

Navigating Uncertain Futures: Applied Foresight Modelling and Anticipatory Governance for Food System Transformation

Daniel Mason-D'Croz

Propositions

1. Anticipatory governance is better at ruling out bad ideas than identifying good ones. (this thesis)
2. Fundamental uncertainty is a muse for what could be, not a monster to be tamed. (this thesis)
3. The messenger matters more than the message in science-policy discourse.
4. Paywalled science makes evidence-based decision-making a privilege of the wealthy.
5. Painting within disciplinary lines obstructs the imagination of futures that transcend present realities.
6. Science with cold proofs and sterile prose interrogates what only warm rhythm and rich rhyme can illuminate.
7. Resilience and safety are fundamentally in tension: societies that seek to eradicate risk may ultimately pay for it in fragility.
8. Civic engagement strengthens society less through its stated goals than through the solidarity created by collective action.

Propositions belonging to the thesis, entitled

Navigating Uncertain Futures: Applied Foresight Modelling and Anticipatory Governance for Food System Transformation

Daniel Mason-D'Croz
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Navigating Uncertain Futures:

Applied Foresight Modelling and Anticipatory Governance for Food System Transformation

Daniel Mason-D'Croz

THESIS COMMITTEE

Promotors

Prof. Dr J.C.M. van Meijl
Special Professor in Agricultural Economics and Rural Policy
Wageningen University & Research

Prof. Dr M. Herrero
Nancy and Peter Meinig Family Investigator in the Life Sciences
Ashley School for Global Development and the Environment, Cornell University, Ithaca, NY, USA

Other members

Prof. Dr. *ir.* E.H. Bulte, Wageningen University & Research
Prof. Dr. M. Banse, Thunen Institute of Market Analysis, Germany
Dr. K. Kok, Wageningen University & Research
Prof. Dr. *ir.* E.J.M. Feskens, Wageningen University & Research

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Navigating Uncertain Futures:

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for Food System Transformation

Daniel Mason-D'Croz

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AUTHOR CONTRIBUTIONS

This thesis is based on six published case studies, each representing an application of food system foresight research and anticipatory governance. Daniel Mason-D'Croz is the lead and corresponding author on five of the six published papers (Chapters 2–6) and was the lead author of the modelling section in the second EAT–Lancet report (Chapter 7). He was responsible for conceptualization, scenario design, quantitative modelling and analysis, and the writing of original drafts across all chapters. He was also responsible for responding to all peer review comments, and revisions of original manuscripts. Daniel Mason-D'Croz's specific contributions and those of the thesis supervisors (Mario Herrero and Hans van Meijl) are described below by chapter.

Chapter 2: Ethical and Economic Implications of the Adoption of Plant-Based Alternatives to Beef[1]

- Daniel Mason-D'Croz led the conceptualization of this research in coordination with other co-authors and project leads. He was the primary bridge between the Ethics and Food Systems team at Johns Hopkins University and the USAGE economic modelling team at CoPS (Victoria University). He developed the scenarios, and collected the data used to disaggregate USAGE in the development of USAGE-Food. He led the writing of the original draft, and the revising and editing of the manuscript as a part of the peer review process.
- Mario Herrero was a co-author and contributed to conceptualization, supervision, and review and editing of the manuscript. He also contributed with organizing funding through Johns Hopkins University and the Stavros Niarchos Foundation for this work.
- Hans van Meijl, while not a co-author on this chapter, assisted in the inclusion of the article in the thesis, helping to place this work in the context of the broader literature of food system modelling and its contribution to the overall thesis as described in the Introductory and Conclusion chapters.

Chapter 3: Gaps Between Fruit and Vegetable Production, Demand, and Healthy Consumption[2]

- Daniel Mason-D'Croz led the conceptualization, IMPACT model development and application, scenario design, quantitative analysis, and writing of the original draft.
- Mario Herrero contributed to conceptualization, supervision, review and editing. He also contributed to funding acquisition from the Bill and Melinda Gates Foundation.
- Hans van Meijl, while not a co-author on this chapter, assisted in the inclusion of the article in the thesis, helping to place this work in the context of the broader literature of food system modelling and its contribution to the overall thesis as described in the Introductory and Conclusion chapters.

Chapter 4: Modelling the Global Economic Consequences of a major African Swine Fever Outbreak in China[3]

The chapter was jointly conceived by Charles Godfray, Sherman Robinson, and Daniel Mason-D'Croz.

- Daniel Mason-D'Croz developed the comparative static framework used with the IMPACT model. He led the quantitative modelling, analysis, and visualization of results. He also led the writing of the paper, and the revisions to the manuscript before publication.
- Mario Herrero contributed to the execution and write-up of the paper and facilitated funding for this work with the Australian Centre for International Agricultural Research.
- Hans van Meijl, while not a co-author on this chapter, assisted in the inclusion of the article in the thesis, helping to place this work in the context of the broader literature of food system modelling and its contribution to the overall thesis as described in the Introductory and Conclusion chapters.

Chapter 5: Agricultural R&D Investments and Contributions to Reducing Hunger in Africa[4]

This chapter was jointly conceived by Keith Wiebe, Mark Rosegrant, and Daniel Mason-D'Croz.

- Daniel Mason-D'Croz was the principal investigator of the FAO-commissioned project that formed the basis of this article. In coordination with Alejandro Nin Pratt, he developed and implemented the perpetual inventory model used to translate R&D investments into changes in productivity. He then worked with Dirk Willenbockel in the coupling of IMPACT and GLOBE. He led in the scenario design, quantitative modelling, visualization, and analysis. He led the writing of the manuscript and the revisions before publication.
- Mario Herrero, while not a co-author on this article, provided valuable advice on how to manage a challenging peer review process in the *World Development* journal. Along with Prof. van Meijl, he also helped with situating this chapter within the broader context of the thesis.
- Hans van Meijl, while not a co-author on this chapter, assisted in the inclusion of the article in the thesis, helping to place this work in the context of the broader literature of food system modelling and its contribution to the overall thesis as described in the Introductory and Conclusion chapters.

Chapter 6: Multi-Factor, Multi-State, Multi-Model Scenarios for Southeast Asia[5]

This chapter was jointly conceived by Joost Vervoort, Philip Thornton, Amanda Palazzo, and Daniel Mason-D'Croz.

- Daniel Mason-D'Croz led the writing of this paper with support from Joost Vervoort and Stephen Lord. He contributed to running and facilitating participatory scenarios, and along with Joost Vervoort and Amanda Palazzo converted the semi-quantification

of scenario drivers for use in IMPACT and GLOBIOM. He ran the IMPACT model. He led on the analysis and visualization of the regional scenarios. He was also the lead PI for IFPRI in the CGIAR CCAFS regional scenarios.

- Mario Herrero, while not a co-author of this article, contributed to the initial conceptualization of the CCAFS regional scenario methodology and supported initial scenario development in East Africa, the first of the CCAFS regional scenarios.[6] He has also helped with situating this chapter within the broader context of the thesis.
- Hans van Meijl, while not a co-author on this chapter, was a fundamental part of the first multi-model comparisons as a part of the Agricultural Model Intercomparison and Improvement Project (AgMIP), with many of the lessons learned from this exercise contributing to the interpretation and comparison of IMPACT and GLOBIOM results in this chapter.[7] Furthermore, he assisted in the inclusion of the article in the thesis, helping to place this work in the context of the broader literature of food system modelling and its contribution to the overall thesis as described in the Introductory and Conclusion chapters.

Chapter 7: Modelling for EAT-Lancet to assess potential environmental and socioeconomic consequences of a food systems transformation[8]

The overall conceptualization of the second EAT–Lancet Commission report was done in collaboration across the Commission and contributing authors, of which Daniel Mason-D'Croz was the leading economic modeler, under the leadership of the Co-Chairs Johan Rockström, Walter Willett, and Shakuntala Thilsted.

- Daniel Mason-D'Croz conceptualized the initial scenario construction used in this report in coordination with Mario Herrero, Hermann Lotze-Campen, and Alexander Popp. He then coordinated the multi-model ensemble, scenario revision and reporting process. He supervised and directed the data collection and led the model results interpretation and analysis for the chapter. He coordinated linkages between the modelling work and the other sections of the report. He led the writing of the modelling section, as well as responding to all peer review comments on the modelling section. He contributed to the environment, justice, and transformation sections, and assisted as one of the primary editors of the full report alongside Fabrice DeClerck and Ellen Wright. He directly supported the running of scenarios in the IMPACT model led by Abhijeet Mishra.[9] Alongside Mario Herrero, he coordinated the publication of a series of background papers that heavily informed the chapter, including a special issue in *The Lancet Planetary Health*.[10–13]
- Mario Herrero was a Commissioner and the modelling section lead. He contributed to the initial conceptualization of the Commission's modelling approach and contributed to reviewing and analyzing modelling results and interpretation. Alongside Daniel, Detlef van Vuuren and Marco Springmann (fellow commissioner) were the leads on communication and explaining modelling results to the rest of the EAT–Lancet Commission. Alongside Daniel, he coordinated the publication of background papers and a Special Issue in *The Lancet Planetary Health*.

- Hans van Meijl contributed to the multi-model ensemble and assessment as a part of the MAGNET modelling team. He also reviewed and assisted in editing the write-up of modelling results, contributing to several of the background papers from which the EAT–Lancet analysis was partially based.[10,12–15]

Supervisory roles

Mario Herrero (Cornell University) and Hans van Meijl (Wageningen University and Research) served as PhD supervisors for this thesis. Their supervisory contributions spanned intellectual mentorship, review of thesis chapters and publications, guidance on research design and framing, and support for the development of the anticipatory governance framework that underpins the thesis.

