY	
BFA	Burkina Faso	BFA	
BGD	Bangladesh	BGD	

BGR	Bulgaria	BGR	
BHR	Bahrain	BHR	
BHS	The Bahamas	BHS	
BIH	Bosnia and Herzegovina	BHF	Geounit is a component area of 1 of 242 ISO 3166 defined countries explicitly included in the model.
	Brcko District	BHB	
	Republic Srpska	BIS	
BLM	Saint Barthelemy	BLM	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
BLR	Belarus	BLR	
BLZ	Belize	BLZ	
BMU	Bermuda	BMU	
BOL	Bolivia	BOL	
BRA	Brazil	BRA	
BRB	Barbados	BRB	
BRN	Brunei	BRN	
BTN	Bhutan	BTN	
BWA	Botswana	BWA	
CAF	Central African Republic	CAF	
CAN	Canada	CAN	
CCK	Cocos (Keeling) Islands	CCK	
CHE	Switzerland	CHE	
CHL	Chile	CHL	
CHN	China	CHN	
	Paracel Islands	PFA	Geounit is a disputed territory currently under administration of 1 of 242 ISO 3166 defined countries explicitly included in the model; landmass is mapped to administering country.
	Scarborough Reef	SCR	
CIV	Ivory Coast	CIV	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
CMR	Cameroon	CMR	
COD	Democratic Republic of the Congo	COD	
COG	Republic of the Congo	COG	
COK	Cook Islands	COK	
COL	Bajo Nuevo Bank (Petrel Is.)	BJN	Geounit is a disputed territory currently under administration of 1 of 242 ISO 3166 defined countries explicitly included in the model; landmass is mapped to administering country.
	Colombia	COL	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
	Serranilla Bank	SER	Geounit is a disputed territory currently under administration of 1 of 242 ISO 3166 defined countries explicitly included in the model; landmass is mapped to administering country.
COM	Comoros	COM	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
CPV	Cabo Verde	CPV	
CRI	Costa Rica	CRI	
CUB	Cuba	CUB	
	US Naval Base Guantanamo Bay	USG	Geounit is under a lease arrangement between 2 of 242 ISO 3166 defined countries explicitly included in the model; landmass is mapped to leasing country.
CUW	Curaçao	CUW	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
CXR	Christmas Island	CXR	
CYM	Cayman Islands	CYM	
CYP	Cyprus	CYP	
	Northern Cyprus	CYN	Geounit is a component area of 1 of 242 ISO 3166 defined countries explicitly included in the model.
CZE	Czechia	CZE	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
DEU	Germany	DEU	
DJI	Djibouti	DJI	
DMA	Dominica	DMA	
DNK	Denmark	DNK	
DOM	Dominican Republic	DOM	
DZA	Algeria	DZA	
ECU	Ecuador	ECU	
EGY	Egypt	EGY	
ERI	Eritrea	ERI	
ESH	Western Sahara	SAH	
ESP	Spain	ESP	
EST	Estonia	EST	
ETH	Ethiopia	ETH	
FIN	Finland	FIN	
FJI	Fiji	FJI	
FLK	Falkland Islands	FLK	
FRA	Clipperton Island	CLP	Geounit is an overseas territory of 1 of 242 ISO 3166 defined countries explicitly included in the model; landmass is mapped to sovereign country.
	France	FXX	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
	French Southern and Antarctic Lands	ATF	Geounit is 1 of 7 ISO 3166 defined countries (coded ATF) not explicitly included in the model but that is an overseas territory of 1 of 242 ISO 3166 defined countries explicitly included in the model; landmass is mapped to sovereign country.

FRO	Faroe Islands	FRO	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
FSM	Federated States of Micronesia	FSM	
GAB	Gabon	GAB	
GBR	Akrotiri Sovereign Base Area	WSB	Geounit is an overseas territory of 1 of 242 ISO 3166 defined countries explicitly included in the model; landmass is mapped to sovereign country.
	British Indian Ocean Territory	IOT	Geounit is 1 of 7 ISO 3166 defined countries (coded IOT) not explicitly included in the model but that is an overseas territory of 1 of 242 ISO 3166 defined countries explicitly included in the model; landmass is mapped to sovereign country.
	Dhekelia Sovereign Base Area	ESB	Geounit is an overseas territory of 1 of 242 ISO 3166 defined countries explicitly included in the model; landmass is mapped to sovereign country.
	England	ENG	Geounit is a component area of 1 of 242 ISO 3166 defined countries explicitly included in the model.
	Northern Ireland	NIR	
	Scotland	SCT	
	South Georgia and the Islands	SGS	Geounit is 1 of 7 ISO 3166 defined countries (coded SGS) not explicitly included in the model but that is an overseas territory of 1 of 242 ISO 3166 defined countries explicitly included in the model; landmass is mapped to sovereign country.
	Wales	WLS	Geounit is a component area of 1 of 242 ISO 3166 defined countries explicitly included in the model.
GEO	Ajaria	GEA	
	Georgia	GEG	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
GGY	Guernsey	GGY	
GHA	Ghana	GHA	
GIB	Gibraltar	GIB	
GIN	Guinea	GIN	
GLP	Guadeloupe	GLP	
GMB	Gambia	GMB	
GNB	Guinea-Bissau	GNB	
GNQ	Equatorial Guinea	GNQ	
GRC	Greece	GRC	
GRD	Grenada	GRD	
GRL	Greenland	GRL	
GTM	Guatemala	GTM	
GUF	French Guiana	GUF	
GUM	Guam	GUM	
GUY	Guyana	GUY	
HKG	Hong Kong S.A.R.	HKG	
HND	Honduras	HND	
HRV	Croatia	HRV	
HTI	Haiti	HTI	
HUN	Hungary	HUN	
IDN	Indonesia	IDN	
IMN	Isle of Man	IMN	
IND	India	IND	
	Siachen Glacier	KAS	Geounit is a disputed territory currently under administration of 1 of 242 ISO 3166 defined countries explicitly included in the model; landmass is mapped to administering country.
IRL	Ireland	IRL	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
IRN	Iran	IRN	
IRQ	Iraq	IRR	
	Iraqi Kurdistan	IRK	Geounit is a component area of 1 of 242 ISO 3166 defined countries explicitly included in the model.
ISL	Iceland	ISL	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model
ISR	Israel	ISR	
ITA	Italy	ITA	
JAM	Jamaica	JAM	
JEY	Jersey	JEY	
JOR	Jordan	JOR	
JPN	Japan	JPN	
KAZ	Baykonur Cosmodrome	KAB	Geounit is under a lease arrangement between 2 of 242 ISO 3166 defined countries explicitly included in the model; landmass is mapped to leasing country.
	Kazakhstan	KAZ	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
KEN	Kenya	KEN	
KGZ	Kyrgyzstan	KGZ	
KHM	Cambodia	KHM	
KIR	Kiribati	KIR	
KNA	Saint Kitts and Nevis	KNA	
KOR	South Korea	KOR	
KWT	Kuwait	KWT	
LAO	Laos	LAO	
LBN	Lebanon	LBN	
LBR	Liberia	LBR	
LBY	Libya	LBY	
LCA	Saint Lucia	LCA	

LIE	Liechtenstein	LIE	
LKA	Sri Lanka	LKA	
LSO	Lesotho	LSO	
LTU	Lithuania	LTU	
LUX	Luxembourg	LUX	
LVA	Latvia	LVA	
MAC	Macao S.A.R	MAC	
MAF	Saint Martin	MAF	
MAR	Morocco	MAR	
MCO	Monaco	MCO	
MDA	Moldova	MDA	
MDG	Madagascar	MDG	
MDV	Maldives	MDV	
MEX	Mexico	MEX	
MHL	Marshall Islands	MHL	
MKD	Macedonia	MKD	
MLI	Mali	MLI	
MLT	Malta	MLT	
MMR	Myanmar	MMR	
MNE	Montenegro	MNE	
MNG	Mongolia	MNG	
MNP	Northern Mariana Islands	MNP	
MOZ	Mozambique	MOZ	
MRT	Mauritania	MRT	
MSR	Montserrat	MSR	
MTQ	Martinique	MTQ	
MUS	Mauritius	MUS	
MWI	Malawi	MWI	
MYS	Malaysia	MYS	
MYT	Mayotte	MYT	
NAM	Namibia	NAM	
NCL	New Caledonia	NCL	
NER	Niger	NER	
NFK	Norfolk Island	NFK	
NGA	Nigeria	NGA	
NIC	Nicaragua	NIC	
NIU	Niue	NIU	
NLD	Netherlands	NLX	
NOR	Bouvet Island	BVT	Geounit is 1 of 7 ISO 3166 defined countries (coded BVT) not explicitly included in the model but that is an overseas territory of 1 of 242 ISO 3166 defined countries explicitly included in the model; landmass is mapped to sovereign country.
	Norway	NOW	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
NPL	Nepal	NPL	
NRU	Nauru	NRU	
NZL	New Zealand	NZL	
OMN	Oman	OMN	
PAK	Pakistan	PAK	
PAN	Panama	PAN	
PCN	Pitcairn Islands	PCN	
PER	Peru	PER	
PHL	Philippines	PHL	
PLW	Palau	PLW	
PNG	Bougainville	PNB	Geounit is a component area of 1 of 242 ISO 3166 defined countries explicitly included in the model.
	Papua New Guinea	PNX	
POL	Poland	POL	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
PRI	Puerto Rico	PRI	
PRK	North Korea	PRK	
PRT	Azores	PAZ	Geounit is a component area of 1 of 242 ISO 3166 defined countries explicitly included in the model.
	Madeira	PMD	
	Portugal	PRX	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
PRY	Paraguay	PRY	
PSE	Gaza	GAZ	Geounit is a component area of 1 of 242 ISO 3166 defined countries explicitly included in the model.
	West Bank	WEB	
PYF	French Polynesia	PYF	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
QAT	Qatar	QAT	
REU	Reunion	REU	
ROU	Romania	ROU	
RUS	Russia	RUS	
RWA	Rwanda	RWA	
SAU	Saudi Arabia	SAU	
SDN	Sudan	SDN	

SEN	Senegal	SEN	
SGP	Singapore	SGP	
SHN	Saint Helena	SHN	
SJM	Jan Mayen	NJM	Geounit is a component area of 1 of 242 ISO 3166 defined countries explicitly included in the model.
	Svalbard	NSV	
SLB	Solomon Islands	SLB	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model
SLE	Sierra Leone	SLE	
SLV	El Salvador	SLV	
SMR	San Marino	SMR	
SOM	Puntland	SOP	Geounit is a component area of 1 of 242 ISO 3166 defined countries explicitly included in the model.
	Somalia	SOX	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
	Somaliland	SOL	Geounit is a component area of 1 of 242 ISO 3166 defined countries explicitly included in the model.
SPM	Saint Pierre and Miquelon	SPM	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
SRB	Kosovo	KOS	Geounit is a component area of 1 of 242 ISO 3166 defined countries explicitly included in the model.
	Serbia	SRS	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
	Vojvodina	SRV	Geounit is a component area of 1 of 242 ISO 3166 defined countries explicitly included in the model.
SSD	South Sudan	SDS	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
STP	São Tomé and Principe	STP	
SUR	Suriname	SUR	
SVK	Slovakia	SVK	
SVN	Slovenia	SVN	
SWE	Sweden	SWE	
SWZ	eSwatini	SWZ	
SXM	Sint Maarten	SXM	
SYC	Seychelles	SYC	
SYR	Syria	SYX	
TCA	Turks and Caicos Islands	TCA	
TCD	Chad	TCD	
TGO	Togo	TGO	
THA	Thailand	THA	
TJK	Tajikistan	TJK	
TKL	Tokelau	TKL	
TKM	Turkmenistan	TKM	
TLS	East Timor	TLS	
TON	Tonga	TON	
TTO	Trinidad and Tobago	TTO	
TUN	Tunisia	TUN	
TUR	Turkey	TUR	
TUV	Tuvalu	TUV	
TWN	Taiwan	TWN	
TZA	Tanzania	TZA	
	Zanzibar	TZZ	Geounit is a component area of 1 of 242 ISO 3166 defined countries explicitly included in the model.
UGA	Uganda	UGA	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model
UKR	Ukraine	UKR	
URY	Uruguay	URY	
USA	Baker Island	FQI	Geounit is 1 of 7 ISO 3166 defined countries (coded UMI) not explicitly included in the model but that is an overseas territory of 1 of 242 ISO 3166 defined countries explicitly included in the model; landmass is mapped to sovereign country.
	Howland Island	HQI	
	Jarvis Island	DQI	
	Johnston Atoll	JQI	
	Kingman Reef	KQI	
	Midway Islands	MQI	
	Navassa Island	BQI	
	Palmyra Atoll	LQI	
	United States of America	USA	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
	Wake Atoll	WQI	Geounit is 1 of 7 ISO 3166 defined countries (coded UMI) not explicitly included in the model but that is an overseas territory of 1 of 242 ISO 3166 defined countries explicitly included in the model; landmass is mapped to sovereign country.
UZB	Uzbekistan	UZB	Geounit is 1 of 242 ISO 3166 defined countries explicitly included in the model.
VAT	Vatican	VAT	
VCT	Saint Vincent and the Grenadines	VCT	
VEN	Venezuela	VEN	
VGB	British Virgin Islands	VGB	
VIR	United States Virgin Islands	VIR	
VNM	Vietnam	VNM	
VUT	Vanuatu	VUT	
WLF	Wallis and Futuna	WLF	
WSM	Samoa	WSM	

YEM	Yemen	YEM	
ZAF	South Africa	ZAF	
ZMB	Zambia	ZMB	
ZWE	Zimbabwe	ZWE	
-	Antarctica	ATA	Not mapped. Geounit is 1 of 7 ISO 3166 defined countries (coded ATA) not explicitly included in the model and landmass is not implicitly included in the model under a sovereign country as it is administered by multiple countries under Antarctic Treaty.
-	Cyprus No Mans Area	CNM	Not mapped. Geounit is a demilitarized zone (UN Buffer Zone in Cyprus).
-	Korean Demilitarized Zone (north)	KNZ	Not mapped. Geounit is a demilitarized zone (Korean Demilitarized Zone).
-	Korean Demilitarized Zone (south)	KNX	
-	Spratly Islands	PGA	Not mapped. Geounit is a disputed territory administered by multiple countries.
-	UNDOF	SYU	Not mapped. Geounit is a demilitarized zone (United Nations Disengagement Observer Force).

B.2 Chapter 4 & 5: *population_historical*

Step 1. A raw data file was downloaded from the World Population Prospects database (UNDESA 2019): (1.) Download Data Files; (2.) Files: Total Population – Both Sexes. This file contains total population (units of thousands of persons) estimates for countries and regions in yearly increments from 1950 to 2020.

Step 2. Total population values for year 2000 to 2020 were mapped to the country list (Table B.1) to obtain a working dataset, i.e. values in the dataset corresponding to one of the 242 country definitions were included, while those not corresponding to a country definition were excluded.

Step 3. The working dataset was cleaned by identifying incomplete total population values for each of the 242 countries over the 2000-to-2020-year period and then performing remediation calculations/making assumptions to populate missing values. 231 countries required no further data cleaning and 11 countries required further data cleaning, as summarised in Table B.4.

Step 4. Units were converted from thousands of persons to persons to obtain the input dataset.

Table B.4: Documentation of raw data to final input data cleaning issues for population_historical

Raw data issue	General remediation / assumption approach	Model country	Country specific aspects of data cleaning
1. Missing all total population values for this country.	1-a. Missing values were populated by: identifying total population information from official census-based sources; linearly extrapolating from and/or interpolating between known/identified total population value(s); and, then rounding these total population values to the nearest thousand to be consistent with the working dataset unless otherwise specified in country specific notes.	ALA	Values for year 2000 to 2019 were sourced from (eurostat 2021). Value for year 2020 was calculated by extrapolating from the known 2000 to 2019 values.
		CCK	Values for year 2001, 2006, 2011 and 2016 were sourced from (Australian Bureau of Statistics 2021). Values for year 2000, 2002 to 2005, 2007 to 2010, 2012 to 2015 and 2017 to 2020 were calculated by interpolating between/extrapolating from the known 2001, 2006, 2011 and 2016 values. These values were then rounded to the nearest hundred, as rounding to the nearest thousand resulted in zero values.
		CXR	Values for year 2001, 2006, 2011 and 2016 were sourced from (Australian Bureau of Statistics 2021). Values for year 2000, 2002 to 2005, 2007 to 2010, 2012 to 2015 and 2017 to 2020 were calculated by interpolating between/extrapolating from the known 2001, 2006, 2011 and 2016 values.
		GGY	Values for year 2001 and 2009 to 2020 were sourced from (States of Guernsey 2021). Values for year 2000 and 2002 to 2008 were calculated by interpolating between/extrapolating from the known 2001 and 2009 to 2020 values.
		JEY	Values for year 2001 to 2011 were sourced from (States of Jersey 2021). Values for year 2000 and 2002 to 2010 were calculated by interpolating between/extrapolating from the known 2001 and 2011 values. Values for the year 2012 to 2020 were calculated by subtracting the respective value for GGY (above) from the respective value for the 'Channel Islands' region, consisting of JEY and GGY, recorded in the WPP (2019) data set.
		NFK	Values for year 2001, 2006, 2011 and 2016 were sourced from (Australian Bureau of Statistics 2021). Values for year 2000, 2002 to 2005, 2007 to 2010, 2012 to 2015 and 2017 to 2020 were calculated by interpolating between/extrapolating from the known 2001, 2006, 2011 and 2016 values.
		PCN	Values for year 2000 to 2020 were sourced from (SDD 2021). These values were then rounded to the nearest ten, as rounding to the nearest thousand resulted in zero values.
		SJM	Values for year 2009 to 2020 were sourced from (Statistics Norway 2021). Values for year 2000 to 2008 were calculated by extrapolating from the known 2009 to 2020 values.

2. Contains complete total population values for this country, however, these values include the population of one or more Country units identified in Raw Data Issue 1 as overseas territories.	2-a. Calculated values of included overseas territories identified in Raw Data Issue 1 subtracted from this country's raw data value.	AUS	Values for AUS for year 2000 to 2020 had the respective CCK, CXR and NFK value subtracted.
		FIN	Values for FIN for year 2000 to 2020 had the respective ALA value subtracted.
		NOR	Values for NOR for year 2000 to 2020 had the respective SJM value subtracted.

B.3 Chapter 4 & 5: *gdp_pc_historical*

Step 1. A raw data file was downloaded from the WDI database (The World Bank 2021): (1.) Database: World Development Indicators; (2.) Country: select all; (3.) Series: GDP per capita, PPP (constant 2017 international dollars); (4.) Time: 2000 - 2020. This file contains GDP|PPP per capita (in units of constant 2017 international dollars) estimates for countries and regions in yearly increments from 2000 to 2020.

Step 2. GDP|PPP per capita values for year 2000 to 2020 were mapped to the country list (Table B.1) to obtain a working dataset, i.e. values in the dataset corresponding to one of the 242 country definitions were included, while those not corresponding to a country definition were excluded.

Step 3. The working dataset was cleaned by identifying incomplete total population values for each of the 242 countries over the 2000-to-2020-year period and then performing remediation calculations/ making assumptions to populate missing values to obtain the input dataset. 172 countries required no further data cleaning and 70 countries required further data cleaning, as summarised in Table B.5.