Mario Herrero's supervisory engagement was expressed primarily as the day-to-day supervisor, and research collaborator over their mutual time in the CGIAR, CSIRO, and at Cornell University. He was a co-author on Chapters 2, 3, 4, and 7 and contributed to the conceptualization of methods applied in Chapter 6, and provided moral support during the final revisions of Chapter 5. He was also fundamental in acquiring the resources to sustain much of the research included in this thesis.

Hans van Meijl's supervisory engagement was expressed through three primary channels. First, through the institutional framework of the Wageningen PhD programme. He played a critical role in supporting the completion of thesis requirements and facilitating the administrative and logistical aspects of completing the PhD. He advised on the selection of appropriate courses, and on important reading materials to supplement and improve the theoretical underpinning of this work. Second, through long-standing mentorship as a part of the Agricultural Model Intercomparison and Improvement Project (AgMIP). This project was foundational in terms of developing key modelling and quantitative analysis skills, and directly contributed to approaches that were used to do multi-model comparisons in Chapters 6 and 7. Third, he was an important guide and mentor in navigating the challenges of conducting economic modelling in a politically challenging arena like that of EAT–Lancet and food system transformation.

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ON EPIGRAPHS: INTERWOVEN DIALOGUES

This thesis opens with a short story by Jorge Luis Borges about a map the size of an empire and closes with a passage from Italo Calvino about futures not pursued, and the dead branches of the past, the possible lives that were never realized. Between them, seven more epigraphs mark the opening of each chapter, and one final epigraph accompanying the acknowledgements. Each of these epigraphs represents ideas and thinkers who have inspired me while writing or reflecting on systemic change and transformation, and this note provides an explanation behind my decision to include them.

One through-line I have learned over a decade of experience in anticipatory governance and foresight research is that understanding food systems in all their complexity requires more than technical modelling. It requires imagination, as well as deep reflection on what we value. The quantitative tools applied across the thesis's six case studies are powerful instruments for engaging systematically with complexity and uncertainty, but they are also simplifications of realities. Foresight modelling at its most useful is not a machine for producing answers but a framework for asking better questions. They let us hold up a mirror to alternative visions of the future, making embedded assumptions and values transparent and more open to contestation.

Literature, poetry, and political philosophy go places that models cannot. They speak directly to intrinsic values, such as justice and beauty, which resist the certainty of clean quantitative outputs. However, it is in the mess of these values where human judgement must ultimately reside, and while technical analysis is helpful in informing these judgements, they cannot substitute for it. The epigraphs in this thesis were selected because I see them as companions to the chapters, walking alongside them, acting not as decoration but as a parallel form of reasoning, a second voice that frames the scientific content in its fuller human and political context.

The selection of epigraphs spans a range of thinkers, poets, and authors and reflects in part the chorus of artistic and philosophical influences that have inspired and challenged me throughout my life. The constellation assembled here hopefully reflects the conviction expressed throughout this thesis: that plurality of visions and perspectives is critical, and that imagining transformative futures will require transcending siloed thinking.

WHY THESE LITERARY COMPANIONS?

Chapter 1 — Jorge Luis Borges, *On Exactitude in Science*, trans. Andrew Hurley

The thesis opens with Borges's one-paragraph story about an empire whose cartographers built a map the size of the empire itself, which proved useless and was eventually abandoned. It is a powerful metaphor for efforts at developing ever more complex and precise system models, and a reminder of the need for humility and not letting the models be the driving focus of research efforts. Every model in this thesis is a map smaller than the territory it represents. That is not a failure but a precondition for usefulness.

Chapter 2 — Octavia E. Butler, *Parable of the Sower*

Butler's mantra of change describes the challenges of thinking about transformative change, as the very paradigms and values we use to judge this change are themselves co-evolving. This chapter's multi-perspective ethical analysis is an attempt to more holistically think about the consequences of technological change, not only in who wins and loses, but also to more fundamentally think about what we want our food systems to do. It recognizes that complex systems are ever changing, and that efforts to shape the food system will not only change the system but will require changing ourselves. This endogeneity is one of the sources of the fundamental uncertainty with which we must engage.

Chapter 3 — Pablo Neruda, *Oda a la Cebolla*, trans. Wally Swist

Food is so much more than energy, nutrients, or trade flows. Food is culture and identity, and pleasure and joy. Food is central to so much of what we think of as beautiful, delicious, decadent, reviving. When working with models it can sometimes be easy to forget that systems analysis is more than 0's and 1's. Neruda's Ode to the Onion is a reminder of the simple pleasures that food can provide. It makes us stop and appreciate the aromas and tactile pleasures of food, nodding more broadly to the abundance of values that we derive from food, and how it can alleviate many desires beyond hunger, even as it hints at inequities of who can access food. This last note is all the more important as, despite decades of progress, there is still a long way to go to ensure that everyone can enjoy sufficient, healthy, and nourishing food.

Chapter 4 — John Donne, *Meditation XVII*

Donne wrote his Meditation XVII while seriously ill, hearing church bells toll for the dead and uncertain whether the next bell would toll for him. The meditation is about systemic interconnectedness, and how a loss anywhere diminishes everyone everywhere. This idea speaks to the interconnected nature of modern food systems, where a shock in one far-distant location can have unexpected and sometimes tragic consequences elsewhere. Furthermore, this poem speaks to the timing of the writing and publication of this chapter at the threshold of the global pandemic, and the political inward shift that seeded doubts on the commitment

to liberal and democratic ideals, undermining the idea of mutually beneficial cooperation, solidarity beyond nationality and ethnicity, and the value of pluralistic interconnection.

Chapter 5 — Elizabeth Bishop, *Questions of Travel*

Bishop asks whether it is lack of imagination that makes us come to imagined places rather than staying at home. Chapter 5 is a study conducted primarily by researchers in institutions in the Global North, modelling what agricultural investment could achieve for hunger reduction in Africa. Bishop's question does not answer itself, and she ends her poem without a clear resolution, but with a lingering question. This hopefully is a reminder for humility, and to not overstate the precision of projections, and while the choice of the researcher and the studied population is "never wide and never free," imagination and exploration may yet be of service.

Chapter 6 — Amartya Sen, *The Idea of Justice*

Sen argues that there is a need for reasoned argument in dealing with conflicting claims, and that disengaged toleration—where "you are right in your community and I am right in mine"—is insufficient. Even rigorous reasoning may leave competing priorities unresolved, he acknowledges; but the plurality with which we then end up will be the result of reasoning, not of abstention from it. This passage was chosen for two reasons. First, it speaks directly to the participatory scenario methodology presented in this chapter, which was an example of the public reasoning Sen described, in that stakeholders from across Cambodia, Vietnam, and Laos came together to reason collectively about what the future of their food systems could be. Second, it speaks to a broader political commitment. At a moment of democratic backsliding and authoritarian governance globally, it is appropriate to recommit to foundational principles of development: that development is best achieved through the exercise of societies' and individuals' own agency and public reason, and not through the dictate of outside experts. Research for development should therefore aim more to build decision-making capacity.

Chapter 7 — Dr Seuss, *The Lorax*, and W.S. Merwin, *Witness*

Chapter 7 carries two epigraphs in dialogue. *The Lorax* was published in 1971, the same year as the first Earth Day, and its argument about industrial overreach, ecological collapse, and the failure of economic systems to internalize environmental costs anticipates the planetary boundaries framework applied in Chapter 7. The selected passage describes the "Street of the Lifted Lorax," now absent its former guardian, and bereft of its former biodiversity. W.S. Merwin's two-line poem *Witness* frames the same question in a different register.

Chapter 8 - Italo Calvino, Invisible Cities

Calvino's passage frames the thesis's closing reflection on what anticipatory governance is ultimately for. Marco Polo encounters cities as encounters with his own past selves and possible futures. Lives that could have been, futures not achieved, dead branches in the past. Anticipatory governance is precisely the practice of keeping branches alive, of acting in the present in ways that preserve future possibilities rather than foreclosing them. The thesis has explored, across six case studies, how food system decisions made today shape the space of food system futures available tomorrow. Calvino frames this project a reminder to keep alive the futures we have not yet chosen.

Acknowledgements — Antonio Machado, Caminante. trans. Mary G Berg and Dennis Maloney

Antonio Machado is one of my favorite poets and this poem is offered in gratitude to everyone who walked alongside me in this academic journey.

CONTENTS

Funding Acknowledgement V

Author contributions VI

On epigraphs: interwoven dialogues XI

Chapter 1 1
Introduction

Chapter 2 41
Ethical and economic implications of the adoption of novel plant-based beef substitutes in the USA: a general equilibrium modelling study

Chapter 3 69
Gaps between fruit and vegetable production, demand, and recommended consumption at global and national levels: an integrated modelling study

Chapter 4 95
Modelling the global economic consequences of a major African swine fever outbreak in China

Chapter 5 117
Agricultural investments and hunger in Africa modeling potential contributions to SDG2-zero hunger

Chapter 6 153
Multi-factor, multi-state, multi-model scenarios: exploring food and climate futures for Southeast Asia

Chapter 7 185
Modelling for EAT-Lancet to assess potential environmental and socioeconomic consequences of a food systems transformation

Chapter 8 211
Discussion and conclusions

Appendices and data availability 251

Summary 257

Acknowledgements 263

About the author 269





Introduction

En aquel Imperio, el Arte de la Cartografía logró tal Perfección que el mapa de una sola Provincia ocupaba toda una Ciudad, y el mapa del Imperio, toda una Provincia. Con el tiempo, estos Mapas Desmesurados no satisficieron y los Colegios de Cartógrafos levantaron un Mapa del Imperio, que tenía el tamaño del Imperio y coincidía puntualmente con él. Menos Adictas al Estudio de la Cartografía, las Generaciones Siguientes entendieron que ese dilatado Mapa era Inútil y no sin Impiedad lo entregaron a las Inclemencias del Sol y los Inviernos. En los desiertos del Oeste perduran despedazadas Ruinas del Mapa, habitadas por Animales y por Mendigos; en todo el País no hay otra reliquia de las Disciplinas Geográficas.

In that Empire, the Art of Cartography attained such Perfection that the map of a single Province occupied the entirety of a City, and the map of the Empire, the entirety of a Province. In time, those Unconscionable Maps no longer satisfied, and the Cartographers Guilds struck a Map of the Empire whose size was that of the Empire, and which coincided point for point with it. The following Generations, who were not so fond of the Study of Cartography as their Forebears had been, saw that that vast Map was Useless, and not without some Pitilessness was it, that they delivered it up to the Inclemencies of Sun and Winters. In the Deserts of the West, still today, there are Tattered Ruins of that Map, inhabited by Animals and Beggars; in all the Land there is no other Relic of the Disciplines of Geography.

Jorge Luis Borges, *On Exactitude in Science*, trans. Andrew Hurley

1.1 Background

Food systems are among the most consequential human systems, and have been foundational to the survival and development of human societies since at least the Neolithic Revolution[1,2]. They have both been shaped by human actions and helped to shape the evolution of *Homo sapiens* as a species (e.g., the cooking hypothesis[3]). Today, global food systems feed over eight billion people and employ roughly one-third of the world's labour force, and in many ways are a modern wonder. And yet they fail to supply healthy diets for all[4], and sit at the intersection of nearly every major sustainability challenge[4–8], and are increasingly challenged by geopolitical shocks[9–11], pandemics[12,13], outbreaks of animal and crop diseases[14–16], extreme weather[17,18], technological disruption[19,20], and the consequences of their own environmental footprint. Transitioning towards more sustainable, healthy, and just food systems will therefore be one of the defining governance challenges of this century.

However, food system complexity and fundamental future uncertainty make such a food system transformation difficult to anticipate, design, and achieve[6,21,22]. Decisions made today about agricultural investments, dietary policy, and food system innovation will help to define future food system trajectories for decades to come. Yet, the consequences of these decisions are often counterintuitive, difficult to anticipate, and unequally distributed across societies and geographies. Policymakers must act under conditions of imperfect knowledge[23], constrained agency, diverse stakeholder values[24], competing objectives[25], and irreducible uncer-

tainty[26]. Still, inaction is also a choice, and one that is becoming increasingly costly[27]. Taken together, these constraints mean policymakers must make hard choices[28] to tackle wicked[29] food system problems, and accept real trade-offs as even the best solutions cannot ensure food systems improve across all relevant dimensions for all people at all times.

Against this backdrop, a growing body of scholarship has focused on developing approaches to assist decision-makers to systematically engage with system complexity and future uncertainty, that is to anticipate, prepare for, and shape the future rather than simply react to it[30–38]. This thesis contributes to that body of work, focusing specifically on how scenario analysis and quantitative foresight modelling can be combined to explore how food systems function and to inform food policy towards more sustainable, healthy, and just futures. These approaches are part of the anticipatory governance (AG) toolkit, and help decision-makers systematically, rigorously, and reflexively engage with and shape uncertain futures[35].

AG includes a range of applied methods such as scenario development[31,39,40], theories of change[41], systems mapping, horizon scanning, and quantitative foresight modelling[34]. AG builds on a foundation of "systems thinking", an analytical approach to thinking about systems that looks to: (1) identify and understand systems and system components, (2) anticipate system behaviours and outcomes, and (3) develop interventions to produce desired outcomes[42]. When systems thinking is combined with futures and participatory approaches, AG can help expand the perceived possibility space, surface hidden assumptions, reveal potential trade-offs, and guide more informed policy dialogues. AG can facilitate the combination of qualitative and quantitative knowledge in coherent narratives[43–46] that can help not only to better conceptualize futures, but also to organize action to shape and define the future[35]. AG has evolved in parallel with and been informed by a tradition of research for development (R4D) and is an applied discipline which looks to encourage and inform more transparent and rigorous evidence-based decision-making. Figure 1.1 presents a stylized impact pathway of anticipatory governance research, with the research outputs only being part of a broader story of informing food policy and contributing to improved food systems (outcomes and impact).

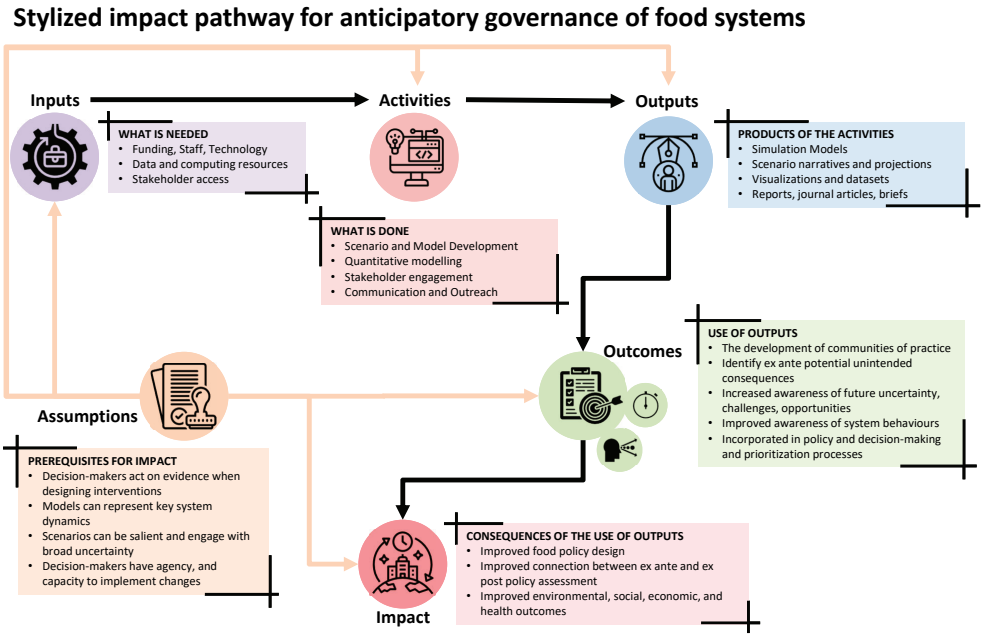

Figure 1.1: Stylized impact pathway for food systems foresight research and anticipatory governance
Notes: Informed by figures in Schuetz et al.[47].

Within the domain of food and agricultural policy, there is a long tradition of scenario planning, particularly in the building of baseline projections (i.e., plausible/likely estimates assuming a continuation of current conditions and trends) to consider the potential mid- and long-term evolution of regional and global food systems[38]. The United States Department of Agriculture (USDA) began its annual Agricultural Outlook forum in 1923, bringing together experts from all over agriculture to develop and review 10-year agricultural commodity forecasts[48]. The UN's Food and Agriculture Organization (FAO), published its first multi-decadal food projection in the early 1980s in response to the 1974 World Food Conference's proposed goal of eradicating hunger by the mid-1980s[49]. Since then, many additional efforts have been made to develop plausible baselines projections. Increasingly, multi-decadal baseline scenarios were developed from the late 1980s onwards including work supporting the United Nations' Intergovernmental Panel on Climate Change (IPCC) to estimate potential consequences of climate change since the first assessment report[50], followed by efforts in the mid-1990s by the International Food Policy Research Institute (IFPRI) to estimate changes in global food security by 2020[51] as well as global efforts such as the Millennium Ecosystem Assessment[52] and the International Assessment of Agricultural Knowledge, Science and Technology for Development[53] among others. All these efforts developed rigorous baseline projections based on assumptions on key drivers of food system change including population and economic growth, food and agriculture policy environment, technological progress, and consumer behaviour. These projections were often informed through statistical projection, but increasingly used sophisticated economic simulation models including detailed sector,

or partial equilibrium models, such as IFPRI's IMPACT[54], FAO's Aglink-Cosimo[55], IIASA's GLOBIOM[56], and PIK's MAGPIE[57], general equilibrium, or whole-of-economy models such as WUR's MAGNET[58], CSIRO's GTEM[59], and ENVISAGE[60] models, as well as a range of more micro-level models of household, and farm-level behaviour.

Simulation models have played a crucial role in AG by providing systematic frameworks for exploring how complex food systems might respond to various shocks, policies, and trends (e.g., population growth or economic development). These models can be broadly categorised into (1) biophysical models, which simulate natural processes such as crop growth, water cycling, and climate dynamics, and (2) socioeconomic models, which represent human decision-making, market dynamics, and economic interactions[38]. Integrated Assessment Models (IAMs), are models which bridge these two classes, integrating biophysical and social modelling to capture feedback loops between social and biophysical systems. Among socioeconomic models, equilibrium models are particularly valuable for policy analysis as they describe how economic systems adjust to changes through price mechanisms and resource reallocation until supply and demand reach balance. Equilibrium models can vary in their detail, as well as coverage of the overall economy. And due to data and computational constraints there are usually trade-offs between breadth of coverage (e.g., single sector vs. the whole economy, or national vs global) and the level of detail that specific economic activities can be simulated. On the broader end of the spectrum fall Computable General Equilibrium (CGE) models that simulate the whole economy, including factor markets (e.g., labour, land, capital, etc.). This framework allows for better simulation of the many interconnections across the economy, including around analysis on livelihoods, employment, and changes in income. Partial Equilibrium (PE) models focus on one or more sectors, and tend to simulate these economic activities, including production systems, material flows, and market structures in greater detail. This sectoral focus when applied to agricultural production and food systems can enable analysis in natural units (e.g. kilogrammes, calories, hectares) and facilitate food security and environmental assessments.