Table B.5: Documentation of raw data to final input data cleaning issues for gdp_pc_historical

Raw data issue	General remediation / assumption approach	Model country	Country specific aspects of data cleaning
1. Missing some GDP|PPP per capita values for this country.	1-a. Missing values populated by extrapolating from the respective country's known GDP per capita value using a constant ratio to the average GDP PPP per capita value of other countries with complete values in the raw data set that belong to the same geographic region.	ABW	Values for year 2018 to 2020 populated by extrapolation from known 2017 value.
		AFG	Values for year 2000 to 2001 populated by extrapolation from known 2002 value.
		ARE	Value for year 2020 populated by extrapolation from known 2019 value.
		BMU	
		CUW	
		CYM	Values for year 2000 to 2005 populated by extrapolation from known 2006 value. Value for year 2020 populated by extrapolation from known 2019 value.
		DJI	Values for year 2000 to 2012 populated by extrapolation from known 2013 value.
		FSM	Value for year 2020 populated by extrapolation from known 2019 value.
		JPN	
		KWT	
		MHL	
		NRU	Values for year 2000 to 2003 populated by extrapolation from known 2004 value. Value for year 2020 populated by extrapolation from known 2019 value.
		OMN	Value for year 2020 populated by extrapolation from known 2019 value.
		PLW	
		SMR	
		SOM	Values for year 2000 to 2012 populated by extrapolation from known 2013 value.
		STP	Value for year 2000 populated by extrapolation from known 2001 value.
		SXM	Values for year 2000 to 2008 populated by extrapolation from known 2009 value. Values for year 2019 to 2020 populated by extrapolation from known 2018 value.
		TCA	Values for year 2000 to 2010 populated by extrapolation from known 2011 value.
		TKM	Value for year 2020 populated by extrapolation from known 2019 value.
		TON	
2. Missing all GDP|PPP per capita values for this country.	2-a. Missing values populated by: identifying GDP per capita information from official sources;	AIA	Value for year 2008 was sourced from (CIA 2021a): GDP|PPP per capita $12,200 in 2008 dollars converted to $14,023 in 2017 dollars. Values for year 2000 to 2007 and 2009 to 2020 populated by extrapolation from known 2008 value.
		ALA	Value for year 2015 was sourced from (OECD 2021): GDP|PPP per capita $52,787 in 2015 dollars converted to $54,275 in 2017 dollars. Values for year 2000 to 2014 and 2016 to 2020 populated by extrapolation from known 2015 value.

	converting identified GDP per capita value to PPP and/or 2017 international dollars as required; and, then extrapolating from this known GDP per capita value using a constant ratio to the average GDP|PPP per capita value of other countries with complete values in the raw data set that belong to the same geographic region.	AND	Value for year 2015 was sourced from (CIA 2021a): GDP|PPP per capita $49,900 in 2015 dollars converted to $51,307 in 2017 dollars. Values for year 2000 to 2014 and 2016 to 2020 populated by extrapolation from known 2015 value.
		ASM	Value for year 2016 was sourced from (CIA 2021a): GDP|PPP per capita $11,200 in 2016 dollars converted to $11,432 in 2017 dollars. Values for year 2000 to 2015 and 2017 to 2020 populated by extrapolation from known 2016 value.
		COK	Value for year 2016 was sourced from (CIA 2021a): GDP|PPP per capita $16,700 in 2016 dollars converted to $17,046 in 2017 dollars. Values for year 2000 to 2015 and 2017 to 2020 populated by extrapolation from known 2016 value.
		CUB	Value for year 2016 was sourced from (CIA 2021a): GDP|PPP per capita $12,300 in 2016 dollars converted to $12,555 in 2017 dollars. Values for year 2000 to 2015 and 2017 to 2020 populated by extrapolation from known 2016 value.
		ERI	Value for year 2017 was sourced from (CIA 2021a): GDP|PPP per capita $1,600 in 2017 dollars. Values for year 2000 to 2016 and 2018 to 2020 populated by extrapolation from known 2017 value.
		ESH	Value for year 2007 was sourced from (CIA 2020): GDP|PPP per capita $2,500 in 2007 dollars converted to $2,991 in 2017 dollars. Values for year 2000 to 2006 and 2008 to 2020 populated by extrapolation from known 2007 value.
		FLK	Value for year 2015 was sourced from (CIA 2021a): GDP|PPP per capita $70,800 in 2015 dollars converted to $72,796 in 2017 dollars. Values for year 2000 to 2014 and 2016 to 2020 populated by extrapolation from known 2015 value.
		FRO	Value for year 2014 was sourced from (CIA 2021a): GDP|PPP per capita $40,000 in 2014 dollars converted to $41,439 in 2017 dollars. Values for year 2000 to 2013 and 2015 to 2020 populated by extrapolation from known 2014 value.
		GGY	Value for year 2014 was sourced from (CIA 2021a): GDP|PPP per capita $52,500 in 2014 dollars converted to $54,388 in 2017 dollars. Values for year 2000 to 2013 and 2015 to 2020 populated by extrapolation from known 2014 value.
		GIB	Value for year 2014 was sourced from (CIA 2021a): GDP|PPP per capita $61,700 in 2014 dollars converted to $63,919 in 2017 dollars. Values for year 2000 to 2013 and 2015 to 2020 populated by extrapolation from known 2014 value.
		GLP	Value for year 2015 was sourced from (OECD 2021): GDP|PPP per capita $24,555 in 2015 dollars converted to $25,247 in 2017 dollars. Values for year 2000 to 2014 and 2016 to 2020 populated by extrapolation from known 2015 value.
		GRL	Value for year 2015 was sourced from (CIA 2021a): GDP|PPP per capita $41,800 in 2015 dollars converted to $42,978 in 2017 dollars. Values for year 2000 to 2014 and 2016 to 2020 populated by extrapolation from known 2015 value.
		GUF	Value for year 2015 was sourced from (OECD 2021): GDP|PPP per capita $18,660 in 2015 dollars converted to $19,186 in 2017 dollars. Values for year 2000 to 2014 and 2016 to 2020 populated by extrapolation from known 2015 value.
		GUM	Value for year 2016 was sourced from (CIA 2021a): GDP|PPP per capita $35,600 in 2016 dollars converted to $36,339 in 2017 dollars. Values for year 2000 to 2015 and 2017 to 2020 populated by extrapolation from known 2016 value.
		IMN	Value for year 2014 was sourced from (CIA 2021a): GDP|PPP per capita $84,600 in 2014 dollars converted to $87,643 in 2017 dollars. Values for year 2000 to 2013 and 2015 to 2020 populated by extrapolation from known 2014 value.
		JEY	Value for year 2016 was sourced from (CIA 2021a): GDP|PPP per capita $56,600 in 2016 dollars converted to $57,774 in 2017 dollars. Values for year 2000 to 2015 and 2017 to 2020 populated by extrapolation from known 2016 value.
		LIE	Value for year 2009 was sourced from (CIA 2021a): GDP|PPP per capita $139,100 in 2009 dollars converted to $159,746 in 2017 dollars. Values for year 2000 to 2008 and 2010 to 2020 populated by extrapolation from known 2009 value.
		MAF	Value for year 2005 was sourced from (CIA 2021a): GDP|PPP per capita $19,300 in 2005 dollars converted to $24,486 in 2017 dollars. Values for year 2000 to 2004 and 2006 to 2020 populated by extrapolation from known 2005 value.
		MCO	Value for year 2015 was sourced from (CIA 2021a): GDP|PPP per capita $115,700 in 2015 dollars converted to $118,962 in 2017 dollars. Values for year 2000 to 2014 and 2016 to 2020 populated by extrapolation from known 2015 value.
		MNP	Value for year 2016 was sourced from (CIA 2021a): GDP|PPP per capita $24,500 in 2016 dollars converted to $25,008 in 2017 dollars. Values for year 2000 to 2015 and 2017 to 2020 populated by extrapolation from known 2016 value.
		MSR	Value for year 2011 was sourced from (CIA 2021a): GDP|PPP per capita $34,000 in 2011 dollars converted to $37,452 in 2017 dollars. Values for year 2000 to 2010 and 2012 to 2020 populated by extrapolation from known 2011 value.
		MTQ	Value for year 2015 was sourced from (OECD 2021): GDP|PPP per capita $28,321 in 2015 dollars converted to $29,119 in 2017 dollars. Values for year 2000 to 2014 and 2016 to 2020 populated by extrapolation from known 2015 value.
		MYT	Value for year 2015 was sourced from (OECD 2021): GDP|PPP per capita $10,866 in 2015 dollars converted to $11,172 in 2017 dollars. Values for year 2000 to 2015 and 2016 to 2020 populated by extrapolation from known 2015 value.
		NCL	Value for year 2015 was sourced from (CIA 2021a): GDP|PPP per capita $31,100 in 2015 dollars converted to $31,977 in 2017 dollars. Values for year 2000 to 2014 and 2016 to 2020 populated by extrapolation from known 2015 value.

		NIU	Value for year 2003 was sourced from (CIA 2021a): GDP|PPP per capita $5,800 in 2003 dollars converted to $7,741 in 2017 dollars. Values for year 2000 to 2002 and 2004 to 2020 populated by extrapolation from known 2003 value.
		PCN	Value for year 2005 was sourced from (Government of the Pitcairn Islands 2013): GDP per capita NZ$4,340 in 2005 New Zealand dollars converted to GDP|PPP per capita $3,854 in 2017 dollars using 2005 exchange rate of 0.7. Values for year 2000 to 2004 and 2006 to 2020 populated by extrapolation from known 2005 value.
		PRK	Value for year 2015 was sourced from (CIA 2021a): GDP|PPP per capita $1,700 in 2015 dollars converted to $1,748 in 2017 dollars. Values for year 2000 to 2014 and 2016 to 2020 populated by extrapolation from known 2015 value.
		PYF	Value for year 2015 was sourced from (CIA 2021a): GDP|PPP per capita $17,000 in 2015 dollars converted to $17,479 in 2017 dollars. Values for year 2000 to 2014 and 2016 to 2020 populated by extrapolation from known 2015 value.
		REU	Value for year 2015 was sourced from (OECD 2021): GDP|PPP per capita $25,484 in 2015 dollars converted to $26,202 in 2017 dollars. Values for year 2000 to 2015 and 2016 to 2020 populated by extrapolation from known 2015 value.
		SHN	Value for year 2010 was sourced from (CIA 2021a): GDP|PPP per capita $7,800 in 2010 dollars converted to $8,720 in 2017 dollars. Values for year 2000 to 2009 and 2011 to 2020 populated by extrapolation from known 2010 value.
		SPM	Value for year 2006 was sourced from (CIA 2021a): GDP|PPP per capita $46,200 in 2006 dollars converted to $56,678 in 2017 dollars. Values for year 2000 to 2005 and 2007 to 2020 populated by extrapolation from known 2006 value.
		SSD	Value for year 2017 was sourced from (CIA 2021a): GDP|PPP per capita $1,600 in 2017 dollars. Values for year 2000 to 2016 and 2018 to 2020 populated by extrapolation from known 2017 value.
		SYR	Value for year 2015 was sourced from (CIA 2021a): GDP|PPP per capita $2,900 in 2015 dollars converted to $2,982 in 2017 dollars. Values for year 2000 to 2014 and 2016 to 2020 populated by extrapolation from known 2015 value.
		TKL	Value for year 2017 was sourced from (CIA 2021a): GDP|PPP per capita $6,004 in 2017 dollars. Values for year 2000 to 2016 and 2018 to 2020 populated by extrapolation from known 2017 value.
		TWN	Value for year 2018 was sourced from (CIA 2021a): GDP|PPP per capita $24,502 in 2018 dollars converted to $23,906 in 2017 dollars. Values for year 2000 to 2017 and 2019 to 2020 populated by extrapolation from known 2018 value.
		VEN	Value for year 2018 was sourced from (CIA 2021a): GDP|PPP per capita $7,704 in 2018 dollars converted to $7,517 in 2017 dollars. Values for year 2000 to 2017 and 2019 to 2020 populated by extrapolation from known 2018 value.
		VGB	Value for year 2017 was sourced from (CIA 2021a): GDP|PPP per capita $34,200 in 2017 dollars. Values for year 2000 to 2016 and 2018 to 2020 populated by extrapolation from known 2017 value.
		VIR	Value for year 2016 was sourced from (CIA 2021a): GDP|PPP per capita $37,000 in 2016 dollars converted to $37,768 in 2017 dollars. Values for year 2000 to 2015 and 2017 to 2020 populated by extrapolation from known 2016 value.
		WLF	Value for year 2004 was sourced from (CIA 2021a): GDP|PPP per capita $3,800 in 2004 dollars converted to $4,978 in 2017 dollars. Values for year 2000 to 2003 and 2005 to 2020 populated by extrapolation from known 2004 value.
		YEM	Value for year 2017 was sourced from (CIA 2021a): GDP|PPP per capita $2,500 in 2017 dollars. Values for year 2000 to 2016 and 2018 to 2020 populated by extrapolation from known 2017 value.
	2-b. Due to lack of GDP per capita data identified in official sources as per (2-a.), missing values for year 2000 to 2020 populated by calculating the average GDP|PPP per capita, in the respective year, of other countries with complete values in the raw data set that belong to the same geographic region.	BES	Geographic regions as per Table B.1.
		BLM	
		CCK	
		CXR	
		NFK	
		SJM	
		VAT	

B.4 Chapter 4 & 5: *food_production_historical*

Step 1. Eight raw data files ('i' to 'viii' following) – one for each primary food crop group – were downloaded from the FAOSTAT database (FAO 2021): (1.) Domain: Production > Crop and livestock products; (2.) Countries: select all; (3.) Elements: Production Quantity; (4.) Items Aggregated: "Crops Primary > (List)" > "Cereals, Total + (Total)" *for 'i', or* "Fruit Primary + (Total)" *for 'ii',* "Oilcrops + (Total)" *for 'iii',* "Pulses, Total + (Total)" *for 'iv',* "Roots and Tubers, Total + (Total)" *for 'v',* "Sugar Crops Primary + (Total)" *for 'vi',* "Treenuts, Total + (Total)" *for 'vii',* "Vegetables Primary + (Total)" *for 'viii'*; (5.) Years: 2000 – 2019. These files contain the production quantity of the eight primary food crops, in units of tonnes as harvested, estimates for countries in yearly increments from 2000 to 2019.

Step 2. Crop group food production quantity values for year 2000 to 2019 were mapped to the country list (Table B.1) to obtain eight individual working datasets, i.e. values in the dataset corresponding to one of the 242 country definitions were included, while those not corresponding to a country definition were excluded. A value of zero was set for any missing values within these individual working datasets. A record of missing values is presented in Table B.6 (Raw Data Issue 1 and 2).

Step 3. Crop group food production quantity values in each of the eight individual working datasets were converted to energy-equivalent-grain-weight values using the respective conversion factor for the food crop group, as shown in Table B.7. The derivation of these energy-equivalent-grain-weight conversion factors is presented in Section B.8.

Step 4. A combined working dataset of total food production quantity values for each country for year 2000 to 2019 was obtained by calculating the sum of the respective component values from the eight individual crop group food production working datasets.

Step 5. Working dataset of total food production quantity values was cleaned by identifying incomplete food production values for each of the 242 countries over the 2000-to-2019-year period and performing remediation calculations/making assumptions to populate missing values. 73 countries required no further data cleaning and 163 countries required further data cleaning, summarised in Table B.6.

Step 6. Missing food production values for all countries for year 2020 were populated by extrapolating from the known 2019 values to obtain the input dataset.

Table B.6: Documentation of raw data to final input data cleaning issues for food_production_historical

Raw data issue	General remediation / assumption approach	Model country	Country specific aspects of data cleaning
1. Missing some or all food production quantity values for one or more (but not all) crops groups for this country.	1-a. Missing crop group food production quantity values found not to have a significant impact on total food production quantity, based on further research (general Google and Wikipedia searching) indicating that crop groups with missing values are not a staple for the country, therefore no modifications made.	ARE	Missing all values for oilcrops, pulses, sugarcrops.
		ARM	Missing values from year 2000 to 2003 for treenuts.
		ATG	Missing all values for pulses, treenuts, sugarcrops.
		BDI	Missing values from year 2000 to 2016 for treenuts.
		BEL	Missing values from year 2018 to 2019 for treenuts.
		BGD	Missing all values for treenuts.
		BGR	Missing values from year 2008 to 2019 for sugarcrops.
		BHR	Missing all values for cereals, oilcrops, sugarcrops.
		BHS	Missing values from year 2000 to 2009 for oilcrops and all values for treenuts.
		BIH	Missing values from year 2004 to 2005 for sugarcrops.
		BLZ	Missing values from year 2012 to 2013 and 2016-2019 for treenuts.
		BRB	Missing all values for treenuts.
		BRN	Missing all values for pulses, sugarcrops, treenuts.
		BTN	Missing values from year 2000 to 2003 and 2006 for treenuts.
		BWA	Missing all values for sugarcrops, treenuts.
		CAF	Missing all values for treenuts.
		CAN	
		COD	
		COG	
		COK	Missing all values for cereals, pulses, sugarcrops, treenuts.
		COM	Missing all values sugarcrops, treenuts.
		CPV	Missing all values for treenuts.
		CUB	Missing all values for treenuts.
		CYP	Missing all values sugarcrops.
		DEU	Missing values from year 2018 to 2019 for treenuts.
		DJI	Missing all values for oilcrops, roots and tubers, treenuts.
		DMA	Missing values from year 2014 to 2019 for treenuts.
		DNK	Missing values from year 2000 to 2003 for treenuts.
		DZA	Missing all values sugarcrops.
		ECU	Missing all values for treenuts.
		ERI	Missing all values for sugarcrops, treenuts.
		EST	
		FIN	Missing all values for treenuts.
		FJI	
		FRO	Missing all values for cereals, fruits, oilcrops, pulses, sugarcrops, treenuts, vegetables.
		FSM	Missing all values for pulses, sugarcrops, treenuts.
		GAB	Missing all values for treenuts.
		GBR	
		GEO	Missing values from year 2004 to 2019 for sugarcrops.
		GMB	Missing all values for sugarcrops and values from year 2000 to 2007 for treenuts.
		GNQ	Missing all values for cereals, pulses, sugarcrops, treenuts, vegetables.
		GRD	Missing all values for treenuts.
		GUY	
		HKG	Missing all values for cereals, oilcrops, pulses, sugarcrops, treenuts.
		HTI	Missing all values for treenuts.
		IRL	Missing values from year 2018 to 2019 for sugarcrops and all values for treenuts.
		ISL	Missing values from year 2015 to 2019 for cereals, and all values for fruits, oilcrops, pulses, sugarcrops, treenuts.
		ISR	Missing all values for sugarcrops.
		JAM	Missing all values for treenuts.
		JOR	Missing all values for sugarcrops.
		KIR	Missing all values for cereals, pulses, sugarcrops.
		KNA	Missing all values for cereals, values from year 2006 to 2019 for sugarcrops (true significant impact on total production quantity due to production of sugarcrops being ceased in 2005), and all values for treenuts.
		KOR	Missing all values for sugarcrops.
		KWT	Missing all values for pulses, sugarcrops, treenuts.
		LAO	Missing all values for treenuts.
		LBN	Missing values from year 2002 to 2004 for sugarcrops.
		LBY	Missing all values for sugarcrops.
		LCA	Missing all values for cereals, sugarcrops, treenuts.
		LSO	Missing all values for oilcrops, sugarcrops, treenuts.
		LTU	Missing all values for treenuts.
		LUX	Missing all values for sugarcrops.
		LVA	Missing values from year 2008 to 2019 for sugarcrops and all values for treenuts.
		MDV	Missing all values for sugarcrops.