These quantitative modelling tools are particularly valuable for exploring long-term structural transitions, stress-testing systems under plausible shocks, and identifying investment priorities with multiple co-benefits when they are linked to qualitative narratives (i.e., scenarios) that can explore a broad range of alternative assumptions around key system drivers (e.g., population, income, consumer preferences, changes in policy, etc.).

Scenarios are a critical tool for anticipating and planning for the future. In practice, scenarios are what if questions.

- What if the world looked differently than the present?
- What if we enacted a policy (e.g., raised a tax)?
- What if values in society changed (e.g., the adoption of a new religion)?
- What if a new technology were widely adopted?

We develop scenarios from a combination of qualitative and quantitative elements, and in contrast to other scenarios (e.g., baseline projections) or a representation of the present (e.g., vs status quo). Scenarios serve to provide a logical scaffolding to alternative realities and ensure that these visions of alternative realities are internally and logically consistent. For example, a scenario with high fossil fuel use would not be consistent in a low emissions future, unless the scenario also included some way of capturing and storing greenhouse gases (e.g., highly efficient direct air capture). When scenarios are quantified and simulated in quantitative models it facilitates more rigorous system analysis, and can help to better understand potential system outcomes including potential unintended consequences[61–63].

Anticipatory governance and foresight analysis are useful tools for navigating an uncertain future, facilitating a systematic exploration of a wide range of potential futures. Their strength is less as tools of prediction, than to facilitate exploration of complex systems, future uncertainty, and the many often untransparent assumptions and values that are held. They can help assess potential trajectories of change, prepare for plausible shocks, and design interventions that can help ensure that food systems continue to fulfil their fundamental role in supporting human welfare and social stability in an era of rapid change. This thesis will explore a body of applied research in Anticipatory Governance, focusing on how scenario analysis can be combined with quantitative systems modelling to inform food policy.

1.2 Research objectives

The complexity of the global food system and fundamental uncertainty about future developments create fundamental challenges to evidence-based food policy. This thesis contributes to the growing research area of anticipatory governance by demonstrating, across six case studies, how the deliberate combination of qualitative scenario analysis and quantitative foresight modelling can inform food policy aimed at achieving more sustainable, healthy, and just food systems. To address this overarching question, the thesis seeks to better understand the following questions:

- What is the role of food system innovation in facilitating food system transformations?
- How resilient are food systems to external shocks (e.g., climate change, pest and diseases, and technological change)?
- How do changes across food systems contribute to changes in diets and nutrition and food security?
- How does food policy contribute (or not) to achieving desired outcomes?
- What are the environmental consequences of food system change?

In the process of exploring these questions, a range of methodological approaches in scenario design and foresight modelling will be applied to explore future uncertainty and engage with food system complexity across a range of spatial (national to regional to global) and temporal (short to long term time horizons) scales. Figure 1.2 gives a high-level summary of the questions and approaches taken across thesis chapters.

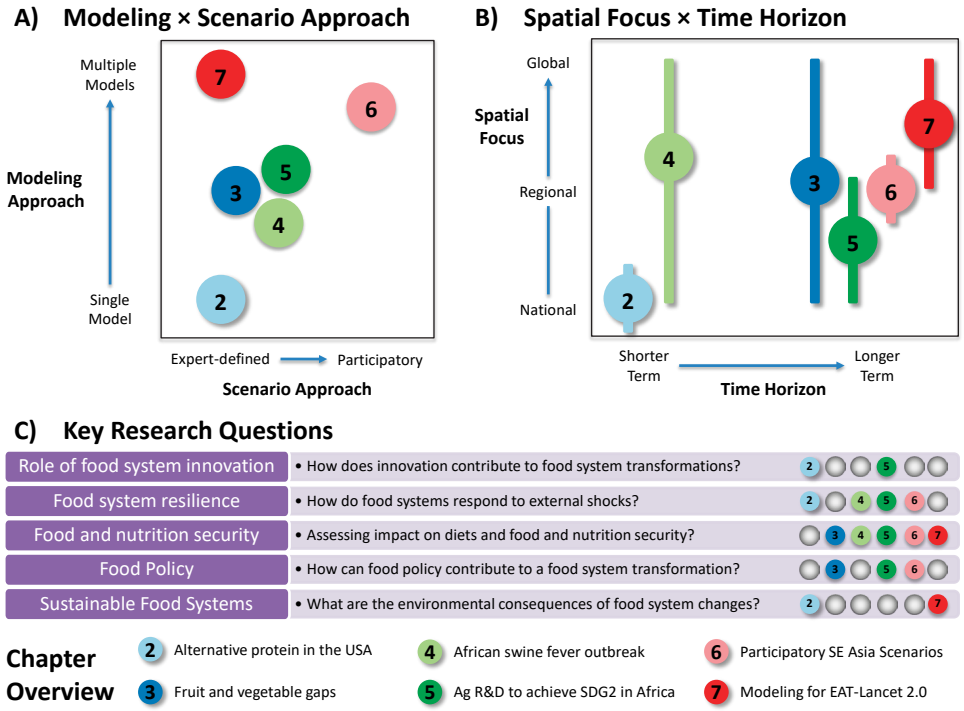

Figure 1.2: Graphical summary of the research undertaken.

1.3 Methodology

Food systems are complex systems, that is they are composed of many smaller systems with non-linear interactions and emergent behaviours that cannot be understood by analysing components in isolation, and where the complexity of sub-systems is not reduced by zooming in greater detail (e.g., focusing on a single landscape, or individual commodity market)[64]. Different actors and decision-makers have the capacity to impact food outcomes at different scales. Individual consumers, for example, on their own have limited capacity to change broad food system trends, but their decisions can have important consequences on household nutrition and food security, whereas national policymakers through the application of government power can change incentives to encourage broader system changes, but are themselves constrained by limited local knowledge, and external trends outside their scope of immediate control (e.g., climate change). To inform food policy then requires tools that can be applied to different geographic and sectoral scales (see figure 1.3). The research summarized in this thesis applies scenario analysis and quantitative modelling primarily at the macro level, i.e. national to global scales (see figure 1.2), however, many of these approaches can be adapted to or scaled down to meso- and micro-scales[40,65–68]. For example, scenarios developed in Chapter 6[70] were later linked to LANDSHIFT[71], a land-use change model, to assess potential changes to local ecosystems and biodiversity[72,73].

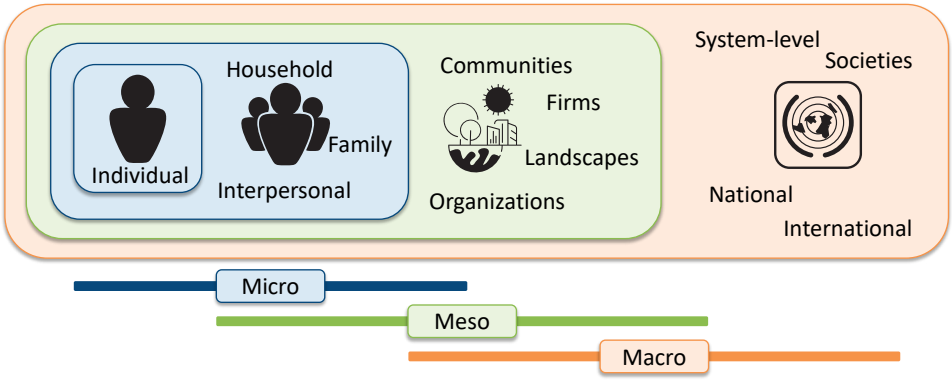

Figure 1.3: Scales of decision-making

Notes: Informed by multiple sources.[74–76]

In addition to the scale, decision-making in the food system is challenged by drivers of change that can operate on different time horizons. For example, the impact of extreme weather events can be instant requiring actions that work on short-time horizons of days or even hours. Whereas, other changes can happen on longer time scales, such as population growth or climate change. Developing food policy in anticipation of these varied challenges, requires applying anticipatory governance recognizing that decisionmakers can be constrained in diverse ways under short- and long-term planning. This thesis highlights anticipatory governance that informs both short- and long-term planning challenges (figure 1.2). For short term planning, scenarios are developed in comparative statics, which they compare equilibrium states before and after a single exogenous shock. For example, in Chapter 4, the exogenous shock is the outbreak of African Swine Fever in China[77]. This chapter focuses on the initial consequences of a severe outbreak, to assess the scale of impacts that could occur, but does not explore how systems could respond to and adapt to this shock over time. In longer run scenarios, suites of scenarios are developed and compared to a baseline scenario that projects how food systems may evolve following current trends (i.e., business-as-usual). For example, Chapter 5 considers the longer time horizons between investments in R&D and changes in agricultural productivity[69]. This analysis used an expert developed baseline scenario assuming current investment levels and productivity growth trends[54], and then explored the consequences of increasing investments in agricultural R&D.

Scenarios can range from more exploratory in nature (i.e., trying to understand potential consequences or outcomes of changes in system drivers), or more strategic (i.e., inform or prioritize actions to achieve specific future outcomes). Scenario development approaches can vary substantially in their implied cost, the ease of replicability, and the capacity to incorporate diverse local knowledge. No single approach is universally applicable, and this thesis applies multiple scenario development approaches, ranging from participatory stakeholder workshops (Chapter 6) to expert elicitation and econometric parameterization (Chapter 5)

to the application of established scenario frameworks (Chapters 3 and 7). Sections 1.3.1 and 1.3.2 summarise the types of scenarios developed and the scenario design processes used in this thesis.

Quantitative modelling complements scenario analysis by providing rigorous frameworks for structured inquiry into food system dynamics, and, when done well, the transparent translation of qualitative scenario assumptions into quantitative parameters. However, all models are simplifications of reality, and no single food system model is appropriate for all questions or contexts. Therefore, this thesis applies a range of modelling approaches matched to the spatial and temporal scales of each research question (figure 1.2). Sections 1.3.3 and 1.3.4 describe the classes of quantitative modelling, and modelling configuration applied in this thesis.

The responsible application of anticipatory governance must engage with the question of by whom, and for whom, anticipatory governance is conducted. The scenarios, models, data sources, and analytical frameworks that are applied in this thesis embed choices about which futures are worth exploring, which actors and outcomes deserve attention, and which system dynamics are considered important. These choices are often driven by pragmatic constraints including funding and project timelines. For example, the use of national and international production statistics can foreground a food supply orientation at the expense of more consumer-focused perspectives, even as national and international production statistics remain the most complete historical datasets for building food system models. Nevertheless, the use of these datasets and models can inadvertently prioritise certain pasts, presents, and futures at the expense of others. Addressing this point requires intentional efforts to broaden whose perspectives are reflected in anticipatory governance research, and to engage critically with the power dynamics that shape not only the present, but who gets to imagine the future[35]. The thesis addresses this point in several ways: Chapter 6 most explicitly embeds participatory stakeholder perspectives in scenario design; Chapter 2 deliberately foregrounds distributional justice through an explicit ethical assessment framework; and Chapters 3, 5, and 7 prioritise food security and nutrition outcomes for the most vulnerable populations as primary rather than secondary metrics. Nevertheless, despite efforts to more pluralistically ground the research in this thesis, it is important to recognize that tensions around questions of anticipatory governance for whom and by whom have not been entirely resolved, and future anticipatory governance research must engage with a broader range of futures[78,79].

1.3.1 Scenario types

Scenarios incorporate external drivers that are outside of the scope of control of the scenario users (i.e., drivers to which the users must respond to)[80–82]. Scenarios are developed in sets to contrast to other alternative realities. As such a fundamental part of using scenarios is the careful design of counterfactuals across the scenario set, to ensure each scenario is unique,

and that the differences in assumptions are clear, to facilitate explaining the difference in outcomes.

Scenario sets can be developed for many purposes, to inform different anticipatory governance objectives[35]. Following the general scenario classification suggested by Börjeson and colleagues[82], scenario sets used in this thesis can be described across 2 dimensions.

- Type of future action scenarios were designed to inform. Are they designed to question the future (exploratory) or are they designed to help inform actions in the present to shape the future (strategic)?
- Type of future that is envisioned. Are they trying to project the future (probable), or to consider a broad range of potential futures (plausible) or to define or imagine a normative future (desired)

Work in this thesis includes both exploratory and strategic scenarios. More exploratory scenario sets focus on considering potential opportunities and challenges in various alternative futures. For example, in Chapter 6 the regional scenario set was designed to explore a broad range of plausible futures to consider how these different futures could present different challenges to regional climate adaptation. Several of the scenario sets developed in this thesis are more strategic, they are action-oriented with a goal of exploring and informing actions to achieve more specific goals. For example, the scenarios developed in Chapter 5 were designed to assess the benefit-cost of increasing Agricultural R&D investments with respect to reducing hunger in Africa.

Box 1: The Calibrated Baseline Scenario — Constructing a Credible Counterfactual

A robust counterfactual is a prerequisite for rigorous quantitative foresight modelling. In short run analysis it is possible to use the current state as the counterfactual, but in long run analysis (i.e., decades into the future) it is critical to develop a counterfactual of how the system might have evolved over time without a shock to the system. The baseline scenario is a conditional projection of what could happen absent substantial structural change. It is constructed assuming that key drivers (e.g., population growth, economic development, technological progress, consumer preferences, and existing policies) continue along trajectories consistent with the recent past. The baseline scenario establishes the reference trajectory against which alternative futures are compared, enabling assessment of how policy changes and other external shocks (e.g., climate related, or a pandemic) could produce meaningful deviations from this reference trajectory. The quality of foresight modelling is therefore in part a function of the quality of this baseline. As such, modelling teams dedicate substantial effort in justifying and validating the assumptions that underpin their baseline scenarios. This process begins with using authoritative data sources (e.g., national and international statistics and projections) and often includes some overlap with the recent past

to facilitate model calibration to observed system behaviour. In this thesis, baseline socioeconomic assumptions are anchored in the Shared Socioeconomic Pathways, most commonly SSP2 (the "middle of the road" pathway) consistent with a body of global modelling for the IPCC and beyond[83–85]. Agricultural production, demand, and trade are primarily based on FAO statistics[86], supplemented by national statistics and quantitative modelling[87]. These projections are then continually reviewed and revised, including updating and revising elasticities of supply and demand, parameters of technological change, and land-use conversion based on recent literature and expert feedback[54,88], as well as from structured multi-model comparisons conducted through initiatives such as AgMIP[89–93].

Different types of futures can be envisioned using scenarios. For better understood processes scenarios can be used to assist in developing consistent projections of the future. This can be done using statistical methods to forecast outcomes with margins of error, or as conditional projections that attempt to simulate more likely futures. The calibrated baseline scenario described above is an example of more probable scenarios that are applied in this thesis. Where processes of change are less understood, then scenario sets can be developed to explore a broader range of alternative futures. Most of the scenarios applied in this thesis fall into this category. The goal of plausible scenario sets is to expand the possibility space that is considered, with the goal of engaging with future uncertainty and gaining a broader understanding of possible interactions and unintended consequences. Normative scenarios on the other hand are less about likelihood than about thinking about desirable futures, and what pathways of change would be needed to achieve these futures. They can also be helpful in developing the vision of what is a desirable future, by considering potential downsides of different changes, to iteratively redefine what shared futures should be acted upon. For example, in Chapter 7 the scenario set was developed to assess the socioeconomic and environmental consequences of achieving an EAT-Lancet style food system transformation composed of a shift to a healthy diet, increased agricultural productivity, and reduced food loss and waste. The scenario results suggested there could be equity concerns, and that not all environmental targets would be achieved, which suggested that while such a change could contribute to a more sustainable food system, additional actions would need to be included in the transformation bundle to ensure an environmentally sustainable, healthy, and just food system.

Figure 1.4A summarizes the scenario sets applied in this thesis across these two dimensions. Scenarios can be composed of a range of qualitative and quantitative elements. The scenario sets developed in this thesis are semi-quantitative, with a mix of qualitative and quantitative elements, but in general tend to be more quantitative in nature, as highlighted in figure 1.4B.

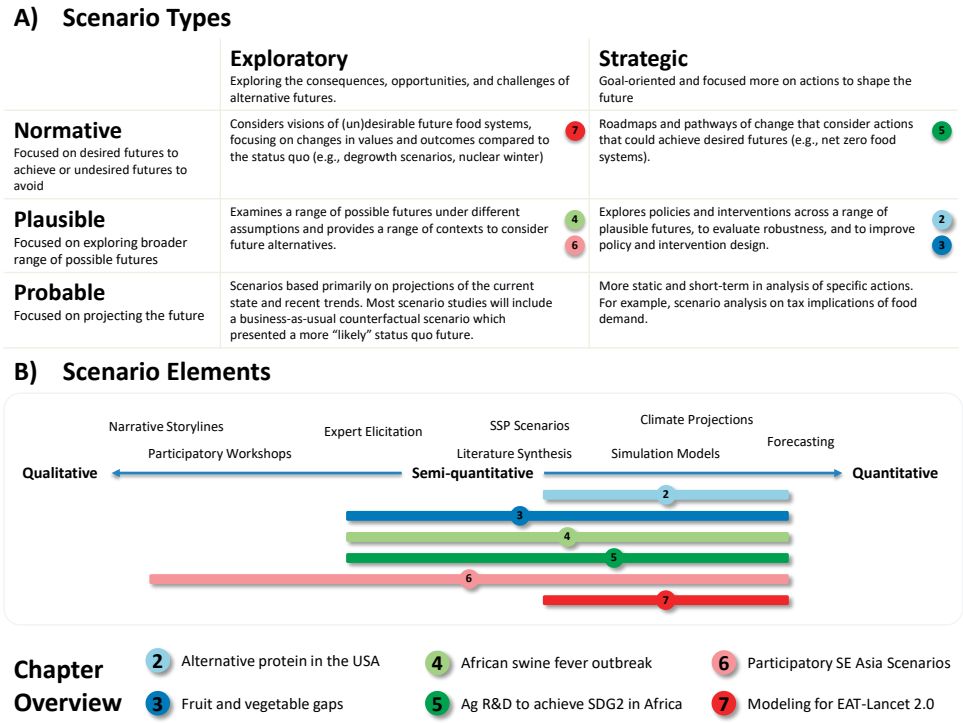

Figure 1.4: Summary of scenario types and scenario elements by thesis chapter.

1.3.2 Scenario design

Scenarios vary with respect to how they are developed, and who participates in their development. Scenario development approaches exist along a continuum from highly structured, expert-driven (top-down) methods to collaborative, stakeholder-engaged (bottom-up/participatory) processes. Most of the scenarios in this thesis are primarily top-down expert-based scenarios. However, even within these top-down scenarios there are examples of elements that try to pull together a broad range of perspectives from literature and expert elicitation. The baseline scenario used in the IMPACT model (used in Chapters 3-7) for example, has been developed iteratively, and reviewed carefully by commodity and country experts across the CGIAR to improve their representation of a business-as-usual future[54,88]. Multi-model ensemble exercises such as the one used to inform the second EAT-Lancet report[4] (Chapter 7), created iterative scenario development processes with opportunities for multiple modelling groups to review and revise scenario construction. Even in more participatory scenarios, not all elements of the scenario are co-developed, recognizing that there may be areas that

stakeholders have limited expertise or control over that are better suited to be incorporated as exogenous scenario inputs to help ensure plausibility (e.g., climate change in Chapter 6). Each of these two scenario development approaches, summarized in figure 1.5, has distinct strengths and weaknesses, and ultimately the choice of where on the continuum scenario design will fall depends on project objectives, policy context, and available resources and time.