		MHL	Missing all values for cereals, fruits, pulses, roots and tubers, sugarcrops, treenuts, vegetables.
		MNG	Missing values from year 2006 to 2019 for oilcrops and all values for sugarcrops.
		MRT	Missing all values for sugarcrops, treenuts.
		MUS	Missing all values for pulses.
		MYS	
		NAM	Missing all values for sugarcrops, treenuts.
		NCL	Missing values for year 2009 for pulses and all values for sugarcrops, treenuts.
		NER	Missing all values for treenuts.
		NIC	
		NIU	Missing all values for cereals, pulses, sugarcrops, treenuts.
		NLD	Missing values from year 2018 to 2019 for pulses and all values for treenuts.
		NOR	Missing values from year 2000 to 2002 for pulses and all values for sugarcrops, treenuts.
		NRU	Missing values from year 2000 to 2016 and 2019 for cereals and missing all values for pulses, roots and tubers, sugarcrops and treenuts.
		NZL	Missing all values for sugarcrops, treenuts.
		OMN	Missing all values for oilcrops and pulses, values from year 2000 to 2002 for sugarcrops, and all values for treenuts.
		PAN	Missing all values for treenuts.
		PRI	Missing values from year 2003 to 2019 for sugarcrops and all values for treenuts.
		PRK	Missing all values for sugarcrops.
		PRT	Missing values from year 2018 to 2019 for sugarcrops.
		PRY	Missing all values for treenuts.
		PSE	Missing values from year 2001 to 2019 for sugarcrops.
		PYF	Missing all values for cereals, pulses, treenuts.
		QAT	Missing all values for oilcrops, pulses, sugarcrops, treenuts.
		RWA	Missing all values for treenuts.
		SAU	Missing all values for sugarcrops, treenuts.
		SDN	Missing all values for treenuts.
		SGP	Missing all values for cereals, pulses, sugarcrops, treenuts.
		SLB	Missing all values for sugarcrops.
		SLE	Missing all values for treenuts.
		SOM	
		SSD	
		STP	Missing all values for pulses, sugarcrops, treenuts.
		SUR	Missing all values for treenuts.
		SVN	Missing values from year 2007 to 2018 for sugarcrops.
		SWE	Missing all values for treenuts.
		SYC	Missing all values for cereals, pulses, sugarcrops, treenuts.
		TCD	Missing all values for treenuts.
		TGO	Missing all values for sugarcrops.
		TJK	
		TKL	Missing all values for cereals, pulses, sugarcrops, treenuts, vegetables.
		TLS	Missing all values for sugarcrops, treenuts.
		TON	Missing all values for cereals, pulses, sugarcrops, treenuts.
		TTO	Missing values from year 2008 to 2019 for sugarcrops and all values for treenuts.
		TUN	Missing values from year 2001 to 2011 for sugarcrops.
		TUV	Missing all values for cereals, pulses, sugarcrops, treenuts.
		TWN	Missing all values for treenuts.
		UGA	
		URY	
		UZB	Missing values from year 2003 to 2019 for sugarcrops.
		VCT	Missing all values for treenuts.
		VEN	
		VUT	Missing all values for pulses, sugarcrops, treenuts.
		WSM	Missing all values for cereals, pulses, treenuts.
		YEM	Missing all values for sugarcrops.
		ZMB	Missing all values for treenuts.
	1-b. Some missing crop group food production quantity values have a significant impact on the total food production quantity values, therefore total food production quantity values are populated by	GLP	Missing all values for cereals – addressed by 1-a. Missing values for year 2007 to 2019 for all other crop groups, which are significant, therefore populated by taking the average of known values over year 2000 to 2006.
		GUF	Missing all values for pulses and treenuts – addressed by 1-a. Missing values for year 2007 to 2019 for all other crop groups, which are significant, therefore populated by taking the average of known values over year 2000 to 2006.
		MTQ	Missing all values for cereals and treenuts – addressed by 1-a. Missing values for year 2007 to 2019 for all other crop groups, which are significant, therefore populated by taking the average of known values over year 2000 to 2006.
		REU	Missing all values for treenuts – addressed by 1-a. Missing values for year 2007 to 2019 for all other crop groups, which are significant, therefore populated by taking the average of known values over year 2000 to 2006.
		MLT	Missing all values for sugarcrops and treenuts – addressed by 1-a. Missing values for year 2018 to 2019 for cereals, for year 2018 for oilcrops and for years 2018 to 2019 for

	taking average of relevant known values as noted in country specifics.		pulses, which are significant, therefore populated by taking the average of known values over year 2000 to 2017.
2. Missing all crop group (cereals, fruits, oilcrops, pulses, roots and tubers, sugarcrops, treenuts, vegetables) food production quantity values for this country.	2-a. Missing total food production quantity values for year 2000 to 2018 populated by multiplying the country's total land area by the minimum food production yield of other countries in the same region (referred to as a "land-scaled regional minimum" (LSRM)), unless otherwise noted in country specifics. The land area data preparation used in calculated LSRM is presented in Section B.7.	ABW	Limited agriculture but produces some key crops locally. Geographic region as per Table B.1.
		AIA	
		ALA	Limited agriculture but produces some key crops locally. Geographic region being Europe: Northern Europe (as per Table B.1.) excluding ISL, which is an outlier in terms of food production yield in this region due to significantly colder climate and landmass incorporating permanent ice.
		AND	Limited agriculture but produces some key crops locally. Geographic region as per Table B.1.
		ASM	
		BES	
		BLM	
		BMU	
		CCK	
		CUW	
		CXR	
		CYM	
		ESH	
		FLK	
		GGY	Limited agriculture but produces some key crops locally. All countries in actual region (as per Table B.1.) were missing values, so adopts LSRM for next closest region, being Europe: Northern Europe excluding ISL, which is an outlier in terms of food production yield in this region due to significantly colder climate and landmass incorporating permanent ice.
		GIB	Negligible traditional agriculture (0.0% of economy) as land use is urbanized, but increasingly producing some key crops locally using urban agriculture. Geographic region as per Table B.1.
		GRL	Limited agriculture but produces some key crops locally. LSRM is calculated using food production yield of ISL, which has a more relevant food production yield than GRL's actual region (as per Table B.1.) due to significantly colder climate and landmass incorporating permanent ice, and accounting for difference in permanent ice (GRL 50%, ISL 10%).
		GUM	Limited agriculture but produces some key crops locally. Geographic region as per Table B.1.
		IMN	Limited agriculture but produces some key crops locally. Geographic region as per Table B.1. but excluding ISL, which is an outlier in terms of food production yield in this region due to significantly colder climate and landmass incorporating permanent ice.
		JEY	Limited agriculture but produces some key crops locally. All countries in actual region (as per Table B.1.) were missing values, so adopts LSRM for next closest region, being Europe: Northern Europe excluding ISL, which is an outlier in terms of food production yield in this region due to significantly colder climate and landmass incorporating permanent ice.
		LIE	Limited agriculture but produces some key crops locally. Geographic region as per Table B.1.
		MAC	
		MAF	
		MCO	Negligible traditional agriculture (0.0% of economy) as land use is urbanized, but increasingly producing some key crops locally using urban agriculture. Geographic region as per Table B.1.
		MNP	Limited agriculture but produces some key crops locally. Geographic region as per Table B.1.
		MSR	
		MYT	
		NFK	
		PCN	
		PLW	
		SHN	
		SJM	Limited agriculture but produces some key crops locally. Geographic region being Europe: Northern Europe (as per Table B.1.). However, LSRM is calculated using food production yield of ISL, which has the most relevant food production yield within the region due to significantly colder climate and landmass incorporating permanent ice, and accounting for difference in permanent ice (SJM 45%, ISL 10%).
		SMR	Limited agriculture but produces some key crops locally. Geographic region as per Table B.1.
		SPM	
		SXM	
		TCA	
		VAT	Negligible traditional agriculture (0.0% of economy) as land use is urbanized, but increasingly producing some key crops locally using urban agriculture. Geographic region as per Table B.1.
		VGB	Limited agriculture but produces some key crops locally. Geographic region as per Table B.1.
		VIR	
		WLF	

Table B.7: Energy-equivalent-grain-weight conversion factors

Constituent primary food crop group	Energy-equivalent-grain-weight conversion factor
Cereals	1.013
Fruits	0.175
Oilcrops	0.953
Pulses	1.084
Roots and Tubers	0.298
Sugar Crops	0.120
Treenuts	0.681
Vegetables	0.096

B.5 Chapter 4 & 5: *food_demand_pc_historical*

Step 1. Two raw data files ('i' and 'ii' following) were downloaded from the FAOSTAT database (FAO 2021): (1.) Domain: Food Balances (-2013, old methodology and population) *for 'i', or* Food Balances (2014-) *for 'ii'*; (2.) Countries: select all; (3.) Elements: Food Supply (kcal/capita/day); (4.) Items Aggregated: Grand Total + (Total); (5.) Years: 2000 – 2013 *for 'i', or* 2014-2018 *for 'ii'*. These files contain food supply per capita, in units of kilocalories per day, estimates for countries in yearly increments from 2000 to 2018. Food supply is the food available for consumption, i.e. amount of food actually consumed not including consumption waste, which is converted into food demand in Step 6.

Step 2. Food supply per capita values for year 2000 to 2018 were mapped to the country list (Table B.1) to obtain a working dataset, i.e. values in the dataset corresponding to one of the 242 country definitions were included, while those not corresponding to a country definition were excluded.

Step 3. The working dataset of food supply per capita values was cleaned by identifying incomplete food supply per capita values for each of the 242 countries over the 2000-to-2018-year period and then performing remediation calculations/making assumptions to populate missing values. 174 countries required no further data cleaning and 68 countries required further data cleaning, as summarised in Table B.8 (Raw Data Issue 1 and 2).

Step 4. Food supply per capita units were converted from kilocalories per day to energy-equivalent-grain-weight in tonnes per year using the energy content per unit weight of grain factor defined below. The derivation of this factor is presented in Section B.8.

$$\textit{Energy content per unit weight of grain factor} = 3{,}506{,}181 \textit{ kilocalories / tonne}$$

Step 5. Food supply per capita values were converted from an at-consumption to an at-harvest quantity using the conversion factor below. This conversion factor was derived from an analysis of losses, inefficiencies and waste at various stages across the global food system conducted by Alexander et al. (2017), which specifies a 44% loss in dry mass of harvested crops to food available for consumption.

$$\textit{At-consumption to at-harvest conversion factor} = \frac{1}{(1-0.44)}$$

Step 6. The working dataset of food supply per capita values was converted to food demand per capita by taking the maximum of the MLFD (defined in Section B.9) or the food supply per capita value for each country from year 2000 to 2020. In making this conversion, we assume that a food supply value greater than the MLFD reflects an 'excess lifestyle' in food demand met by supply enabled by domestic food production or international trade power, while a food supply value less than the MLFD reflects a supply that does not meet a 'healthy lifestyle' in food demand due to lack of domestic food production or international trade power. 159 countries required no further data cleaning and 83 countries required further data cleaning, as summarised in Table B.8 (Raw Data Issue 3).

Step 7. Missing food demand per capita values for all countries for year 2019 to 2020 were populated by extrapolating from the known 2018 values to obtain the input dataset.

Table B.8: Documentation of raw data to final input data cleaning issues for food_demand_pc_historical

Raw data issue	General remediation / assumption approach	Model country	Country specific aspects of data cleaning
1. Missing some food supply per capita values for this country.	1-a. Missing values populated by extrapolating from the respective country's known food supply per capita value using a constant ratio to the average food supply per capita value of other countries with complete values in the raw data set that belong to the same geographic region.	BES	Values for year 2011 to 2018 populated by extrapolation from known 2010 value.
		BMU	Values for year 2014 to 2018 populated by extrapolation from known 2013 value.
		BRN	Values for year 2014 to 2018 populated by extrapolation from known 2013 value.
2. Missing all food supply per capita values for this country.	2-a. Missing values for year 2000 to 2018 populated by calculating the average food demand per capita, in the respective year, of other countries with complete values in the raw data set that belong to the same geographic region.	ABW	Geographic region as per Table B.1.
		AIA	
		ALA	
		AND	
		ASM	
		BDI	
		BHR	
		BLM	
		BTN	
		CCK	
		COK	
		COM	
		CUW	
		CXR	
		CYM	
		ERI	
		ESH	
		FLK	
		FRO	
		FSM	
		GGY	All countries in actual region (as per Table B.1.) were missing values, so adopts region-average for next closest region, being Europe: Northern Europe.
		GIB	Geographic region as per Table B.1.
		GLP	

		GNQ	
		GRL	
		GUF	
		GUM	
		IMN	
		JEY	All countries in actual region (as per Table B.1.) were missing values, so adopts region-average for next closest region, being Europe: Northern Europe.
		LBY	Geographic region as per Table B.1.
		LIE	
		MAF	
		MCO	
		MHL	
		MNP	
		MSR	
		MTQ	
		MYT	
		NFK	
		NIU	
		NRU	
		PCN	
		PLW	
		PNG	
		PRI	
		PSE	
		QAT	
		REU	
		SGP	
		SHN	
		SJM	
		SMR	
		SOM	
		SPM	
		SXM	
		SYC	
		SYR	
		TCA	
		TKL	
		TON	
		TUV	
		VAT	
		VGB	
		VIR	
		WLF	
3. Food supply per capita values less than the MLFD for this country.	3-a. Respective values overwritten with Minimum Lifestyle Food Demand (MLFD) value.	AFG	All values (year 2000 to 2018) overwritten with MLFD.
		AGO	Values for year 2000 to 2012 and 2015 to 2018 overwritten with MLFD.
		ARM	Values for year 2000 to 2002 overwritten with MLFD.
		ATG	Values for year 2000 to 2006, 2008 to 2012, 2014 to 2016 overwritten with MLFD.
		AZE	Values for year 2000 to 2001 overwritten with MLFD.
		BDI	All values (year 2000 to 2018) overwritten with MLFD.
		BEN	Values for year 2000 to 2003 overwritten with MLFD.
		BFA	Values for year 2000 to 2001 overwritten with MLFD.
		BGD	Values for year 2000 to 2006 and 2008 overwritten with MLFD.
		BOL	Values for year 2000 to 2017 overwritten with MLFD.
		BTN	Values for year 2000 to 2006 overwritten with MLFD.
		BWA	All values (year 2000 to 2018) overwritten with MLFD.
		CAF	
		CMR	Values for year 2000 to 2007 overwritten with MLFD.
		COD	All values (year 2000 to 2018) overwritten with MLFD.
		COG	
		COM	
		CPV	Values for year 2000 to 2003 overwritten with MLFD.
		DJI	Values for year 2000 to 2002 overwritten with MLFD.
		DOM	Values for year 2000 to 2009 overwritten with MLFD.
		ECU	Values for year 2000 to 2013 overwritten with MLFD.
		ERI	All values (year 2000 to 2018) overwritten with MLFD.
		ETH	
		GIN	Values for year 2000 to 2003 overwritten with MLFD.
		GMB	Values for year 2006 overwritten with MLFD.
		GNB	All values (year 2000 to 2018) overwritten with MLFD.
		GNQ	
		GRD	Values for year 2000 to 2007, 2014 to 2015, 2017 to 2018 overwritten with MLFD.

		GTM	Values for year 2000 to 2005 and 2008 overwritten with MLFD.
		HND	Values for year 2000 overwritten with MLFD.
		HTI	All values (year 2000 to 2018) overwritten with MLFD.
		IND	Values for year 2000 to 2007 overwritten with MLFD.
		IRQ	Values for year 2000 to 2008 overwritten with MLFD.
		KEN	All values (year 2000 to 2018) overwritten with MLFD.
		KGZ	Values for year 2000 overwritten with MLFD.
		KHM	Values for year 2000 to 2008 overwritten with MLFD.
		KNA	Values for year 2005 overwritten with MLFD.
		LAO	Values for year 2000 to 2012 overwritten with MLFD.
		LBR	All values (year 2000 to 2018) overwritten with MLFD.
		LKA	Values for year 2000 to 2007 overwritten with MLFD.
		LSO	Values for year 2014 to 2016 and 2018 overwritten with MLFD.
		MDA	
		MDG	All values (year 2000 to 2018) overwritten with MLFD.
		MDV	Values for year 2003, 2006 and 2014 to 2018 overwritten with MLFD.
		MMR	Values for year 2000 to 2009 overwritten with MLFD.
		MNG	Values for year 2000 to 2008 overwritten with MLFD.
		MOZ	All values (year 2000 to 2018) overwritten with MLFD.
		MWI	Values for year 2000 to 2013, 2016 and 2018 overwritten with MLFD.
		MYT	All values (year 2000 to 2018) overwritten with MLFD.
		NAM	Values for year 2000 to 2014 overwritten with MLFD.
		NER	Values for year 2000 to 2003 overwritten with MLFD.
		NIC	Values for year 2000 to 2005 overwritten with MLFD.
		NPL	Values for year 2000 to 2006 overwritten with MLFD.
		PAK	
		PAN	
		PER	Values for year 2000 to 2005 overwritten with MLFD.
		PHL	Values for year 2000 to 2003 overwritten with MLFD.
		PRK	All values (year 2000 to 2018) overwritten with MLFD.
		REU	
		RWA	
		SDN	Values for year 2001 to 2013 overwritten with MLFD.
		SEN	Values for year 2000 to 2007 overwritten with MLFD.
		SGP	Values for year 2000 to 2005 overwritten with MLFD.
		SHN	Values for year 2000 to 2003 overwritten with MLFD.
		SLB	Values for year 2000 to 2004 and 2013 to 2017 overwritten with MLFD.
		SLE	All values (year 2000 to 2018) overwritten with MLFD.
		SOM	
		SSD	Values for year 2000 to 2013 overwritten with MLFD.
		STP	Values for year 2000 to 2001, 2010 to 2015, and 2017 overwritten with MLFD.
		SWZ	Values for year 2000 to 2003, 2005 to 2017 overwritten with MLFD.
		SYC	All values (year 2000 to 2018) overwritten with MLFD.
		TCD	
		TGO	Values for year 2000 to 2011 overwritten with MLFD.
		TJK	All values (year 2000 to 2018) overwritten with MLFD.
		TLS	
		TZA	
		UGA	
		UZB	Values for year 2000 to 2004 overwritten with MLFD.
		VEN	Values for year 2002 and 2016 to 2018 overwritten with MLFD.
		VNM	Values for year 2000 to 2002 overwritten with MLFD.
		YEM	All values (year 2000 to 2018) overwritten with MLFD.
		ZMB	
		ZWE	

B.6 Chapter 4 & 5: *trade_distance*

Step 1. The dyadic "dist_cepii" raw data file was downloaded from the CEPII GeoDist database (Mayer and Zignano 2011). The distance "dist", in units of kilometres, values for each country were extracted from the database for use in this study. These distance values are the geodesic distances "calculated following the great circle formula, which uses latitudes and longitudes of the most important cities/agglomerations (in terms of population)".

Step 2. Country values were mapped to the country list (Table B.1), i.e. values for countries in the datasets matching a country definition were included, while those not matching a country definition were excluded.

Step 3. The raw data was converted from stacked to unstacked format of trade distance between country x (rows) and country y (columns) for all pair combinations of the 242 countries.

Step 4. Where the country pair (*country_x, country_y*) was the tabular match of the same country (e.g. Australia being both *country_x* and *country_y*), the trade distance value was set to zero if not already (i.e. the raw data contained negligible trade distance values close to zero in some instances).