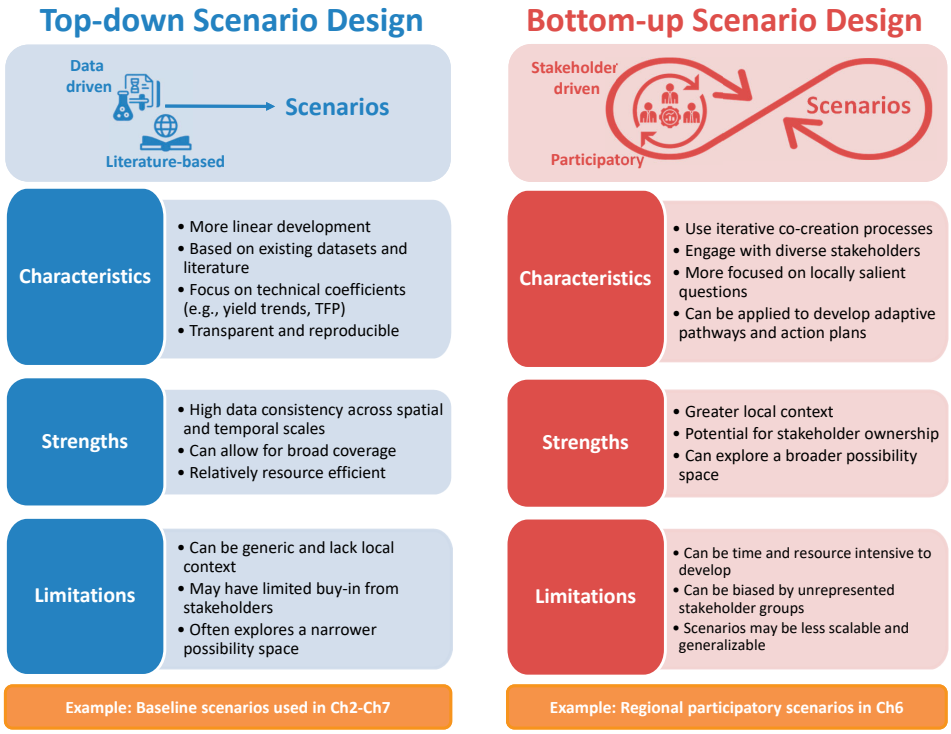

Figure 1.5: Scenario development approaches - a stylized comparison.

Top-down data-driven scenarios are usually led by technical experts and researchers, who use formal analytical frameworks (i.e., quantitative models). They are developed using a range of inputs such as literature reviews, expert elicitation, statistical forecasting based on historical trends, as well as applying pre-existing scenario frameworks such as the IPCC's Shared Socioeconomic Pathways[84]. This approach prioritizes scientific rigor, reproducibility, and transparency of data sources and assumptions. Typically, top-down scenarios are faster and less resource intensive to develop compared to more participatory scenarios. However, they can be narrower in their scope and less connected to locally salient context of policymakers. The scenario sets developed in Chapters 2 and 7 are examples of exclusively top-down scenarios constructed either from literature reviews, or existing scenario frameworks.

Bottom-up participatory scenarios are co-developed through interactions with diverse stakeholders. These interactions can apply a range of participatory and visioning methods (e.g.,

backcasting, community mapping, visioning exercises, group-based model building, etc.), and look to incorporate local knowledge, and build a shared understanding of challenges and opportunities facing the participating stakeholders[32,45,94–101]. They tend to be focused on specific topics that are salient and within the control of stakeholders and can borrow from top-down approaches in areas where stakeholders have more limited expertise or control. These participatory approaches can increase the legitimacy and ownership of the scenarios by the participants. These processes can also be useful tools for building local anticipatory governance capacity and improve the interpretation and use of scenarios. Participatory future exercises can be valuable future shaping processes, and through dialogue can build trust and a shared vision of desirable futures. Nevertheless, participatory processes tend to be expensive and time-intensive to develop, requiring substantial travel and logistics to ensure stakeholder engagement. Participatory scenarios are heavily influenced by participating stakeholders, and are not easily replicable (i.e., different stakeholders may have different visions of the future).

Translating qualitative storylines whether they are developed using top-down or bottom-up approaches for use in quantitative models requires careful translation to ensure the narratives are faithfully represented in the models. In Chapter 6, for example, participatory scenario narratives were developed by defining Factors of Change, and Factor States, then were semi-quantified through iterative rounds of translation before being simulated in two global partial equilibrium models (IMPACT and GLOBIOM). The following sections describe the classes of quantitative models applied across this thesis and how the models were configured for each research question.

1.3.3 Quantitative models

There are many classes of quantitative simulation models that can be used to analyse food systems, including but not limited to system dynamics, agent-based models, input-output models, optimization models, gravity trade models, land use change models, and equilibrium models. Each approach has strengths and weaknesses. Given that the work in this thesis focuses on the macro level (i.e., national to global, figure 1.2) and questions of broad-based changes equilibrium models were chosen as the primary economic assessment tools.

Economic equilibrium models are based on general equilibrium theory, where economic agents (consumers, producers) are rational (i.e., they respond to price changes) and are constrained by resource scarcity (e.g., time, income, etc.). Economic agents respond to prices (e.g., high prices encourage more production but less consumer demand), such that the economy achieves equilibrium where supply equals demand across markets. Economic equilibrium models are deterministic steady state models, meaning that if no changes are made to model parameters it will reproduce the original equilibrium. When applied for policy analysis these models are shocked out of equilibrium (e.g., introduction of a new tax), with the model finding a new equilibrium given the new conditions. This approach is particularly

useful where it projects far into the future, allowing for the transition between the present and that future to be broken into smaller time steps. This can be done in a range of time steps (annually, five-year, decadal), and it allows for the application of pathways of change, as well as to assess intermediate changes between endpoints. This modelling approach is called recursive dynamics, which for each time-step the model is shocked out of equilibrium, and the new equilibrium then serves as the starting equilibrium for the next time-step. This approach contrasts with comparative statics, mentioned earlier, which is best suited for short time horizons, where fewer things may be changing simultaneously as a baseline scenario is not needed. Economic equilibrium models come in two flavours (1) partial equilibrium, and (2) computable general equilibrium.

Box 2: IFPRI's IMPACT Model — A Global Partial Equilibrium Model

Historical Background The IMPACT model was developed at the International Food Policy Research Institute in the early 1990s to address a critical lack of long-term vision and consensus on how to feed the world, reduce poverty, and protect the natural resource base. The model's development was launched in 1993 as part of IFPRI's 2020 Vision for Food, Agriculture, and the Environment Initiative. Since its creation, the model has been continuously improved (currently in version 3) in response to increasingly complex policy questions.

Model Capabilities IMPACT 3 is an integrated modelling system that links biophysical models (i.e., climate models, crop models, and water models) to a core global partial equilibrium multi-market agriculture sector model. IMPACT simulates sixty-two commodity markets across 158 countries/regions between 2005 and 2050 at an annual time step. Agricultural production is modelled sub-nationally in 320 food production units, which are defined as the intersection of national boundaries and major watersheds. Primary IMPACT outputs include projections for world prices, agricultural production, demand, productivity, net trade, and harvested area. Additionally, IMPACT generates a range of food and nutrition security indicators.

Applications IMPACT is one of the oldest and best known global agricultural models and has been employed extensively to assess potential food security challenges to global food systems. Major applications include exploring linkages between agricultural production and food security, evaluating the global effects of biofuels production, analysing water resource constraints on agriculture, assessing economic effects of alternative climate mitigation policies, and simulating technology adoption scenarios.

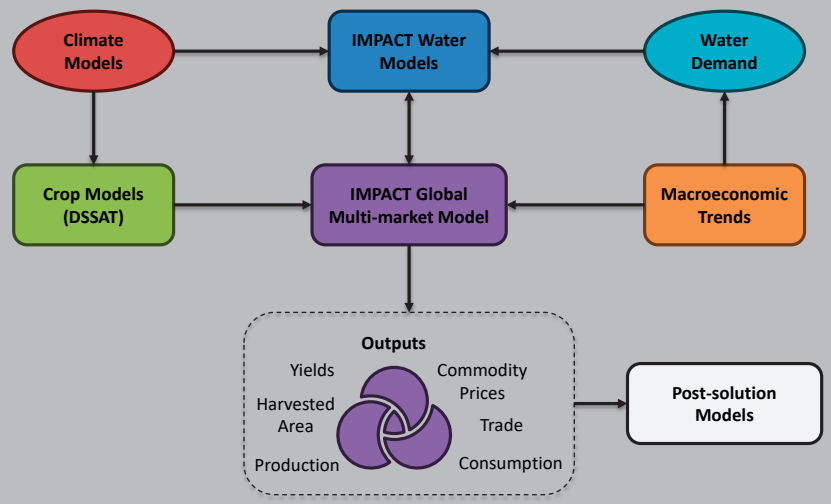

Figure 1.6: Summary figure of IMPACT model based on Robinson et al. 2015.[54]

Partial equilibrium (PE) models are considered partial because they focus on parts of the overall economy, as opposed to the entire economy. PE models can vary in scale from simulating single markets to multiple interconnected markets or sectors. In these models there are the endogenous markets, that is markets that are directly simulated by the model and for which prices adjust, and exogenous markets, or markets outside the scope of the model where prices are held constant or adjusted exogenously based on scenario storylines. For example, PE models of the food system do not tend to simulate labour supply and demand, as such wages and income are treated as exogenous variables (usually parameterized using GDP and population projections). PE models are well suited to simulating in greater detail specific sectors and are often designed to simulate material and economic flows in natural units (i.e., not solely in monetary terms), which can facilitate analysis with an environmental or nutritional focus, where natural units (e.g., kg, calories, etc.) are more applicable. PE models can provide greater sectoral detail, but this comes at the cost of not simulating feedback between endogenous and exogenous markets.