Step 5. The working dataset was cleaned by identifying incomplete trade distance values for each of the 242 country pairs and then performing remediation calculations/making assumptions to populate missing values. 222 countries required no further data cleaning and 20 countries required further data cleaning, as summarised in Table B.9.

Table B.9: Documentation of raw to input data cleaning issues for trade_distance

Raw data issue	General remediation / assumption approach	Model country	Country specific aspects of data cleaning
1. Missing all values for pairs with this country.	1-a. Missing values populated by adopting the respective trade distance values for the closest neighbour (say *country_y*) of this country (say *country_x*), except for the *country_a-country_b* pair for which the missing value was	ALA	Closest neighbour being FIN.
		ASM	Closest neighbour being WSM.
		BES	Closest neighbour being ABW.
		BLM	Closest neighbour being AIA.
		CUW	Closest neighbour being ABW.
		GGY	Closest neighbour being GBR.
		GUM	Closest neighbour being MNP.
		IMN	Closest neighbour being GBR.
		JEY	Closest neighbour being GBR.
		LIE	Closest neighbour being CHE.
		MAF	Closest neighbour being AIA.
		MCO	Closest neighbour being ITA.
		MNE	Closest neighbour being ALB.
		MYT	Closest neighbour being COM.

	populated by adopted the straight-line distance between respective capital cities measured in GoogleEarth (Google 2021).	SJM	Closest neighbour being ISL.
		SRB	Closest neighbour being BIH.
		SSD	Closest neighbour being UGA.
		SXM	Closest neighbour being AIA.
		VAT	Closest neighbour being ITA.
		VIR	Closest neighbour being VGB.

B.7 Chapter 4 & 5: Land area values used in *food_production_historical* data preparation

The total land area, in units of square kilometres, of each country is used in the preparation of the *food_production_historical* input dataset, summarised Section B.4. Total land area, rather than arable land area, is used to take a conservative approach by allocating all countries, even those with negligible traditional agriculture, a scaled quantity of food production to account for potential of non-traditional agriculture such as urban farming.

Step 1. A raw data file was downloaded from the WDI database (The World Bank 2021) as follows: (1.) Database: World Development Indicators; (2.) Country: select all; (3.) Series: Land area (sq km); (4.) Time: 2020. This file contains total land area (in units of square kilometres) estimates, excluding inland water bodies (e.g. major rivers and lakes), claims to continental shelf and exclusive economic zones, for countries in year 2020. It was assumed that total land area as defined in year 2020 is constant across the 2000 to 2099 time-period of simulation; land areas within the WDI database, which spans years 1961 to 2020, remain constant except when spatial analysis methods improve or country boundary definitions change.

Step 2. Total land area from the raw data file were mapped to the country list (Table B.1) to obtain the working dataset, i.e. values in the dataset corresponding to one of the 242 country definitions were included, while values in the dataset not corresponding to a country definition were excluded.

Step 3. The working dataset was cleaned by identifying missing total land area values for each of the 242 countries and then performing remediation calculations/making assumptions to populate missing values. 213 countries required no further data cleaning and 29 countries required further data cleaning, as summarised in Table B.10.

Table B.10: Documentation of working data cleaning issues for total land area factors

Raw data issue	General remediation / assumption approach	Model country	Country specific aspects of data cleaning
1. Missing total land area value for this country.	1-a. Missing values populated by identifying total land area information in the CIA World Factbook (CIA 2021b), or Britannica (Encyclopædia	AIA	Value populated using CIA World Factbook.
		ALA	Value populated using Britannica.
		BES	
		BLM	Value populated using CIA World Factbook.
		CCK	
		COK	
		CXR	
		ESH	
		FLK	
		GGY	

	Britannica Inc. 2021) followed by WorldAtlas (WorldAtlas 2021), if values not available in the former source.	GLP	Value populated using WorldAtlas.
		GUF	
		JEY	Value populated using CIA World Factbook.
		MSR	
		MTQ	Value populated using WorldAtlas.
		MYT	Value populated using Britannica.
		NFK	Value populated using CIA World Factbook.
		NIU	
		PCN	
		REU	Value populated using WorldAtlas.
		SDN	Value populated using CIA World Factbook.
		SHN	
		SJM	
		SPM	
		SSD	
		TKL	
		TWN	
		VAT	
		WLF	

B.8 Chapter 4 & 5: Derivation of energy-equivalent-grain-weight conversion factors used in *food_production_historical* data preparation

The energy-equivalent-grain-weight conversion factors are used in the preparation of the *food_production_historical* input dataset, as summarised in Section B.4. The energy content per unit grain weight factor is used in the preparation of the *food_demand_pc_historical* input dataset, as summarised in Section B.5.

Calculate energy content per unit weight of each food crop group

Step 1. An "Item Group" raw data file was downloaded from the FAOSTAT database (FAO 2021): (1.) Data > Production > Crops and livestock products; (2.) "Definitions and Standards – Crops and livestock products". This file contains a list of individual agricultural items and group classifications.

Step 2. The agricultural items (Column ii in Table B.11) belonging to the eight crop groups (Column i in Table B.11) were extracted, while all other agricultural items were discarded, from the "Item Group" raw data file to obtain a working data set.

Step 3. The energy content per 100g of crop item was calculated based on nutritional profiles from the FoodData Central database (USDA 2021), as presented in Table B.11 (Column iii an iv). Calculations were performed where necessary (e.g. wet / dry, with / without shell) to convert the energy content per 100g for entries in the FoodData Central database to the crop items at-harvest form as specified in the FAOSTAT "Item Group" list. Where multiple entries in the FoodData Central database corresponded to a single crop item, the energy content per 100g of that item was calculated as the average of these entries. Where no entries in the FoodData Central database corresponded to any of the crop items in a group, then further research was conducted to identify a value for at least one crop item in that group. Where no entries in the FoodData Central database corresponded to a single crop item but entries were identified for at least one other crop item in the group, the value for that crop item was left blank and later populated with the average energy content per 100g of other crop items in the group with recorded values.

Calculate world production quantity of each food crop group

Step 4. A "Crop Item World Production Quantity" raw data file was downloaded from the FAOSTAT database: (1.) Data > Production > Crops and livestock products; (2.) Regions > "World + (Total)"; (3.) Elements > Production Quantity; (4.) Items Aggregated > "Crops Primary > (List)" > "Cereals, Total > (List)" & "Fruit Primary > (List)" & "Oilcrops > (List)" & "Pulses, Total > (List)" & "Roots and Tubers, Total > (List)" & "Sugar Crops Primary > (List)" & "Treenuts, Total > (List)" & "Vegetables Primary > (List)"; (5.) "Years" > "2000 … 2019". This file contains world production quantities, in units of tonnes, of each crop item in yearly increments for year 2000 to 2019.

Step 4. The average annual world production quantity of each crop item was calculated over the 2000 to 2019 period, as presented in Table B.11 (Column v).

Step 5. The average annual world production quantity of each crop group over the 2000 to 2019 period was calculated by summing the average annual world production quantity of each constituent crop item, as presented in Table B.11 (Column vi).

Step 6. The percentage contribution of each crop item to the crop group average annual world production quantity was calculated, as presented in Table B.11 (Column vii).

Calculate energy content per unit weight of grain and energy-equivalent-grain-weight conversion factors

Step 7. The weight-scaled energy contribution of each crop item to the energy content per 100g of the crop group was calculated by multiplying the crop item energy content per 100g (Step 3 / Column iii Table B.11) by the percentage contribution of each crop item to the crop group average annual world production quantity (Step 6 / Column vii in Table B.11), as presented in Table B.11 (Column viii).

Step 8. The energy content per 100g of the crop group was calculated by summing the weight-scaled energy contribution of constituent crop items, as presented in Table B.11 (Column ix).

Step 9. The energy content per 100g of grain was then calculated by taking the weight-scaled energy content per 100g of constituent crop groups (cereals, oilcrops, pulses):

$$Energy\ content\ per\ unit\ weight\ of\ grain\ factor$$
$$= \frac{\begin{bmatrix} (Cereals\ energy\ content\ per\ 100g\ \times\ Cereals\ average\ annual\ world\ production\ quantity)\ + \\ (Oilcrops\ energy\ content\ per\ 100g\ \times\ Oilcrops\ average\ annual\ world\ production\ quantity)\ + \\ (Pulses\ energy\ content\ per\ 100g\ \times\ Pulses\ average\ annual\ world\ production\ quantity) \end{bmatrix}}{\begin{bmatrix} Cereals\ average\ annual\ world\ production\ quantity\ + \\ Oilcrops\ average\ annual\ world\ production\ quantity\ + \\ Pulses\ average\ annual\ world\ production\ quantity \end{bmatrix}} = 3{,}506{,}181\ kilocalories/tonne$$

The energy content per unit weight of grain factor was obtained by converting the energy content of 351 kilocalories per 100g of grain from units of kilocalories per 100g to kilocalories per tonne.

Step 10. The energy-equivalent-grain-weight conversion factor for each crop group was calculated by dividing energy content per 100g of the crop group by energy content per 100g of grain:

$$Energy\ equivalent\ grain\ weight\ conversion\ factor\ for\ cereals = \frac{Cereals\ energy\ content\ per\ 100g}{Grains\ energy\ content\ per\ 100g} = 1.013$$

$$Energy\ equivalent\ grain\ weight\ conversion\ factor\ for\ fruits = \frac{Fruits\ energy\ content\ per\ 100g}{Grains\ energy\ content\ per\ 100g} = 0.175$$

$$Energy\ equivalent\ grain\ weight\ conversion\ factor\ for\ oilcrops = \frac{Oilcrops\ energy\ content\ per\ 100g}{Grains\ energy\ content\ per\ 100g} = 0.953$$

$$Energy\ equivalent\ grain\ weight\ conversion\ factor\ for\ pulses = \frac{Pulses\ energy\ content\ per\ 100g}{Grains\ energy\ content\ per\ 100g} = 1.084$$

$$Energy\ equivalent\ grain\ weight\ conversion\ factor\ for\ roots\ and\ tubers = \frac{Roots\ and\ tubers\ energy\ content\ per\ 100g}{Grains\ energy\ content\ per\ 100g} = 0.298$$

$$Energy\ equivalent\ grain\ weight\ conversion\ factor\ for\ sugarcrops = \frac{Sugarcrops\ energy\ content\ per\ 100g}{Grains\ energy\ content\ per\ 100g} = 0.120$$

$$Energy\ equivalent\ grain\ weight\ conversion\ factor\ for\ treenuts = \frac{Treenuts\ energy\ content\ per\ 100g}{Grains\ energy\ content\ per\ 100g} = 0.681$$

$$Energy\ equivalent\ grain\ weight\ conversion\ factor\ for\ vegetables = \frac{Vegetables\ energy\ content\ per\ 100g}{Grains\ energy\ content\ per\ 100g} = 0.096$$

This approach assumes a consistent global profile of production of crop items for data efficiency and to adopt more easily comparable conversion factors across the board. In reality, each country will have a slightly different profile of production of crop items.

Table B.11: Documentation of steps in deriving energy-equivalent-grain-weight conversion factors and energy content per unit grain weight factor

i. Crop Group	ii. Crop Item	iii. Crop Item energy content per 100g (kcal)	iv. Crop Item energy content per 100g calculation comments (FDA ID is the identifier of entries in FoodDataCentral database)	v. Crop Item average annual world production quantity (tonnes)	vi. Crop Group average annual world production quantity (tonnes)	vii. Crop Item % contribution to Crop Group average annual world production quantity	viii. Crop Item weight-scaled energy (kcal) content contribution per 100g of Crop Group	ix. Crop Group energy content (kcal) per 100g
Cereals	Barley	354	FDA ID: 170283.	142183936	2511311128	5.66%	20.03	355
	Buckwheat	344	FDA ID: 170286.	2227354		0.09%	0.31	
	Canary seed	355	No relevant food item in database; adopts average of known values in group.	235658		0.01%	0.03	
	Cereals nes	355	No relevant food item in database; adopts average of known values in group.	4888795		0.19%	0.69	
	Fonio	355	No relevant food item in database; adopts average of known values in group.	497128		0.02%	0.07	
	Grain, mixed	355	No relevant food item in database; adopts average of known values in group.	4290860		0.17%	0.61	
	Maize	366	FDA ID: 170288, 168920.	865729641		34.47%	126.06	
	Millet	378	FDA ID: 169702.	29400374		1.17%	4.42	
	Oats	390	FDA ID: 169705.	23977659		0.95%	3.72	
	Quinoa	368	FDA ID: 168874.	97216		0.00%	0.01	
	Rice, paddy	363	FDA ID: 169726, 168883, 168879, 169760, 168881, 168931, 168877, 169756, 169703, 169706, 169706.	680134296		27.08%	98.19	
	Rye	337	FDA ID: 168874.	15492637		0.62%	2.08	
	Sorghum	330	FDA ID: 169716.	59974472		2.39%	7.88	
	Triticale	337	FDA ID: 169718.	13459999		0.54%	1.81	
	Wheat	335	FDA ID: 169721, 169721, 169720, 168889, 168890, 168891.	668721104		26.63%	89.10	
Fruit	Apples	52	FDA ID: 168874.	72100812	731302931	9.86%	5.14	61
	Apricots	48	FDA ID: 171697.	3547024		0.49%	0.23	
	Avocados	160	FDA ID: 171705.	4257125		0.58%	0.93	
	Bananas	89	FDA ID: 173944.	97522226		13.34%	11.82	
	Berries nes	64	No relevant food item in database; adopts average of known values in group.	754297		0.10%	0.07	
	Blueberries	57	FDA ID: 171711.	392267		0.05%	0.03	
	Carobs	64	No relevant food item in database; adopts average of known values in group.	124924		0.02%	0.01	
	Cashewapple	64	No relevant food item in database; adopts average of known values in group.	1792358		0.25%	0.16	
	Cherries	48	FDA ID: 169129, 171719.	2098367		0.29%	0.14	
	Cherries, sour	41	FDA ID: 173954, 171686.	1241513		0.17%	0.07	
	Cranberries	46	FDA ID: 171722.	507490		0.07%	0.03	
	Currants	60	FDA ID: 173963, 173964.	684413		0.09%	0.06	
	Dates	280	FDA ID: 171726, 168191.	7381147		1.01%	2.82	
	Figs	74	FDA ID: 173021.	1092590		0.15%	0.11	
	Fruit, citrus nes	64	No relevant food item in database; adopts average of known values in group.	10958009		1.50%	0.96	
	Fruit, fresh nes	64	No relevant food item in database; adopts average of known values in group.	30041770		4.11%	2.64	
	Fruit, pome nes	64	No relevant food item in database; adopts average of known values in group.	62612		0.01%	0.01	
	Fruit, stone nes	64	No relevant food item in database; adopts average of known values in group.	507346		0.07%	0.04	
	Fruit, tropical fresh nes	64	No relevant food item in database; adopts average of known values in group.	20560983		2.81%	1.81	

	Gooseberries	49	FDA ID: 173043, 173030.	163889		0.02%	0.01	
	Grapefruit (inc. pomelos)	32	FDA ID: 173033.	7221660		0.99%	0.32	
	Grapes	64	FDA ID: 173040, 174682, 174683.	69340352		9.48%	6.09	
	Kiwi fruit	62	FDA ID: 168211, 168153.	2991544		0.41%	0.25	
	Lemons and limes	34	FDA ID: 168155, 167746, 167749.	15089909		2.06%	0.70	
	Mangoes, mangosteens, guavas	60	FDA ID: 169910.	38813995		5.31%	3.17	
	Melons, other (inc. cantaloupes)	33	FDA ID: 169092, 169093, 169911.	24662936		3.37%	1.10	
	Oranges	47	FDA ID: 169097.	68706127		9.40%	4.42	
	Papayas	43	FDA ID: 169926.	10652436		1.46%	0.62	
	Peaches and nectarines	42	FDA ID: 169928, 169914.	20030499		2.74%	1.15	
	Pears	57	FDA ID: 169118, 168177, 167750, 167777, 167776, 167778, 167779.	21529580		2.94%	1.67	
	Persimmons	50	FDA ID: 169941, 169943.	3681065		0.50%	0.25	
	Pineapples	50	FDA ID: 169124.	21562306		2.95%	1.47	
	Plantains and others	137	FDA ID: 168215, 169130.	33330146		4.56%	6.24	
	Plums and sloes	56	FDA ID: 173952, 168150, 169949.	10535357		1.44%	0.81	
	Quinces	57	FDA ID: 168163.	547070		0.07%	0.04	
	Raspberries	53	FDA ID: 167755.	594749		0.08%	0.04	
	Strawberries	33	FDA ID: 167762.	6574921		0.90%	0.29	
	Tangerines, mandarins, clementines, satsumas	50	FDA ID: 169105, 168195, 168195.	26351630		3.60%	1.81	
	Watermelons	30	FDA ID: 167765.	93295487		12.76%	3.87	
Oilcrops	Castor oil seed	439	No relevant food item in database; adopts average of known values in group.	1607941	804568313	0.20%	0.88	334
	Coconuts	186	FDA ID: 170174, 170169.	58371271		7.25%	13.52	
	Groundnuts, with shell	439	No relevant food item in database; adopts average of known values in group.	40966815		5.09%	22.34	
	Hempseed	552	FDA ID: 170148.	107146		0.01%	0.07	
	Jojoba seed	439	No relevant food item in database; adopts average of known values in group.	147		0.00%	0.00	
	Kapok fruit	439	No relevant food item in database; adopts average of known values in group.	314329		0.04%	0.17	
	Karite nuts (sheanuts)	439	No relevant food item in database; adopts average of known values in group.	657781		0.08%	0.36	
	Linseed	439	No relevant food item in database; adopts average of known values in group.	2323841		0.29%	1.27	
	Melonseed	439	No relevant food item in database; adopts average of known values in group.	799805		0.10%	0.44	
	Mustard seed	509	FDA ID: 170929.	580774		0.07%	0.37	
	Oil palm fruit	439	No relevant food item in database; adopts average of known values in group.	255619744		31.77%	139.38	
	Oilseeds nes	439	No relevant food item in database; adopts average of known values in group.	2345704		0.29%	1.28	
	Olives	439	No relevant food item in database; adopts average of known values in group.	18631451		2.32%	10.16	
	Poppy seed	526	FDA ID: 171330.	73054		0.01%	0.05	
	Rapeseed	439	No relevant food item in database; adopts average of known values in group.	57749243		7.18%	31.49	