Computable general equilibrium (CGE) models are quantitative economy-wide models that describe economic linkages between factor markets (e.g., labour, capital, land, etc.), economic activities (e.g., farms, factories, restaurants, etc.), government, and consuming households (Figure 1.7).

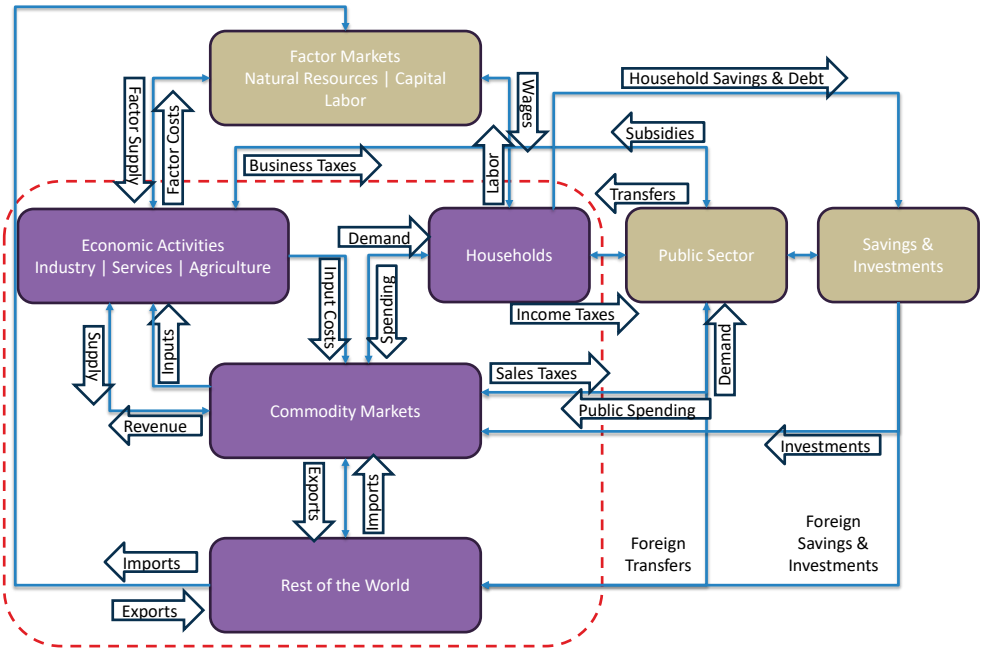

Figure 1.7: Stylized comparison of global CGE and PE models.

Notes: Red dashed line reflects the typical boundary of partial equilibrium models, which focus on economic activities, commodity supply and demand, but exclude factor markets, savings/investments, and the public sector, which are included in general equilibrium models.

CGE models simultaneously solve for equilibria across all markets in an economy, accounting for interdependencies and feedback effects between sectors and economies in the case of global CGE models (i.e., foreign exchange, and balance of trade). These models recognize that changes in one market can impact prices, production, and consumption across the entire economic system.

Table 1.1 summarizes the economic analysis done by chapter, highlighting the geographic scope and time horizon (short vs long run), economic model, and model type.

Table 1.1: Summary of applied economic models by chapter

Chapter	Spatial Scope	Time Horizon	Model	Model Type
2	National (USA)	Short Run (CS)	USAGE-FOOD[102,103]	CGE
3	Global	Long Run (RD)	IMPACT[54]	Agricultural PE
4	Global	Short Run (CS)	GLOBE[104,105]	CGE
			IMPACT	Agricultural PE
5	Global	Long Run (RD)	GLOBE	CGE
			IMPACT	Agricultural PE
6	Global	Long Run (RD)	GLOBIOM[56]	Agricultural PE
			IMPACT	Agricultural PE
7	Global	Long Run (RD)	AIM[106]	IAM CGE
			CAPRI[107]	Agricultural PE
			DIA-GIO[108]	Input-Output
			ENVISAGE[60]	CGE
			FARM[109]	CGE
			GCAM[110]	IAM PE
			GLOBIOM	Agricultural PE
			IMAGE[111]	IAM CGE
			IMPACT	Agricultural PE
			MAGNET[58]	CGE
			MAgPIE[57]	Agricultural PE

Notes: CS = Comparative Statics, RD = Recursive Dynamics; CGE = Computable General Equilibrium, PE = Partial Equilibrium; IAM = Integrated Assessment Model.

A range of additional models were coupled to the above economic models to facilitate the parameterization of scenarios and/or to extend the scope of analysis. These models while coupled to the economic models summarized above, are exogenous to the economic models, and were used to help capture non-economic behaviours and relationships of interest.

These models include:

- Process-based crop models (e.g., DSSAT, EPIC, LPJML, etc.) simulate plant growth under a range of biophysical conditions including soil types, weather, and management practices (i.e., irrigation, fertilization rates). These models are used to translate climate scenarios run by General Circulation or Earth Systems models. They take projected changes in precipitation and temperature and simulate daily plant growth, providing an estimate on potential changes in agricultural productivity that can be used in economic models[89]. Crop models are used to parameterize climate effects in all the chapters that include climate as a food system driver (Chapters 5-7).
- Most global climate and livestock studies have focused on the potential contributions of livestock to climate change either through direct emissions (i.e., methane, and nitrous oxide) or through land-use change. Where climate impacts have been included, they have

tended to focus on the indirect impact of climate change through feed availability. For example, in Chapters 5, and 6 no direct impact of climate change on livestock or labour were included. However, in Chapter 7, econometric models were used to estimate the direct climate impacts on livestock[112] and agricultural labour productivity[113].

- A perpetual inventory model[114] was developed in Chapter 5 to estimate changes in agricultural productivity under a range of R&D investment scenarios. Perpetual inventory models are the workhorse of R&D stock estimation methods and allow for the simulation of the accumulation of knowledge reflecting the advancement of scientific research, as well as the eventual obsolescence of ideas, as they are replaced by new ones.
- A Food and Nutrition Security module was developed for IFPRI's IMPACT model. This is based on econometric estimates around the relationship between calorie availability and malnourished children and the risk of hunger for the overall population[54], applied in Chapter 5. This module was expanded to incorporate nutrient supply estimates to assess potential risk of nutrient supply inadequacy[115], which was applied in Chapter 4.

Section 1.3.4 will discuss in greater detail the coupling and running of multiple models.

1.3.4 Modelling configuration

The modelling approaches applied across this thesis range in complexity from highly stylized reduced-form models (e.g., IMPACT's food and nutrition security module) to more structural models, including coupled biophysical and economic simulation models. This diversity of approaches reflects competing desires for greater breadth and depth of modelling on the one hand and simplicity, transparency, and communicability on the other.

There is substantial temptation in modelling to develop ever more complex and precise tools. Greater model complexity can allow for the simulation of a wider range of system behaviours, which can build legitimacy with end users of model results by signalling analytical sophistication. However, complex modelling suites are prone to false precision, with added detail not always leading to greater accuracy[116]. Food system complexity arises not only from the number of simulated components, but from many nonlinear interactions, feedback loops, and emergent dynamics that may be better represented with less precision by simpler models. Furthermore, increasing model complexity presents modellers and users with a precision-accuracy trade-off, where the more detailed a model, the more sensitive it becomes to errors in underlying parameters and data, which can challenge the applicability of results and risk overpromising what quantitative modelling can meaningfully do[36,63,116].

More complex modelling suites can also reduce the transparency of the modelling, complicating both the analysis and communication of results, which can reduce the potential impact of the analysis. Additionally, complex modelling suites also carry substantial development and maintenance costs and can require substantial computational and person time to run and analyse results, all of which can limit their application in shorter project horizons where time

and resource constraints are binding. As such, the appropriate level of model sophistication must match the research question, the scale of analysis, and available data and resources.

In this thesis, models were coupled in two main ways. Either they were coupled in series (i.e., one model's outputs are inputs to the next model), or the models were run in parallel (i.e., each model was run independently using the same inputs). Figure 1.8 summarizes the different modelling configurations used in this thesis.

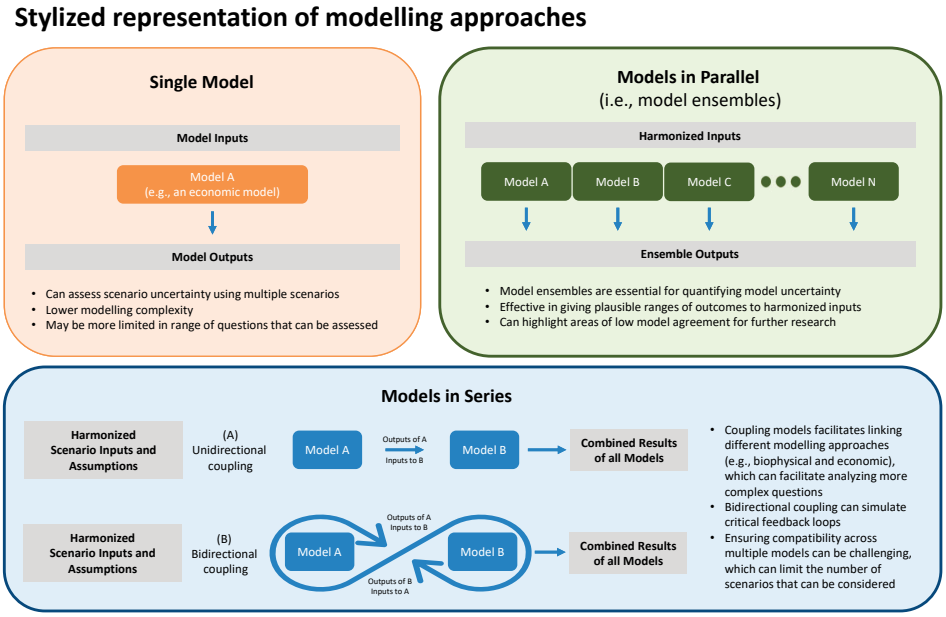

Figure 1.8: High-level summary of multi-model research design.