	Safflower seed	487	FDA ID: 170558. Dried energy of 2160kJ converted by water content of 5.62%.	671845		0.08%	0.41	
	Seed cotton	439	No relevant food item in database; adopts average of known values in group.	68721038		8.54%	37.47	
	Sesame seed	547	FDA ID: 170150. Dried energy of 2400kJ converted by water content of 4.69%.	4425558		0.55%	3.01	
	Soybeans	147	FDA ID: 169282	253747760		31.54%	46.28	
	Sunflower seed	556	FDA ID: 170562. Dried energy of 2400kJ converted by water content of 4.73%.	36407815		4.53%	25.14	
	Tung nuts	439	No relevant food item in database; adopts average of known values in group.	445253		0.06%	0.24	
Pulses	Bambara beans	374	No relevant food item in database; adopts average of known values in group.	147816	71062421	0.21%	0.78	380
	Beans, dry	385	FDA ID: 173727, 173734, 173738, 173745, 173748, 175202, 173751, 175210, 174256, 174259, 174283, 174281, 175189, 175186, 173749, 174252, 175193, 174255, 175199, 175190. Wet average energy of 1435kJ converted by water content of 10.85%.	23683486		33.33%	128.21	
	Broad beans, horse beans, dry	381	FDA ID: 175205. Wet energy of 1420kJ converted by water content of 11%.	4540767		6.39%	24.37	
	Chick peas	378	FDA ID: 173756.	10652564		14.99%	56.61	
	Cow peas, dry	383	FDA ID: 173758, 175208. Wet average energy of 1420kJ converted by water content of 11%.	6211913		8.74%	33.45	
	Lentils	355	FDA ID: 174284, 172420.	4448124		6.26%	22.22	
	Lupins	370	FDA ID: 172423.	1192006		1.68%	6.21	
	Peas, dry	398	FDA ID: 172428. Wet average energy of 1520kJ converted by water content of 8.69%.	11374662		16.01%	63.68	
	Pigeon peas	344	FDA ID: 172436.	4041183		5.69%	19.57	
	Pulses nes	374	No relevant food item in database; adopts average of known values in group.	3787614		5.33%	19.95	
	Vetches	374	No relevant food item in database; adopts average of known values in group.	982287		1.38%	5.17	
Roots and Tubers	Cassava	159	FDA ID: 169985.	242365615	763648263	31.74%	50.60	104
	Potatoes	74	FDA ID: 170026, 170029, 170028, 170027.	339465593		44.45%	32.86	
	Roots and tubers nes	98	No relevant food item in database; adopts average of known values in group.	6077560		0.80%	0.78	
	Sweet potatoes	86	FDA ID: 168482.	108958598		14.27%	12.24	
	Taro (cocoyam)	78	FDA ID: 169310, 169308.	10485836		1.37%	1.07	
	Yams	92	FDA ID: 168432, 170071.	55828715		7.31%	6.76	
	Yautia (cocoyam)	98	FDA ID: 169401.	466346		0.06%	0.06	
Sugar Crops	Sugar beet	42	No relevant food item in database; harvest values identified in further research (MyFitnessPal 2021).	255442575	1896847060	13.47%	5.69	42
	Sugar cane	42	No relevant food item in database; no harvest values identified in further research; adopts average of known values in group.	1640505099		86.49%	36.53	
	Sugar crops nes	42	No relevant food item in database; no harvest values identified in further research; adopts average of known values in group.	899386		0.05%	0.02	
Treenuts	Almonds, with shell	179	FDA ID: 170567. Energy of 2420kJ for nuts without shell, converted by total weight comprising hull = 52%, shell = 33% and kernel = 15%.	2441149	12249042	19.93%	35.73	239
	Brazil nuts, with shell	319	FDA ID: 170569. Energy of 2420kJ for nuts without shell, converted by total weight comprising shell = 50% and kernel = 50%.	66970		0.55%	1.74	
	Cashew nuts, with shell	166	FDA ID: 170162. Energy of 2420kJ for nuts without shell, converted by total weight comprising shell = 70% and kernel = 30%.	2899339		23.67%	39.20	
	Chestnut	197	FDA ID: 170164, 169413, 170574.	1743239		14.23%	28.03	
	Hazelnuts, with shell	267	FDA ID: 170581. Energy of 2420kJ for nuts without shell, converted by total weight comprising shell = 58%, kernel = 42%.	843552		6.89%	18.36	

	Nuts nes	256	No relevant food item in database; adopts average of known values in group.	821119		6.70%	17.14	
	Pistachios	296	FDA ID: 170184.	710179		5.80%	17.19	
	Walnuts, with shell	367	FDA ID: 170187.	2723495		22.23%	81.54	
Vegetables	Artichokes	60	FDA ID: 169236, 169205.	1465432	907973065	0.16%	0.10	34
	Asparagus	20	FDA ID: 168389.	7437964		0.82%	0.17	
	Beans, green	31	FDA ID: 169961.	18920922		2.08%	0.65	
	Cabbages and other brassicas	28	FDA ID: 170388, 169977, 169975.	68253116		7.52%	2.07	
	Carrots and turnips	35	FDA ID: 170393, 170465.	33539370		3.69%	1.28	
	Cauliflowers and broccoli	27	FDA ID: 169986, 170379, 170381, 169404.	21134311		2.33%	0.62	
	Chillies and peppers, green	30	FDA ID: 169394, 168578, 168576, 169395, 170427, 170108, 169383, 170497, 170106.	29236947		3.22%	0.97	
	Cucumbers and gherkins	16	FDA ID: 168409.	61924284		6.82%	1.06	
	Eggplants (aubergines)	25	FDA ID: 169228.	41537815		4.57%	1.14	
	Garlic	149	FDA ID: 169230.	20917223		2.30%	3.43	
	Leeks, other alliaceous vegetables	61	FDA ID: 169246.	2014139		0.22%	0.14	
	Lettuce and chicory	16	FDA ID: 169247, 169249, 168431, 169248, 168429, 169992, 170404.	24237726		2.67%	0.43	
	Maize, green	86	FDA ID: 168538, 169998.	10523200		1.16%	0.99	
	Mushrooms and truffles	29	FDA ID: 167755.	7993201		0.88%	0.26	
	Okra	33	FDA ID: 169260.	7615896		0.84%	0.28	
	Onions, dry	35	FDA ID: 170000, 170008, 170007. Taken as whole partially dried, not packaged dehydrated, to be consistent with other Vegetables entries.	76661006		8.44%	2.97	
	Onions, shallots, green	72	FDA ID: 170499.	4320540		0.48%	0.34	
	Peas, green	62	FDA ID: 170419, 170010.	16044788		1.77%	1.09	
	Pumpkins, squash and gourds	22	FDA ID: 168448, 170489, 170487, 168414, 169232.	22327793		2.46%	0.55	
	Spinach	20	FDA ID: 168462, 168438, 168440.	19559888		2.15%	0.43	
	String beans	31	FDA ID: 1103337.	1916754		0.21%	0.06	
	Tomatoes	18	FDA ID: 170456, 170502, 170096.	148861303		16.39%	2.94	
	Vegetables, fresh nes	41	No relevant food item in database; adopts average of known values in group.	260037334		28.64%	11.77	
	Vegetables, leguminous nes	41	No relevant food item in database; adopts average of known values in group.	1492114		0.16%	0.07	

B.9 Chapter 4 & 5: MLFD constant used in *food_demand_pc_historical* data preparation

The minimum lifestyle food demand 'MLFD' of 0.448 tonnes per capita per year is used in preparation of the *food_demand_pc_historical* input dataset in Section B.5 and in the incremental calculation of *food_demand_pc* throughout the simulations.

Step 1. A raw data file was downloaded from the FAOSTAT database (FAO 2021): (1.) Suite of Food Security Indicators; (2.) Regions: "World + (Total)"; (3.) Elements: Value; (4.) Items: Average dietary energy requirement (ADER) (kcal/cap/day); (5.) Years: "2000/1999-2001" – "2020/2019-2021". This file contains world ADER estimates at-consumption, in units of kilocalories per capita per day, in yearly increments from 2000 to 2020. ADER is the caloric intake needed for an individual to maintain a healthy weight for height alongside light lifestyle activity in the FAO's food security indicators and assumed in this study as representative of minimum lifestyle food demand. (In comparison, the minimum dietary energy requirement (MDER), is the caloric intake below which an individual is classified as 'undernourished' in the FAO's food security indicators.)

Step 2. This raw data was linearly extrapolated to obtain world ADER projections in yearly increments from 2021 to 2099 (i.e. for all remaining years of the simulation). This was done to ensure calculated MLFD represents an average over the whole century examined given that ADER has increase linearly.

Step 3. An average of the world ADER values over the 2000 to 2099 time period (i.e. the entirety of the century examined) was then calculated.

Step 4. The world average ADER was converted from an at-consumption to an at-harvest value using the conversion factor defined in Step 5 of Section B.5, and the units were converted from kilocalories per capita per day to obtain the MLFD.

This approach assumes a globally constant ADER over the period of our simulation, for simplicity and equality in considering food demand for an 'average human'. In reality, ADER values varies by country and over time depending on the age and gender distribution of a given population.

B.10 Chapter 4 & 5: *population_growth*

Chapter 4 only: Step 1. A raw data file was downloaded from the IIASA (2018) database: (1.) Regions: Countries; (2.) Model/Scenarios: Basic Elements > POP > IIASA-WiC Population > SSP5; (3.) Variable: data and data, Population > Total. This file contains total population, in units of million persons, projections for countries in five yearly increments for year 2010 to 2095.

Chapter 5 only: Step 1. Five raw data files ('i' to 'v' following)–one for each of the five SSPs–were downloaded from the IIASA database: (1.) Regions: Countries; (2.) Model/Scenarios: Basic Elements > POP > IIASA-WiC Population > SSP1 for 'i', or SSP2 for 'ii', or SSP3 for 'iii', or SSP4 for 'iv', or SSP5 for 'v'; (3.) Variable: data and data, Population > Total. These files contain total population (units of million persons) projections for countries in five yearly increments for year 2010 to 2095. For each of the five files, Step 2 to 5 were performed to obtain final input data files for each SSP.

Step 2. Total population values for year 2020 to 2095 were mapped to the country list (Table B.1) to obtain a working dataset, i.e. values in the dataset corresponding to one of the 242 country definitions were included, while those not corresponding to a country definition were excluded.

Step 3. Total population values were converted to population growth values in units of average annual percentage growth. For example, the population growth value in year 2020 was calculated as follows:

$$Population\ growth = 100 \times \left(\left(\frac{Population\ in\ 2025}{Population\ in\ 2020} \right)^{1/(2025-2020)} - 1 \right)$$

Step 4. The working dataset was cleaned by identifying incomplete total population growth rate values for each of the 242 countries over the 2020-to-2095-year period and then performing remediation calculations/making assumptions to populate missing values. 193 countries required no further data cleaning and 49 countries required further data cleaning, as summarised in Table B.12.

Step 5. The total population growth rate values were converted from five-yearly increments to yearly increments by adopting the known five-yearly values for all years within the respective five-yearly increment period (i.e. the known 2020 value was adopted for year to 2021 to 2024 … the known 2095 value was adopted for year 2096 to 2099) to obtain the input dataset.

Table B.12: Documentation of raw data to final input data cleaning issues for population_growth

Raw data issue	General remediation / assumption approach	Model country	Country specific aspects of data cleaning
1. Missing all population growth rate values for this country.	1-a. Missing values for year 2020 to 2099 were populated by calculating the average population growth, in the respective year, of other countries with complete values in the raw data set that belong to the same geographic region.	AIA	Geographic region as per Table B.1.
		ALA	
		AND	
		ASM	
		ATG	
		BES	
		BLM	
		BMU	
		CCK	
		COK	
		CUW	
		CXR	
		CYM	
		DMA	
		ESH	
		FLK	
		FRO	
		GGY	All countries in actual region (as per Table B.1.) were missing values, so adopts region-average for next closest region, being Europe: Northern Europe.
		GIB	Geographic region as per Table B.1.
		GRL	
		IMN	
		JEY	All countries in actual region (as per Table B.1.) were missing values, so adopts region-average for next closest region, being Europe: Northern Europe.
		KIR	Geographic region as per Table B.1.
		KNA	
		LIE	
		MAF	
		MCO	
		MHL	
		MNP	
		MSR	
		NFK	
		NIU	
		NRU	
		PCN	
		PLW	
		SHN	
		SJM	
		SMR	
		SPM	
		SSD	
		SXM	
		SYC	
		TCA	
		TKL	
		TUV	
		TWN	
		VAT	
		VGB	
		WLF	

B.11 Chapter 4 & 5: *gdp_pc_growth*

Chapter 4 only: Step 1. A raw data file was downloaded from the IIASA (2018) database: (1.) Regions: Countries; (2.) Model/Scenarios: Basic Elements > GDP > OECD GDP > SSP5; (3.) Variable: data and per capita, GDP > PPP. This file contains GDP|PPP per capita growth rate, in units of annual average percentage, projections for countries in five yearly increments for year 2010 to 2095.

Chapter 5 only: Step 1. Five raw data files ('i' to 'v' following)–one for each of the five SSPs–were downloaded from the IIASA database: (1.) Regions: Countries; (2.) Model/Scenarios: Basic Elements > GDP > OECD GDP > SSP1 for 'i', or SSP2 for 'ii', or SSP3 for 'iii', or SSP4 for 'iv', or SSP5 for 'v'; (3.) Variable: data and per capita, GDP > PPP. These files contain GDP|PPP per capita growth (units of annual average percentage) projections for countries in five yearly increments for year 2010 to 2095. For each of the five files, Step 2 to 5 were performed to obtain final input data files for each SSP.

Step 2. GDP|PPP per capita values for year 2020 to 2095 were mapped to the country list (Table B.1) to obtain a working dataset, i.e. values in the dataset corresponding to one of the 242 country definitions were included, while those not corresponding to a country definition were excluded.

Step 2. GDP|PPP per capita values were converted to GDP|PPP per capita growth values in units of average annual percentage growth. For example, the GDP|PPP per capita value in year 2020 was calculated as follows:

$$GDP|PPP\ per\ capita\ growth = 100 \times \left(\left(\frac{GDP|PPP\ per\ capita\ in\ 2025}{GDP|PPP\ per\ capita\ in\ 2020} \right)^{1/(2025-2020)} - 1 \right)$$

Step 4. The working dataset was cleaned by identifying incomplete GDP|PPP per capita growth rate values for each of the 242 countries over the 2020-to-2095-year period and then performing remediation calculations/making assumptions to populate missing values. 184 countries required no further data cleaning and 58 countries required further data cleaning, as summarised in Table B.13.

Step 5. GDP|PPP per capita growth rate values were converted from five-yearly increments to yearly increments by adopting the known five-yearly values for all years within the respective five-yearly increment period (i.e. the known 2020 value was adopted for year to 2021 to 2024 … the known 2095 value was adopted for year 2096 to 2099) to obtain the input dataset.

Table B.13: Documentation of raw data to final input data cleaning issues for gdp_pc_growth

Raw data issue	General remediation / assumption approach	Model country	Country specific aspects of data cleaning
1. Missing all GDP|PPP per capita growth rate values for this country	1-a. Missing values for year 2020 to 2099 were populated by calculating the average GDP|PPP per capita growth rate, in the respective year, of other countries with complete values in the raw data set that belong to the same geographic region.	AIA	Geographic region as per Table B.1.
		ALA	
		AND	
		ASM	
		ATG	
		BES	
		BLM	
		BMU	
		CCK	
		COK	
		CUW	
		CXR	
		CYM	
		DMA	
		ESH	
		FLK	
		FRO	
		FSM	All countries in actual region (as per Table B.1.) were missing values, so adopts region-average for next closest region, being Oceania: Melanesia.
		GGY	All countries in actual region (as per Table B.1.) were missing values, so adopts region-average for next closest region, being Europe: Northern Europe.
		GIB	Geographic region as per Table B.1.
		GLP	
		GRD	
		GRL	
		GUF	
		GUM	All countries in actual region (as per Table B.1.) were missing values, so adopts region-average for next closest region, being Oceania: Melanesia.
		IMN	Geographic region as per Table B.1.
		JEY	All countries in actual region (as per Table B.1.) were missing values, so adopts region-average for next closest region, being Europe: Northern Europe.
		KIR	All countries in actual region (as per Table B.1.) were missing values, so adopts region-average for next closest region, being Oceania: Melanesia.
		KNA	Geographic region as per Table B.1.
		LIE	
		MAF	
		MCO	
		MHL	All countries in actual region (as per Table B.1.) were missing values, so adopts region-average for next closest region, being Oceania: Melanesia.
		MNP	
		MSR	Geographic region as per Table B.1.
		MTQ	
		MYT	
		NFK	
		NIU	
		NRU	All countries in actual region (as per Table B.1.) were missing values, so adopts region-average for next closest region, being Oceania: Melanesia.
		PCN	Geographic region as per Table B.1.
		PLW	All countries in actual region (as per Table B.1.) were missing values, so adopts region-average for next closest region, being Oceania: Melanesia.
		PRK	Geographic region as per Table B.1.
		REU	
		SHN	
		SJM	
		SMR	
		SPM	
		SSD	
		SXM	
		SYC	
		TCA	
		TKL	
		TUV	
		VAT	
		VGB	
		VIR	
		WLF	

B.12 Chapter 4 & 5: *food_production_growth_cropland*

The 'standard' *food_production_growth_cropland* component of the *food_production_growth* input dataset was derived from the SSP1 (marker model IMAGE), SSP2 (marker model MESSAGE-GLOBIOM), SSP3 (marker model AIM/CGE), SSP4 (marker model GCAM) and SSP5 (marker model REMIND-MAGPIE) data hosted by IAMC and IIASA (2018).

Chapter 4 only: Step 1. Two data files – one for total cropland ('i') and one for energy cropland ('ii') – were downloaded from the IAMC database: (1.) Add timeseries panel; (2.) Select Scenario, Select from list: REMIND-MAgPIE 1.5; (3.) Data Selection: Land Cover > Cropland (TOTAL) *for i, and* Land Cover > Energy Crops *for ii*; (4.) Regions: R5 > R5ASIA, R5LAM, R5MAF, R5OECD90+EU, R5REF; (5.) Ranges: 2020 to 2100. These files contain total cropland and energy cropland, in units of million hectares, projections for five regions (Asia, Latin America, Middle East and Africa, OECD and European Union, Reforming Economies, respectively) in ten-yearly increments from 2020 to 2100.

Chapter 5 only: Step 1. Two sets of data files – one set for total cropland and one for energy cropland ('A' and 'B' following) – were downloaded from the IAMC database. For each set, fifteen raw data files ('i' to 'xv' following) – one for each of the 15 RCP-SSP-SPA framework scenarios – were downloaded: (1.) Add timeseries panel; (2.) Select Scenario, Select from list: IMAGE 3.0.1 > SSP1-26 for 'i' + SSP1-45 for 'ii' + SSP1-60 for 'iii', MESSAGE-GLOBIOM 1.0 > SSP2-26 for 'iv' + SSP2-45 for 'v' + SSP2-60 for 'vi', AIM/CGE 2.0 > SSP3-45 for 'vii' + SSP3-60 for 'viii', GCAM 4.2 > SSP4-26 for 'ix' + SSP4-45 for 'x' + SSP4-60 for 'xi', REMIND-MAgPIE 1.5 > SSP5-26 for 'xii', SSP5-45 for 'xiii', SSP5-60 for 'xiv', SSP5-85 for 'xv'; (3.) Data Selection: Land Cover > Cropland (TOTAL) for 'A' + Land Cover > Energy Crops for 'B'; (4.) Regions: R5 > R5ASIA, R5LAM, R5MAF, R5OECD90+EU, R5REF; (5.) Ranges: 2020 to 2100. These files contain total cropland and energy cropland, in units of million hectares, projections for five regions (Asia, Latin America, Middle East and Africa, OECD and European Union, Reforming Economies, respectively) in ten-yearly increments from 2020 to 2100. For each of the 15 scenarios, Step 2 to 5 were performed to obtain final input data files for each scenario.

Step 2. Food cropland values were calculated from the difference of the total cropland and energy cropland values from the IAMC database as follows:

$$Food\ cropland = \ total\ cropland - energy\ cropland$$

Step 3. Food cropland values were converted to food cropland growth values in units of average annual percentage growth. For example, food cropland growth value in year 2020 was calculated as follows:

$$Food\ cropland\ growth = 100 \times \left(\left(\frac{Food\ cropland\ in\ 2030}{Food\ cropland\ in\ 2020} \right)^{1/(2030-2020)} - 1 \right)$$

Step 4. Food cropland growth values were mapped to the country list (Table B.1) to obtain a working dataset. The allocation of countries to each of the five regions used in the IAMC database, which differ from the UNSD M49 classifications adopted in this study (see Section B.1), are summarised in Table B.14 (Raw Data Issue 1).

Step 5. Food cropland growth values were converted from ten-yearly increments to yearly increments by adopting the known ten-yearly values for all years within the respective ten-yearly increment period (i.e. the known 2020 value was adopted for year to 2021 to 2029 … the known 2090 value was adopted for year 2091 to 2099) to obtain the input dataset.

Table B.14: Documentation of raw data to final input data cleaning issues for food_production_growth_cropland

Raw data issue	General remediation / assumption approach	IIASA (2018) database region	Model country allocation
1. All values specified for regions different to UNSD M49 specification.	1-a. Allocate countries to IAMC database regions as specified in IAMC database documentation and based on geographic location of UNSD M49 region specification if country not included in documentation (indicated *).	ASIA	AFG, ASM*, BGD, BRN, BTN, CHN, COK*, FJI, FSM, HKG, IDN, IND, KHM, KIR*, KOR, LAO, LKA, MAC, MDV, MHL*, MMR, MNG, MNP*, MYS, NCL, NIU*, NPL, NRU*, PAK, PCN*, PHL, PLW*, PNG, PRK, PYF, SGP, SLB, THA, TKL*, TLS, TON*, TUV*, TWN, VNM, VUT, WLF*, WSM
		LAM	ABW, AIA*, ARG, ATG*, BES*, BHS, BLM*, BLZ, BOL, BRA, BRB, CHL, COL, CRI, CUB, CUW*, CYM*, DMA*, DOM, ECU, FLK*, GLP, GRD, GTM, GUF, GUY, HND, HTI, JAM, KNA*, LCA*, MAF*, MEX, MSR*, MTQ, NIC, PAN, PER, PRY, SLV, SUR, SXM*, TCA*, TTO, URY, VCT*, VEN, VGB*, VIR
		MAF	AGO, ARE, BDI, BEN, BFA, BHR, BWA, CAF, CIV, CMR, COD, COG, COM, CPV, DJI, DZA, EGY, ERI, ESH, ETH, GAB, GHA, GIN, GMB, GNB, GNQ, IRN, IRQ, ISR, JOR, KEN, KWT, LBN, LBR, LBY, LSO, MAR, MDG, MLI, MOZ, MRT, MUS, MWI, MYT, NAM, NER, NGA, OMN, PSE, QAT, REU, RWA, SAU, SDN, SEN, SHN*, SLE, SOM, SSD, STP*, SWZ, SYC*, SYR, TCD, TGO, TUN, TZA, UGA, YEM, ZAF, ZMB, ZWE
		OECD	ALA*, ALB, AND*, AUS, AUT, BEL, BGR, BIH, BMU*, CAN, CCK*, CHE, CXR*, CYP, CZE, DEU, DNK, ESP, EST, FIN, FRA, FRO*, GBR, GGY*, GIB*, GRC, GRL*, GUM, HRV, HUN, IMN*, IRL, ISL, ITA, JEY*, JPN, LIE*, LTU, LUX, LVA, MCO*, MKD, MLT, MNE, NFK*, NLD, NOR, NZL, POL, PRI, PRT, ROU, SJM*, SMR*, SPM*, SRB, SVK, SVN, SWE, TUR, USA, VAT*
		REF	ARM, AZE, BLR, GEO, KAZ, KGZ, MDA, RUS, TJK, TKM, UKR, UZB

B.13 Chapter 4 & 5: *food_production_growth_cropyield*

The 'altered' *food_production_growth_cropyield* component of the *food_production_growth* input dataset was derived from high resolution GIS data on climate impacted crop yields for each of the 15 RCP-SSP-SPA scenarios from (Iizumi et al. 2017, 2020) and current land use from (Chen et al. 2020), as follows.

Step 1. GIS-based raw data files were sourced from (Iizumi et al. 2017, 2020) and (Chen et al. 2020).

(Chen et al. 2020) provide projections of land use from a base year of 2015 to 2100 for all RCP-SSP-SPA framework scenarios. Firstly, these projections are all produced by using the GCAM IAM, which is the marker model for SSP4, rather than the respective marker model for each of the other four SSPs. Thus, only the base year cropland GIS data from (Chen et al. 2020) is used to avoid introducing further inconsistencies between this and the other datasets based on the respective marker models, and instead use regional values from the marker models in the IAMC database to inform *food_production_growth_cropland* separately. Secondly, (Chen et al. 2020) base year of 2015 for the base year of 2020 was used, and in doing so assume that changes in land use between 2015 to 2020 are negligible in comparison to introducing GCAM IAM projection related inconsistencies into the dataset by taking the 2020 projections from (Chen et al. 2020).

For Chapter 4, Step 2 to 5 were performed to obtain the final input data file for SSP5-RCP8.5. For Chapter 5, Step 2, 4 and 5 were performed to obtain final input data files for each of the 15 scenarios.

Step 2. GIS-based calculations using the high-resolution crop yield projections and constant land use data were then conducted to obtain annual crop yield related food production values for each country, which are defined spatially by the shape files described in Section B.1, from 2020 to 2100.

To perform the GIS-based calculations the h3 geospatial indexing system (Uber Technologies 2021) at resolution level 6, corresponding to an average hexagonal grid-cell area of 36 km^2 and yielding 14,117,882 unique hexagonal grid-cell indexes, was used to remedy the influence of distortion, which is inherent in the regular longitude-latitude grid form of the raw data, in the calculation of country-level values. The crop yield, rainfed arable land percentage, irrigated arable land percentage and urban land percentage values for each h3 grid-cell were defined by interpolating the raw data at the h3 grid-cell centre coordinates. The calculations conducted in a given year are described below.

Firstly, an average crop yield for maize, rice, soy and wheat under the irrigated and non-irrigated conditions for each h3 grid-cell was calculated from the climate ensemble, which include five slightly different models of the climate system, values from (Iizumi et al. 2017, 2020) in the given year.

Secondly, the rainfed arable land percentage and irrigated arable land percentage for each h3 grid-cell were calculated from the base year (Chen et al. 2020) held constant from 2020 to 2100.

Thirdly, the crop yield related food production quantity of each h3 grid-cell was calculated:

$$
\begin{aligned}
&Maize\ production\ (tonnes)\\
&\quad = [Maize\ rainfed\ yield\ \times\ Maize\ rainfed\ arable\ land\ \% \times\ h3\ gridcell\ area]\\
&\quad + [Maize\ irrigated\ yield\ \times\ Maize\ irrigated\ arable\ land\ \% \times\ h3\ gridcell\ area]\\
&Rice\ production\ (tonnes)\\
&\quad = [Wheat\ rainfed\ yield\ \times\ Wheat\ rainfed\ arable\ land\ \% \times\ h3\ gridcell\ area]\\
&\quad + [Wheat\ irrigated\ yield\ \times\ Wheat\ irrigated\ arable\ land\ \% \times\ h3\ gridcell\ area]\\
&Soy\ production\ (tonnes)\\
&\quad = [Wheat\ rainfed\ yield\ \times\ Wheat\ rainfed\ arable\ land\ \% \times\ h3\ gridcell\ area]\\
&\quad + [Wheat\ irrigated\ yield\ \times\ Wheat\ irrigated\ arable\ land\ \% \times\ h3\ gridcell\ area]\\
&Wheat\ production\ \ (tonnes)\\
&\quad = [Wheat\ rainfed\ yield\ \times\ Wheat\ rainfed\ arable\ land\ \% \times\ h3\ gridcell\ area]\\
&\quad + [Wheat\ irrigated\ yield\ \times\ Wheat\ irrigated\ arable\ land\ \% \times\ h3\ gridcell\ area]\\
&Other\ crop\ production\ (tonnes)\\
&\quad = [Average\ of maize, rice, soy, wheat\ rainfed\ yield\ \times\ Sugarcrop\ rainfed\ arable\ land\ \% \times\ h3\ gridcell\ area]\\
&\quad + [Average\ of maize, rice, soy, wheat\ irrigated\ yield\ \times\ Sugarcrop\ irrigated\ arable\ land\ \% \times\ h3\ gridcell\ area]\\
&\quad + [Average\ of maize, rice, soy, wheat\ rainfed\ yield\ \times\ Other\ crops\ rainfed\ arable\ land\ \% \times\ h3\ gridcell\ area]\\
&\quad + [Average\ of maize, rice, soy, wheat\ irrigated\ yield\ \times\ Other\ crops\ irrigated\ arable\ land\ \% \times\ h3\ gridcell\ area]
\end{aligned}
$$

$$
Total\ production\ (tonnes) = Maize\ production + Rice\ production + Soy\ production\ + Wheat\ production\ + Other\ crop\ production
$$

Fourthly, the total crop yield related food production of each of the 242 countries was calculated by summing the respective total production of h3 grid-cells within a given country's shape file definition.

These GIS-based calculations yielded a 'natural' dataset of crop yield related food production absolute values, in units of tonnes per hectare, for each of the 242 countries in yearly increments from 2020 to 2100. For Chapter 4, the 'natural' dataset is further transformed to reflect the original 'extreme climate change' scenarios in Step 3. For Chapter 5, Step 3 is skipped.

Chapter 4 only: Step 3. To replicate an 'extreme' climate change scenario, the 'natural' dataset of crop yield related food production absolute values was then 'sped up' and 'extrapolated' to obtain to

obtain an 'artificial' version. This involved the *RCP85_climate_forcing* and *W3_climate_forcing* datasets detailed in Section B.15 and Section B.16, respectively, as follows.

Firstly, the absolute yearly values for the simulation period from 2020 to 2100 from both the *RCP85_climate_forcing* and *W3_climate_forcing* input datasets were transformed into working datasets of 'multiplier' yearly values referenced to the initial year 2020, as shown in Figure B.1(a).

Secondly, the *RCP85_climate_forcing* working dataset of 'multiplier' values was matched to the more extreme rate in *W3_climate_forcing,* which required a factor of three 'speed up'.

Doing so effectively sees *RCP85_climate_forcing* 'multiplier' values, say 2.87x in 2100, 'compressed' to match the closest 'multiplier' value, say 2.91x in 2046, of *W3_climate_forcing*. Linearly extrapolating the 'sped up' *RCP85_climate_forcing* 'multiplier' values, using the last 50 years (i.e. 2050-2100) of 'uncompressed' values (i.e. 2037-2046 referencing 'compressed' values), to populate the rest of the century (i.e. 2047-2100) gives a 'sped up' *RCP85_climate_forcing* of 7.4 times the 2020 value in 2100, which corresponds closely to a *W3_climate_forcing* 'multiplier' value of 6.9x in 2100 as shown in Figure B.1(a). Given the absolute CO_2-eq. concentration in 2020 from the *RCP85_climate_forcing* input dataset is ~429 ppm, the 'multiplier' value of 7.4x equates to ~3175 ppm in 2100 under the 'sped up' and 'extrapolated' RCP8.5 version. This ~3175 ppm is ~2.58 times the absolute CO_2-eq. concentration from the *RCP85_climate_forcing* input dataset (i.e. 'uncompressed' values) of ~1231 ppm in 2100. A climate forcing (RCP) of ~22 associated with ~3175 ppm was approximated by linearly extrapolating from known RCP vs CO_2-eq. concentrations (IIASA 2009) as shown in Figure B.1(b). Similarly, global warming of ~10°C associated with an RCP of~22 was approximated by linearly extrapolating from known temperature (reference period 1850-1900) vs RCP (IPCC 2014) as shown in Figure B.1(c).

While the 2100 values for the *W3_climate_forcing* and 'sped up' and 'extrapolated' *RCP85_climate_forcing* working datasets are relatively close, due to the linear extrapolation the 'sped up' and 'extrapolated' *RCP85_climate_forcing* does not capture the peak nor concave down function of the *W3_climate_forcing*, which is associated with a decline in pollution production as the World3 population collapses. The *RCP85_climate_forcing* is based on only the CO_2-eq. concentration of climate forcing agents (e.g. GHG emissions) while the *W3_climate_forcing* is based on persistent pollution that includes climate forcing agents as well as other forms of pollution, such as toxic waste, with different timespans of persistency. An alternative approach could have utilised a function equivalent to the *W3_climate_forcing* curve, however, in mimicking a level of global warming above 8°C by 2100, rather than

replicating World3 forcing exactly, linear extrapolation beyond the available RCP8.5 data for simplicity and transparency. Similarly, the temperature response to climate forcing to CO_2-eq. concentration of climate forcing agents is not linear in reality, linear extrapolation was used in absence of climate forcing data beyond RCP8.5 for a simple and transparent approximation of extreme climate change.

Thirdly, the 'natural' dataset of crop yield related food production absolute values from Step 2, were 'sped up' by the factor of three and linearly 'extrapolated' following the same process as described above to obtain the 'artificial' dataset of crop yield related food production absolute values. An example of this for Aruba (ABW) is shown in Figure B.1(d).

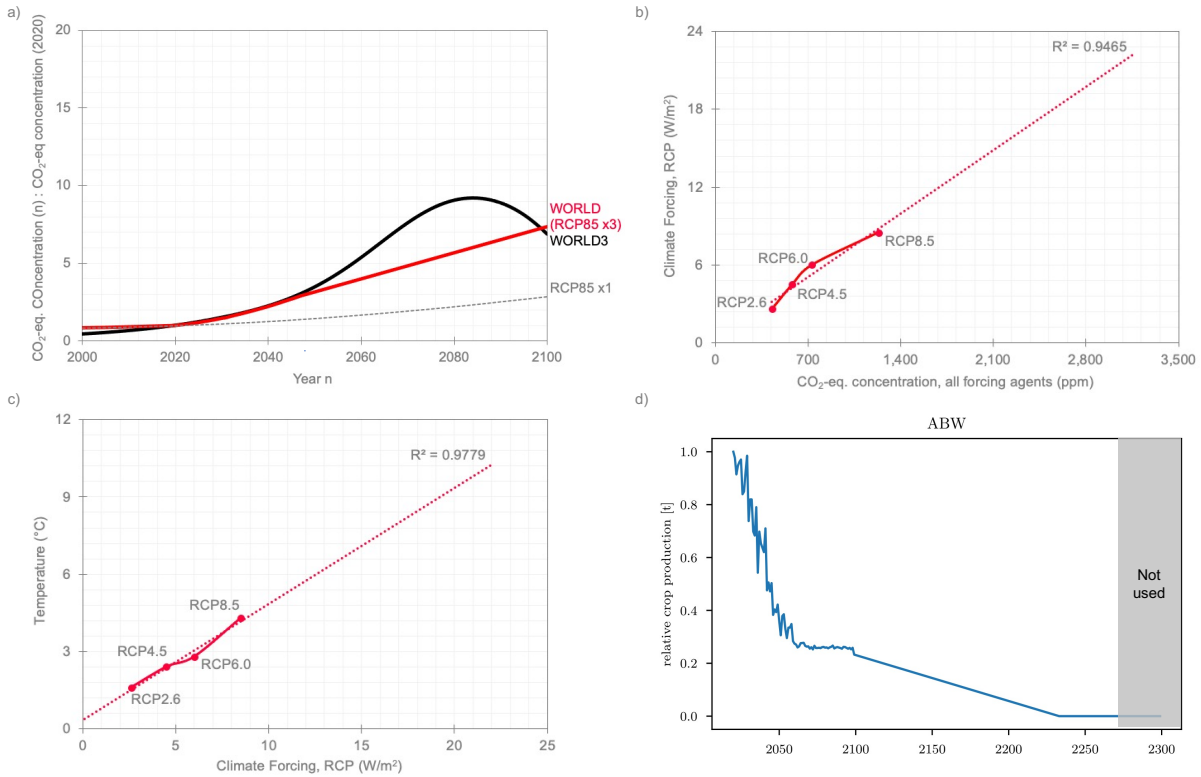


Figure B.1: Defining food_production_growth_cropyield under 'extreme global warming'. a) record of the transformation of the 'natural' absolute values from RCP85_climate_forcing and W3_climate_forcing (Section B.15 and B.16) into 'multiplier' values referenced to the initial simulation year 2020 (grey and black respectively), and record of the 'artificial' 'extreme climate change' trend established using the 3x speed up of RCP85_climate_forcing to match the W3_climate_forcing trend (red) with linear extrapolation from 'natural' 2050-2100 values to populate the 'artificial' values to 2100; b) record of estimating the climate forcing associated with the 'artificial' absolute emissions in 2100 (~3175 ppm) of the 'sped up' RCP85_climate_forcing using linear trend fitted to known IPCC (2021) *emissions versus climate forcing values; c) record of estimating the global warming associated with the 'artificial climate forcing in 2100 (~RCP22) using linear trend fitted to known* IPCC (2021) *emissions versus climate forcing values; d) example of linearly extrapolating from 'natural' 2050-2100 values to populate the 'artificial' crop yield based food production values to 2100.*

Step 4. For Chapter 4, the 'artificial' crop yield related food production absolute values from Step 3 were converted to growth values in units of average annual percentage growth. For Chapter 5, the 'natural' crop yield related food production absolute values from Step 2 were converted to growth

values in units of average annual percentage growth. A lower limit of -99% was applied to prevent countries experiencing -100%, which would result in zero food production from which they could not recover in subsequent years due to the nature of the growth calculations. For example, the crop yield related food production growth value in year 2020 was calculated as follows:

$$Crop\ yield\ related\ food\ production\ growth = MAX\left[100 \times \left(\left(\frac{Crop\ yield\ related\ food\ production\ in\ 2021}{Crop\ yield\ related\ food\ production\ in\ 2020}\right)^{1/(2021-2020)} - 1\right), -99\right]$$

Step 5. The working dataset was cleaned by identifying incomplete crop yield related food production growth rate values for each of the 242 countries over the 2020-to-2099-year period and then performing remediation calculations/making assumptions to populate missing values. 183 countries required no further data cleaning and 59 countries required further data cleaning, as summarised in Table B.15.

Table B.15: Documentation of raw data to final input data cleaning issues for food_production_growth_cropyield

Raw data issue	General remediation / assumption approach	Model country	Country specific aspects of data cleaning
1. Missing all crop yield related food production growth rate values for this country	1-a. Missing values for year 2020 to 2099 were populated by calculating the average crop yield related food production growth rate, in the respective year, of other countries with complete values in the raw data set that belong to the same geographic region.	AIA	Geographic region as per Table B.1.
		ASM	All countries in actual region (as per Table B.1.) were missing values, so adopts region-average for next closest region, being Oceania: Melanesia.
		ATG	Geographic region as per Table B.1.
		BLM	
		BMU	
		BRB	
		CCK	
		COK	All countries in actual region (as per Table B.1.) were missing values, so adopts region-average for next closest region, being Oceania: Melanesia.
		CXR	Geographic region as per Table B.1.
		DMA	
		ESH	
		FJI	
		FLK	
		FRO	
		FSM	
		GGY	All countries in actual region (as per Table B.1.) were missing values, so adopts region-average for next closest region, being Europe: Northern Europe.
		GRD	Geographic region as per Table B.1.
		GRL	
		GUM	
		IMN	
		ISL	
		JEY	All countries in actual region (as per Table B.1.) were missing values, so adopts region-average for next closest region, being Europe: Northern Europe.
		KIR	Geographic region as per Table B.1.
		LCA	
		MAC	
		MAF	
		MDV	
		MHL	
		MLT	
		MNP	
		MSR	
		MTQ	
		MUS	

		MYT	
		NCL	
		NFK	
		NIU	All countries in actual region (as per Table B.1.) were missing values, so adopts region-average for next closest region, being Oceania: Melanesia.
		NRU	Geographic region as per Table B.1.
		PCN	All countries in actual region (as per Table B.1.) were missing values, so adopts region-average for next closest region, being Oceania: Melanesia.
		PYF	
		QAT	Geographic region as per Table B.1.
		REU	
		SHN	
		SJM	
		SLB	
		SPM	
		STP	
		SXM	
		TCA	
		TKL	All countries in actual region (as per Table B.1.) were missing values, so adopts region-average for next closest region, being Oceania: Melanesia.
		TON	
		TUV	
		VAT	Geographic region as per Table B.1.
		VCT	
		VGB	
		VIR	
		VUT	
		WLF	All countries in actual region (as per Table B.1.) were missing values, so adopts region-average for next closest region, being Oceania: Melanesia.
		WSM	

B.14 Chapter 4 & 5: *food_demand_pc_growth*

The *food_demand_pc_growth* input datasets were derived from the SSP1 (marker model IMAGE), SSP2 (marker model MESSAGE-GLOBIOM), SSP3 (marker model AIM/CGE), SSP4 (marker model GCAM) and SSP5 (marker model REMIND-MAGPIE) data in the IAMC 1.5°C Scenario Explorer hosted by IIASA (IAMC and IIASA 2018), which contains IAM data at regional level for the RCP-SSP-SPA framework scenarios, as follows.

Chapter 4 only: Step 1. A raw data file was downloaded from the IAMC database as follows: (1.) Add timeseries panel; (2.) Select Scenario, Select from list: REMIND-MAgPIE 1.5; (3.) Data Selection: Food Demand (TOTAL); (4.) Regions: R5 > R5ASIA, R5LAM, R5MAF, R5OECD90+EU, R5REF; (5.) Ranges: 2020 to 2100. This file contains the food demand per capita (units of kilocalories per day) projections for five regions (Asia, Latin America, Middle East and Africa, OECD and European Union, Reforming Economies, respectively) in ten-yearly increments from 2020 to 2100.

Chapter 5 only: Step 1. Fifteen raw data files ('i' to 'xv' following) – one for each of the 15 RCP-SSP-SPA framework scenarios – were downloaded from the IAMC database as follows: (1.) Add timeseries panel; (2.) Select Scenario, Select from list: IMAGE 3.0.1 > SSP1-26 for 'i' + SSP1-45 for 'ii' + SSP1-60 for 'iii', MESSAGE-GLOBIOM 1.0 > SSP2-26 for 'iv' + SSP2-45 for 'v' + SSP2-60 for 'vi', AIM/CGE 2.0 > SSP3-45 for 'vii' + SSP3-60 for 'viii', GCAM 4.2 > SSP4-26 for 'ix' + SSP4-45 for 'x' + SSP4-60 for 'xi', REMIND-MAgPIE 1.5 > SSP5-26 for 'xii', SSP5-45 for 'xiii', SSP5-60 for 'xiv', SSP5-85 for 'xv'; (3.) Data Selection: Food Demand (TOTAL); (4.) Regions: R5 > R5ASIA, R5LAM, R5MAF, R5OECD90+EU, R5REF; (5.) Ranges: 2020 to 2100. These files contain food demand per capita growth (units of kilocalories per day) projections for five regions (Asia, Latin America, Middle East and Africa, OECD and European Union, Reforming Economies, respectively) in ten-yearly increments from 2020 to 2100. For each of the 15 scenarios, Step 2 to 4 were performed to obtain final input data files for each scenario.

Step 2. The food demand per capita absolute values from the IAMC database were converted to food demand per capita growth values in units of average annual percentage growth. For example, the food demand per capita growth value in year 2020 was calculated as follows:

$$Food\ demand\ per\ capita\ growth = 100 \times \left(\left(\frac{Food\ demand\ per\ capita\ in\ 2030}{Food\ demand\ per\ capita\ in\ 2020} \right)^{1/(2030-2020)} - 1 \right)$$

Step 3. The food demand per capita growth values were mapped to the country list (Table B.1). The allocation of countries to each of the five regions used in the IAMC database, which differ from the UNSD M49 classifications adopted in this study (described in Section B.1), are summarised in Table B.16 (Raw Data Issue 1).

Step 4. Finally, the food demand per capita growth values were converted from ten-yearly increments to yearly increments by adopting the known ten-yearly values for all years within the respective ten-yearly increment period (i.e. the known 2020 value was adopted for year to 2021 to 2029 … the known 2090 value was adopted for year 2091 to 2099) to obtain the final input dataset.

Table B.16: Documentation of raw data to final input data cleaning issues for food_demand_pc_growth

Raw data issue	General remediation / assumption approach	IIASA (2018) database region	Model country allocation
1. All values specified for regions different to UNSD M49 specification.	1-a. Allocate countries to IAMC database regions as specified in IAMC database documentation and based on geographic location of UNSD M49 region specification if country not included in documentation (indicated *).	ASIA	AFG, ASM*, BGD, BRN, BTN, CHN, COK*, FJI, FSM, HKG, IDN, IND, KHM, KIR*, KOR, LAO, LKA, MAC, MDV, MHL*, MMR, MNG, MNP*, MYS, NCL, NIU*, NPL, NRU*, PAK, PCN*, PHL, PLW*, PNG, PRK, PYF, SGP, SLB, THA, TKL*, TLS, TON*, TUV*, TWN, VNM, VUT, WLF*, WSM
		LAM	ABW, AIA*, ARG, ATG*, BES*, BHS, BLM*, BLZ, BOL, BRA, BRB, CHL, COL, CRI, CUB, CUW*, CYM*, DMA*, DOM, ECU, FLK*, GLP, GRD, GTM, GUF, GUY, HND, HTI, JAM, KNA*, LCA*, MAF*, MEX, MSR*, MTQ, NIC, PAN, PER, PRY, SLV, SUR, SXM*, TCA*, TTO, URY, VCT*, VEN, VGB*, VIR
		MAF	AGO, ARE, BDI, BEN, BFA, BHR, BWA, CAF, CIV, CMR, COD, COG, COM, CPV, DJI, DZA, EGY, ERI, ESH, ETH, GAB, GHA, GIN, GMB, GNB, GNQ, IRN, IRQ, ISR, JOR, KEN, KWT, LBN, LBR, LBY, LSO, MAR, MDG, MLI, MOZ, MRT, MUS, MWI, MYT, NAM, NER, NGA, OMN, PSE, QAT, REU, RWA, SAU, SDN, SEN, SHN*, SLE, SOM, SSD, STP*, SWZ, SYC*, SYR, TCD, TGO, TUN, TZA, UGA, YEM, ZAF, ZMB, ZWE
		OECD	ALA*, ALB, AND*, AUS, AUT, BEL, BGR, BIH, BMU*, CAN, CCK*, CHE, CXR*, CYP, CZE, DEU, DNK, ESP, EST, FIN, FRA, FRO*, GBR, GGY*, GIB*, GRC, GRL*, GUM, HRV, HUN, IMN*, IRL, ISL, ITA, JEY*, JPN, LIE*, LTU, LUX, LVA, MCO*, MKD, MLT, MNE, NFK*, NLD, NOR, NZL, POL, PRI, PRT, ROU, SJM*, SMR*, SPM*, SRB, SVK, SVN, SWE, TUR, USA, VAT*
		REF	ARM, AZE, BLR, GEO, KAZ, KGZ, MDA, RUS, TJK, TKM, UKR, UZB

B.15 Chapter 4: *RCP85_climate_forcing*

Step 1. A raw data file was downloaded from the IIASA (2009) database as follows: (1.) Regions: World; (2.) Scenarios: MESSAGE > RCP 8.5; (3.) Variables: Climate indicators > Concentration > CO2 equivalent concentration (incl. all forc. agents). This file contains CO_2-equivalent concentration of climate forcing agents, in units of parts per million (ppm), projections for the world in ten yearly increments for year 2000 to 2100.

Step 2. Finally, the CO_2-equivalent concentration values were converted from ten-yearly increments to yearly increments by interpolating between the known values to obtain the final dataset.

A graph of the *RCP85_climate_forcing* data is presented in Figure B.2, alongside historical atmospheric CO_2 concentration from 1900 to 2020 sourced from for comparison with the 1900 to 2100 *W3_climate_forcing* graph in Section B.16.

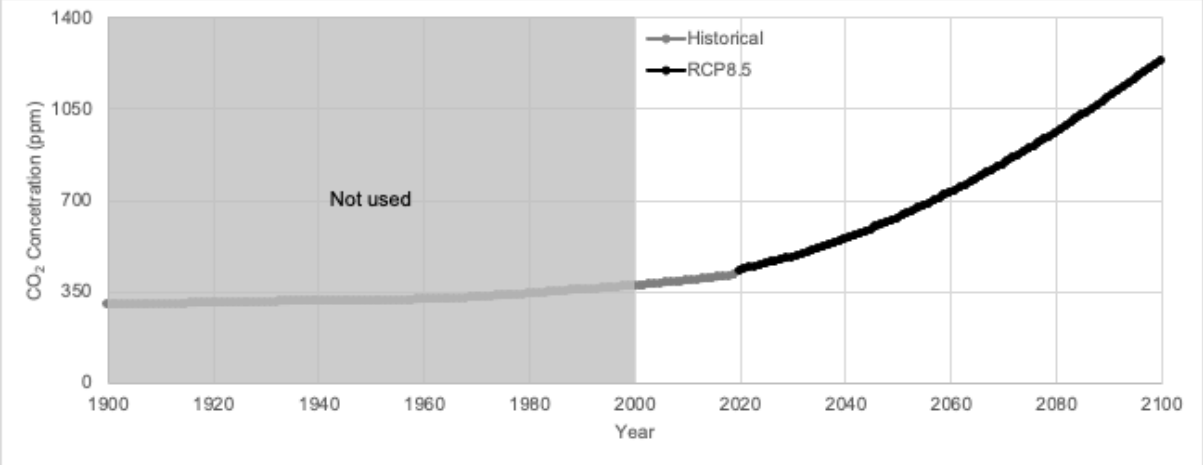


Figure B.2: Documentation of RCP85_climate_forcing input data. Historical data shown for reference (1900 to 1999).

B.16 Chapter 4: *W3_climate_forcing, W3_population, W3_gdp, W3_food_production, W3_food_demand*

The input datasets were derived from the World3 BAU-CC scenario. A copy of World3-03, in STELLA Architect, was kindly provided by Professor Jorgen Randers, one of the original creators. To obtain the final input datasets the World3 model was run, and raw data was processed as follows.

Step 1. World3-03 was run under Scenario 2, as detailed in *The Limits to Growth: the 30-Year Update* (Meadows et al. 2004), according to the corresponding setup instructions accompanying the copy of World3-03 in STELLA Architect.

The simulation results for the same major variables shown in *The Limits to Growth: the 30-Year Update* (Meadows et al. 2004) for this scenario are presented graphically in Figure B.3, for record. The simulation results for the World-3-03 variables of interest to this study, namely *pers pollution 142, population 1*, *GDP per capita 2*, *food 87*, *indic food pc 89* and were extracted.

Step 2. Using this raw data extracted from World3-03, the following calculations were performed to obtain the final input data for Model variables *W3_climate_forcing, W3_population, W3_gdp, W3_food_production, W3_food_demand,* for year 2000 to 2100. Graphs of the final input data for each of these variables are presented Figure B.4.

$$W3_climate_forcing = pers\ pollution\ 142$$
$$W3_gdp = GDP\ per\ capita\ 2 \times population\ 1$$
$$W3_food_demand = s\ indic\ food\ pc\ 89 \times population\ 1$$
$$W3_food_production = food\ 87$$
$$W3_population = population\ 1$$

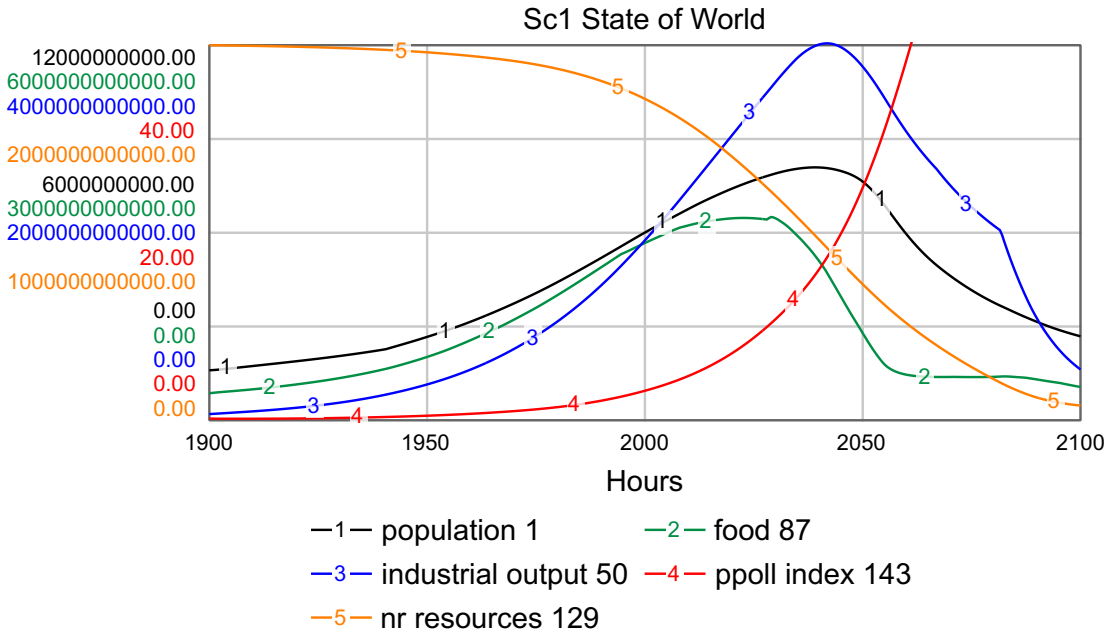


Figure B.3: World3-03 BAU-CC output. Graph as shown in Meadows et al. (2004).

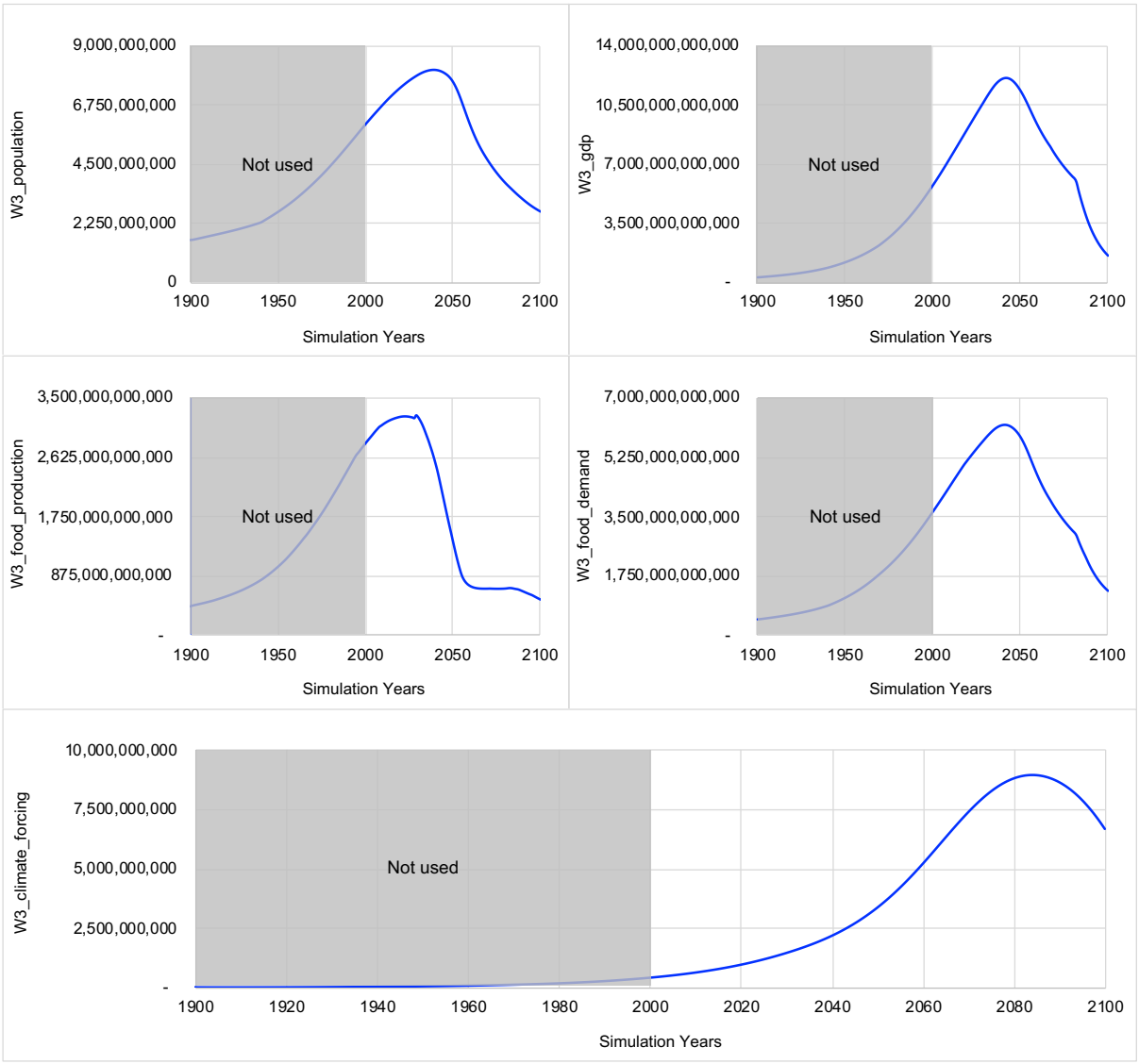


Figure B.4: Documentation of W3_climate_forcing, W3_population, W3_gdp, W3_food_production, W3_food_demand input data. Historical World3 output (1900 to 1999) shown for reference.

B.17 Chapter 4: Verification of results

To check that the simulation produced logical results countries experiencing starvation deaths in the future simulation were compared with a ranking of the current 'percentage of population undernourished' from the FAO (2021) Food Security Indicators (FSI). It is important to note that because the simulation covers a period in the future (2020-2100), for which no historical data exists, this is treated as general verification rather than an exact validation.

The FSI was most recently recorded in 2019, as shown in Table B.17. The model analyses 242 countries while the FSI used includes only 162 countries. The FSI countries were assigned one of three general groups of food security rankings of '1 - Low', '2 - Medium' and '3 - High' based on their 'percentage of population undernourished' value.

A check was then performed on whether countries experiencing starvation deaths of the simulation matched the '1 – Low' food security group ranking from the FSI records in 2019, as shown in Table B.18. Given the simulation covers a period in the future (2020-2100), this check was performed for years 2020-2039 (i.e. the first quarter of simulation), which is assumed representative of the present before projected socioeconomic development and climate change make a significant impact. It was found that 100% of countries experiencing starvation deaths in 2020-2039 have a '1 – Low' current (2019) food security ranking, as expected. Subsequently, a check was then performed on an additional 10 years (2040-2049) for further comparison as projected socioeconomic development and climate change begin to have a significant impact on results. It was found that 92% of countries experiencing starvation deaths in 2040-2049 have a '1 – Low' current (2019) food security ranking, a decreased percentage match compared to the 2020-2039 period as expected.

Table B.17: Verification of Chapter 4 results – current population undernourished groups.

FAOSTAT Food Security Indicator (FSI): % population undernourished in 2019					
Food security grouping: 1 - Low		Food security grouping: 2 - Medium		Food security grouping: 3 - High	
Model Country	FSI value	Model Country	FSI value	Model Country	FSI value
DZA	<2.5	BGR	3	COL	8.8
AUS	<2.5	TUN	3	MRT	9.1
AUT	<2.5	CRI	3.1	PRY	9.2
AZE	<2.5	MYS	3.2	LBN	9.3
BLR	<2.5	TWN	3.3	VUT	9.3
BEL	<2.5	ARM	3.4	PHL	9.4
BIH	<2.5	CHL	3.4	JOR	9.5
BRA	<2.5	ARE	3.7	BGD	9.7
BRN	<2.5	PYF	3.8	MLI	10.4
CAN	<2.5	ALB	3.9	SWZ	11.6
HKG	<2.5	ARG	3.9	STP	11.9
CHN	<2.5	SAU	3.9	SDN	12.3
HRV	<2.5	SRB	3.9	ECU	12.4
CUB	<2.5	SVK	4	BOL	12.6

CYP	<2.5	BRB	4.1	PAK	12.9
CZE	<2.5	KIR	4.1	HND	13.5
DNK	<2.5	TUR	4.1	GMB	13.6
EST	<2.5	MAR	4.2	BFA	14.4
FIN	<2.5	MAC	4.3	NGA	14.6
FRA	<2.5	MNG	4.3	CIV	14.9
DEU	<2.5	WSM	4.6	IND	15.3
GRC	<2.5	NPL	4.8	CPV	15.4
HUN	<2.5	GUY	5.2	GAB	15.7
ISL	<2.5	CMR	5.3	DJI	16.2
IRL	<2.5	LAO	5.3	ETH	16.2
ISR	<2.5	EGY	5.4	SLB	16.5
ITA	<2.5	IRN	5.5	GTM	16.8
JPN	<2.5	DMA	5.6	AGO	17.3
KAZ	<2.5	FJI	5.6	MWI	17.3
KWT	<2.5	VCT	5.6	NIC	19.3
LVA	<2.5	BLZ	5.9	NAM	19.8
LTU	<2.5	GHA	6.1	TGO	20.4
LUX	<2.5	KHM	6.2	TLS	22.6
MLT	<2.5	MUS	6.2	LSO	23.5
MNE	<2.5	IDN	6.5	PNG	24.6
NLD	<2.5	ZAF	6.5	KEN	24.8
NZL	<2.5	TTO	6.7	TZA	25.1
NOR	<2.5	VNM	6.7	AFG	25.6
POL	<2.5	LKA	6.8	SLE	26.2
PRT	<2.5	NCL	6.9	VEN	27.4
KOR	<2.5	KGZ	7.2	BWA	29.3
ROU	<2.5	MEX	7.2	MOZ	31.2
RUS	<2.5	PAN	7.5	TCD	31.7
SVN	<2.5	SEN	7.5	RWA	35.2
ESP	<2.5	BEN	7.6	IRQ	37.5
SWE	<2.5	MMR	7.6	COG	37.7
CHE	<2.5	JAM	7.7	LBR	38.9
TUR	<2.5	OMN	8.2	COD	41.7
UKR	<2.5	THA	8.2	PRK	42.4
GBR	<2.5	DOM	8.3	MDG	43.2
USA	<2.5	SLV	8.5	YEM	45.4
URY	<2.5	GEO	8.7	HTI	46.8
UZB	<2.5	PER	8.7	CAF	48.2
MKD	2.7	SUR	8.7	SOM	59.5

Table B.18: Verification of Chapter 4 results – comparison of simulated starvation deaths with current population undernourished groups. Note that no countries experienced deaths in the simulation in 2020-2036.

Year 2037		
Model country	**Starvation deaths**	**Food security grouping**
YEM	35026641	3 - Bad
AFG	32062641	3 - Bad
BDI	5753379	#N/A
ERI	3924895	#N/A
CAF	3570215	3 - Bad
	Match =	100%

Year 2038		
Model country	**Starvation deaths**	**Food security grouping**
UGA	35116932	#N/A
SOM	16582669	3 - Bad
MOZ	13873016	3 - Bad
TCD	12201158	3 - Bad
SSD	11305635	#N/A
PRK	2481790	3 - Bad
NER	752733	#N/A
YEM	407207	3 - Bad
CAF	315047	3 - Bad
ERI	52414	#N/A
	Match =	100%

Year 2039		
Model country	**Starvation deaths**	**Food security grouping**
PAK	140783948	3 - Bad
COD	70337734	3 - Bad
UGA	7230037	#N/A
NER	5946846	#N/A
RWA	5719674	3 - Bad
MOZ	3756424	3 - Bad
LSO	1799659	3 - Bad
BDI	1224266	#N/A
TCD	1008013	3 - Bad
CAF	273381	3 - Bad
SSD	265661	#N/A
SOM	27245	3 - Bad
YEM	22118	3 - Bad
	Match =	100%

Year 2040		
Model country	**Starvation deaths**	**Food security grouping**
SDN	38187644	3 - Bad
COG	5292864	3 - Bad
UGA	4476877	#N/A
PAK	4296601	3 - Bad
TGO	3997860	3 - Bad
COD	3733577	3 - Bad
MOZ	3677239	3 - Bad
NER	1582782	#N/A
TCD	1390108	3 - Bad
PNG	499773	3 - Bad

Year 2041		
Model country	**Starvation deaths**	**Food security grouping**
PAK	18038719	3 - Bad
AGO	5435767	3 - Bad
TJK	1642931	#N/A
UGA	1317290	#N/A
PNG	843862	3 - Bad
MOZ	781232	3 - Bad
CAF	155732	3 - Bad
PRK	135738	3 - Bad
TGO	134620	3 - Bad
YEM	105233	3 - Bad

Year 2042		
Model country	**Starvation deaths**	**Food security grouping**
PAK	12528416	3 - Bad
TZA	2791716	3 - Bad
AGO	1117519	3 - Bad
PNG	307131	3 - Bad
SSD	275964	#N/A
BDI	269881	#N/A
CAF	215486	3 - Bad
TGO	182107	3 - Bad
YEM	147508	3 - Bad
COG	135232	3 - Bad

ESH	289559	#N/A
SSD	245353	#N/A
CAF	127434	3 - Bad
ERI	94227	#N/A
SOM	28930	3 - Bad
	Match =	100%

SOM	48904	3 - Bad
ERI	19832	#N/A
	Match =	100%

ESH	68545	#N/A
SOM	31720	3 - Bad
LSO	18335	3 - Bad
ERI	6869	#N/A
	Match =	100%

Year 2043		
Model country	**Starvation deaths**	**Food security grouping**
IND	186360840	3 - Bad
IRQ	37472149	3 - Bad
KEN	32652494	3 - Bad
TWN	14501845	2 - Mid
ZMB	6252563	#N/A
LBY	6137420	#N/A
LBN	5340688	3 - Bad
PSE	4670026	#N/A
DJI	1166923	3 - Bad
NER	1112181	#N/A
TLS	1018678	3 - Bad
ZWE	814934	#N/A
COM	721460	#N/A
MDV	617358	#N/A
PNG	556511	3 - Bad
ESH	70521	#N/A
SOM	26657	3 - Bad
LSO	21325	3 - Bad
CAF	7256	3 - Bad
	Match =	91%

Year 2044		
Model country	**Starvation deaths**	**Food security grouping**
IND	58280950	3 - Bad
JPN	41939939	1 - Good
KEN	7557265	3 - Bad
ZMB	6616914	#N/A
ZWE	4698011	#N/A
AGO	2942694	3 - Bad
TZA	2523277	3 - Bad
PRK	2431922	3 - Bad
NER	1882918	#N/A
MOZ	1535471	3 - Bad
COD	1369771	3 - Bad
SYR	745059	#N/A
PAK	385853	3 - Bad
TWN	363872	2 - Mid
YEM	239954	3 - Bad
PNG	237627	3 - Bad
CAF	230398	3 - Bad
ERI	158557	#N/A
COG	122150	3 - Bad
LBN	120131	3 - Bad
SLB	103432	3 - Bad
TJK	65720	#N/A
PSE	56112	#N/A
SOM	54606	3 - Bad
SSD	48872	#N/A
LSO	40496	3 - Bad
COM	22869	#N/A
TLS	9055	3 - Bad
TUV	7953	#N/A
DJI	7484	3 - Bad
WLF	1350	#N/A
	Match =	90%

Year 2045		
Model country	**Starvation deaths**	**Food security grouping**
IND	29778112	3 - Bad
COD	6074068	3 - Bad
NER	4640825	#N/A
UGA	3896157	#N/A
SDN	3176673	3 - Bad
ZMB	2190646	#N/A
TCD	1277526	3 - Bad
SSD	154886	#N/A
YEM	154156	3 - Bad
ZWE	121878	#N/A
CAF	81912	3 - Bad
TGO	66071	3 - Bad
SOM	56259	3 - Bad
COM	12934	#N/A
DJI	3201	3 - Bad
MDV	327	#N/A
	Match =	100%

Year 2046		
Model country	**Starvation deaths**	**Food security grouping**
NGA	108546209	3 - Bad
JPN	30974600	1 - Good
VEN	26233523	3 - Bad
DZA	21657656	1 - Good
IND	18530668	3 - Bad
JOR	14721032	3 - Bad
TZA	12970378	3 - Bad
PAK	12435364	3 - Bad
HTI	9648743	3 - Bad
IRN	9456296	2 - Mid
OMN	6335199	2 - Mid
HND	5342842	3 - Bad
MRT	4161485	3 - Bad
IRQ	3792521	3 - Bad
NAM	2517653	3 - Bad
AGO	2394683	3 - Bad
MAR	2152198	2 - Mid
SYR	2067308	#N/A
KEN	1916281	3 - Bad
PNG	1740176	3 - Bad
UZB	1721552	1 - Good
SLV	1665781	2 - Mid
BDI	1497437	#N/A
MNG	1386807	2 - Mid
RWA	1366466	3 - Bad
ARM	1301178	2 - Mid
PRK	1129343	3 - Bad
TKM	899261	#N/A
TWN	700003	2 - Mid
AZE	640054	1 - Good
COD	617049	3 - Bad
MNE	607624	1 - Good
ALB	550870	2 - Mid
LBN	422817	3 - Bad

Year 2047		
Model country	**Starvation deaths**	**Food security grouping**
IND	23084832	3 - Bad
ZWE	1877790	#N/A
COD	1215667	3 - Bad
SDN	539976	3 - Bad
MOZ	350393	3 - Bad
CAF	343191	3 - Bad
SSD	321378	#N/A
TCD	320625	3 - Bad
SOM	247807	3 - Bad
TGO	194478	3 - Bad
COM	38114	#N/A
ERI	6558	#N/A
	Match =	100%

Year 2048		
Model country	**Starvation deaths**	**Food security grouping**
IND	29329331	3 - Bad
NGA	20084942	3 - Bad
COD	2295423	3 - Bad
SDN	1123627	3 - Bad
ZWE	1006261	#N/A
MOZ	793231	3 - Bad
MRT	404966	3 - Bad
TCD	387173	3 - Bad
CAF	157448	3 - Bad
SSD	145892	#N/A
TGO	108579	3 - Bad
SOM	61803	3 - Bad
COG	60325	3 - Bad
ERI	32187	#N/A
ALB	28275	2 - Mid
COM	26221	#N/A
	Match =	92%

Year 2049		
Model country	**Starvation deaths**	**Food security grouping**
IND	29329331	3 - Bad
PAK	5361975	3 - Bad
NGA	3633883	3 - Bad
COD	2295423	3 - Bad
HND	1585863	3 - Bad

COG	356633	3 - Bad
PYF	191064	2 - Mid
SLB	158873	3 - Bad
YEM	148521	3 - Bad
PSE	114076	#N/A
TLS	91891	3 - Bad
TGO	81361	3 - Bad
AFG	70862	3 - Bad
STP	69835	3 - Bad
ERI	34011	#N/A
COM	31339	#N/A
TON	10679	#N/A
WLF	2155	#N/A
ESH	1590	#N/A
DJI	1054	3 - Bad
TUV	622	#N/A
MDV	615	#N/A
	Match % =	65

SDN	1123627	3 - Bad
ZWE	1006261	#N/A
MOZ	793231	3 - Bad
TCD	387173	3 - Bad
CAF	157448	3 - Bad
UGA	154403	#N/A
SSD	145892	#N/A
TGO	108579	3 - Bad
COG	103441	3 - Bad
MRT	91918	3 - Bad
ALB	51705	2 - Mid
ERI	32187	#N/A
COM	26221	#N/A
TLS	16847	3 - Bad
STP	7993	3 - Bad
DJI	203	3 - Bad
MDV	89	#N/A
	Match =	94%

B.18 Chapter 5: Verification of results

To check that the simulation produced logical results, countries recording a population at starvation deaths during 2000 to 2020 historical period were compared with historical data on undernourishment from the Food Security Indicators (FSI) (FAO 2021) and additional research into food crises. It is important to note that because the model explores only food availability and a condition of 'free form' trade, which makes exact calibration to historical data influenced by trade agreements redundant, this is treated as general verification rather than an exact validation.

The world population at risk of starvation from the simulation and the historical undernourishment (FAO 2021) from 2000 to 2020, both in terms of absolute count of population and percentage share of population, are presented in Table B.19 and Figure B.5. The simulation registers a population at risk of starvation that appears to coincide with an uptick in the historical population undernourished from 2000 to 2003, peaking in 2002. Taking an average of the absolute count and share of historical population undernourished for the years in which the simulation recorded population at risks of starvation, it was estimated that the risk of starvation reported here is equivalent to an 'additional' population at risk of starvation above a level of undernourishment experienced during 2000 to 2020 of ~825 million people and 13.1% of the population.

Further research indicates that historical food crises, linked to drought events, requiring Wood Food Programme (WFP) food aid in Sudan (WFP 2001), Ethiopia (WFP 2002) and Somalia (UN 2003) coincide with the countries for which the simulation registers a population at risk of starvation. It should be noted that, as expected, the simulation registers a lower count of population at risk of starvation than was undernourished during 2000 to 2020, and while registering food availability crises in 2002 and 2003 the simulation does not register the complex food price crisis in 2007 and 2008 (FAO 2009). This appears to reflect the assumed simulation conditions alongside the fact that, price dynamics and inequalities aside, there is currently enough food produced to feed the world (UN 2019). To this end, the results appear logical, albeit with limitations inherent to the assumed simulation conditions.

Table B.19: Verification of Chapter 5 results – comparison of simulated risk of starvation with current population undernourished.

Year	Study simulation results on population at risk of starvation		FAO (2021) historical data on undernourishment	
	Absolute count	Share (%)	Absolute count	Share (%)
2000	3,722*	0.00006%	800.3	13
2001	0	0	817.8	13.1
2002	44,700,256*	0.7%	839.6	13.3
2003	5,964,466*	0.09%	834.4	13.1
2004	0	0	836.4	12.9

2005	0	0	810.7	12.4
2006	0	0	764.9	11.5
2007	0	0	711.3	10.6
2008	0	0	685.5	10.1
2009	0	0	684.4	10
2010	0	0	636.8	9.2
2011	0	0	635.8	9
2012	0	0	637.4	8.9
2013	0	0	631.2	8.8
2014	0	0	606.9	8.3
2015	0	0	615.1	8.3
2016	0	0	619.6	8.3
2017	0	0	615	8.1
2018	0	0	633.4	8.3
2019	0	0	650.3	8.4
2020	0	0	768	9.9

* 2000: Sudan records population at risk of starvation = 3,722.
2002: Ethiopia records population at risk of starvation = 36,957,838; Somalia = 7,742,418.
2003: Somalia records population at risk of starvation = 5,964,466.

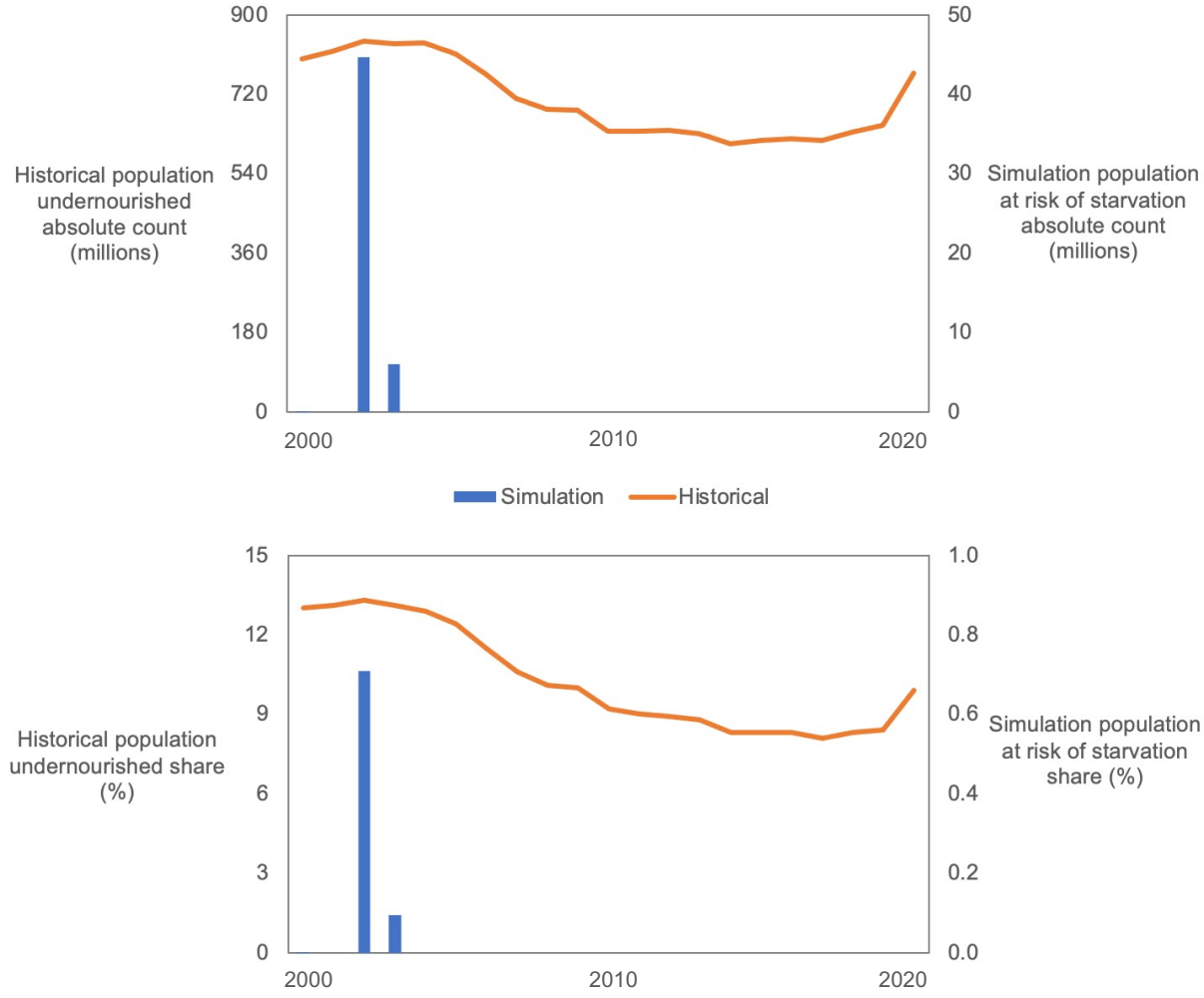


Figure B.5: Verification of Chapter 5 results – comparison of simulated risk of starvation with current population undernourished.

[blank page]