Models are run in series to explore relationships and feedback loops that cannot be captured within a single model. While running models in series can require substantial effort to harmonize model inputs and outputs across the full modelling suite to ensure system changes are simulated consistently, coupled models allow a broadening of the scope of what can be simulated.

Coupled models can be linked to the core economic model in two ways. First, models upstream of the core economic model can be used to translate system processes or scenario narratives into parameter inputs. For example, crop models were used to parameterise changes in crop productivity under a range of climate scenarios in Chapters 5, 6, and 7. Similarly, in Chapter 5 a Perpetual Inventory Model was used to translate changing R&D investment levels into agricultural productivity trends before these were passed to the core economic model. Second, models downstream of the core economic model can be used to extend the economic analysis and project relationships between simulated economic variables and a range

of exogenous outcomes of interest. For example, the food and nutrition security module in IMPACT used in Chapters 4 and 5 takes changes in food supply from IMPACT to estimate changes in malnourished children, the risk of hunger, and nutrient supply inadequacy.

Both approaches can be applied as linear coupling, with no feedback between the coupled models, but can also be run to incorporate feedback loops, running the coupled models iteratively. For example, in Chapters 4 and 5 IMPACT, an agricultural PE model, is linked to GLOBE, a CGE model. This linkage was done iteratively, with changes in the agricultural sector simulated in IMPACT passed to GLOBE, to estimate the consequences of these changes across the entire economy, which were then returned to IMPACT as changes in income to simulate the consequences of economy-wide adjustments on the agriculture sector.

Models that are run in parallel, often called model ensembles, can be used to explore model uncertainty. Model ensembles include multiple models of the same type (i.e., climate models, crop models, economic models, etc.), with the goal of assessing how structurally similar models respond to a common shock. Many examples of multi-model ensembles can be found in the climate modelling literature[7,67,89,117–119]. Multi-model ensembles, similar to models run in series, require substantial harmonization efforts, but here the goal is focused on ensuring consistency in scenario inputs, to ensure all models are representing the same shocks, such that the differences in results are driven primarily by different model structures and/or assumptions, and not due to different inputs. The range of outcomes across the ensemble then gives a sense of the level of agreement across the ensemble, with greater agreement suggesting higher confidence in the results, and where there is less agreement, results signal greater uncertainty, highlighting a need for additional review of model structures and specifications. Chapters 6 and 7 applied multi-model ensemble approaches, running multiple economic models under harmonised scenarios to explore uncertainty around climate-food system interactions (Chapter 6) and a food system transformation consistent with EAT-Lancet dietary recommendations (Chapter 7).

1.4 Thesis structure

The thesis is structured around six case studies that illustrate different applications of food system foresight. They are broadly ordered by increasing complexity of modelling and scenario approaches applied. Each chapter is summarised in detail below, including key questions explored, methods applied, main findings, scientific contributions, and steps to impact:

- Chapter 2: Ethical and economic implications of the adoption of novel plant-based beef substitutes in the USA: a general equilibrium modelling study
- Chapter 3: Gaps between fruit and vegetable production, demand, and recommended consumption at global and national levels: an integrated modelling study
- Chapter 4: Modelling the global economic consequences of a major African swine fever outbreak in China

- Chapter 5: Agricultural investments and hunger in Africa modeling potential contributions to SDG2 – Zero Hunger
- Chapter 6: Multi-factor, multi-state, multi-model scenarios: Exploring food and climate futures for Southeast Asia
- Chapter 7: Modelling for EAT-Lancet to assess potential environmental and socioeconomic consequences of a food systems transformation

The thesis will conclude with a discussion of key lessons learned across these six cases studies and explore the role of anticipatory governance and foresight modelling to help inform food policy for more sustainable, healthy, and just futures.

1.4.1 Chapter 2: Ethical and economic implications of the adoption of novel plant-based beef substitutes in the USA: a general equilibrium modelling study

Based on Mason-D'Croz, Barnhill et al. (2022)[120]

Background and Key Questions The call for a transformation that leads to healthier, more sustainable, and just food systems has been growing[121–123]. A critical component to any such transformation will be food system innovation. However, not all innovations are equally likely to contribute to a sustainable transformation, and there is a growing need to better assess potential innovations to inform more responsible food system innovation[124–126]. This chapter explores the socioeconomic and environmental consequences of the wide-scale adoption of novel plant-based meat alternatives in the U.S.A., a major meat producing and consuming country.

Methods This chapter applies a top-down approach to scenario development and focuses on comparing alternative food systems using a short time horizon, using comparative statics to compare changes across the food system compared to the present food system. These scenarios were developed based on literature and projected adoption of novel plant-based alternatives. This chapter applies a single model, USAGE-FOOD, a disaggregated version of USAGE, a general equilibrium model of the U.S. economy, to simulate in greater detail the U.S. food system. USAGE-FOOD was linked to life-cycle assessment literature to estimate potential changes in environmental outcomes (emissions, water, and land) of substituting beef demand in the U.S. with novel plant-based alternatives.

Findings The adoption of plant-based beef alternatives could reduce the carbon footprint of U.S. food production, by reducing cattle numbers in the beef sector. However, other environmental consequences are ambiguous and will depend on how natural resources are reallocated across the economy. Rapid development of plant-based alternatives to beef may have limited impact on total employment in the food system, and wider economy. Nevertheless, technology adoption could be disruptive to workers in beef production and processing sec-

tors and could have important consequences for rural economies where livestock production remains an important source of livelihoods.

Scientific Contribution This chapter contributes to the scientific literature in two main ways. First, it developed USAGE-FOOD[103], a more disaggregated version of the USAGE model and incorporated environmental coefficients for agricultural production to facilitate future economic and environmental modelling of U.S. food systems. Second, the modelling results were contextualized within a moral framing based on O'Neill et al.[127], conceptualizing the beef sector as a provisioning system with a wide range of inputs and outputs including food and environmental impacts, with important consequences to workers and the wider society.

Steps to Impact The underlying article[120], has according to SCOPUS been cited more than 40 times, including in more than three policy documents according to PlumX Metrics. This paper was important in being invited to contribute to the UNEP's 2023 assessment of novel alternatives to animal-sourced foods[20].

1.4.2 Chapter 3: Gaps between fruit and vegetable production, demand, and recommended consumption at global and national levels: an integrated modelling study

Based on Mason-D'Croz, Bogard, et al. (2019)[128]

Background and Key Questions There is a growing awareness that food systems are contributing to serious environmental challenges at the same time that they are not supplying healthy diets to the majority of people[4,123,129]. In response there has been a call to shift towards healthier diets, which are predominantly plant-based. Part of this would require a substantial increase in the consumption of fruits and vegetables[123,130–134]. To better understand the magnitude of the challenge of achieving healthy consumption levels, this chapter tries to assess the gap between the supply of fruits and vegetables and recommended consumption levels, both in a historical context and under a range of future scenarios.

Methods This chapter applies the existing Shared Socioeconomic Pathways (SSPs)[84], a set of expert-defined future scenarios quantified for climate mitigation and climate adaptation analysis, to provide an envelope of future economic development to explore how future food demand may change in the future. These scenarios were run in a global partial equilibrium model, IMPACT[54], coupled with a range of stylized food loss and waste scenarios to assess future consumption levels. These model results were contextualized using both a historical framing to better understand how projections compare to recent trends, and a policy framing to assess whether current efforts to encourage greater consumption of fruits and vegetables are sufficient.

Findings Historically, low fruit and vegetable availability and consumption have been a consistent challenge to achieving healthy diets. Economic modelling in this chapter suggests that even under optimistic socioeconomic scenarios future supply will be insufficient to achieve recommended levels in many countries. While economic growth is likely to contribute to increased fruit and vegetable consumption in the future, there will be a need for additional food policies targeting the constraints to producing and consuming fruits and vegetables. There will need to be a focus on investment to improve fruit and vegetable production technologies, as well as focusing on improvements across the value chain to help reduce food loss and waste which can challenge achieving healthy consumption levels.

Scientific Contribution This chapter built on previous studies that assessed current gap between supply and consumption, applying a global partial equilibrium model, and testing future food demand under a range of socioeconomic scenarios. Linking these results to historical trends, also added additional context on how this gap has evolved over the second half of the 20th century. Additionally, this chapter bridged two policy frameworks[135,136], facilitating a discussion of food policy, and assessing the current state of food policy to achieve healthy consumption levels.

Steps to Impact The underlying article has been cited more than 300 times according to SCOPUS, including in more than forty policy documents according to PlumX metrics. This paper was fundamental to being invited to participate in the FAO/WHO workshop on promoting healthy fruit and vegetable consumption in 2020[137].

1.4.3 Chapter 4: Modelling the global economic consequences of a major African swine fever outbreak in China

Based on Mason-D'Croz, Bogard, et al. (2020)[77]

Background and Key Questions In the face of an emerging outbreak in China of African swine fever a highly contagious and lethal disease for pigs, this chapter explored the potential consequences of a major outbreak in China to global food systems, including potential ramifications to global and regional food and nutrition security.

Methods This chapter applies a top-down approach for scenario development, based on historical literature on past outbreaks of African swine fever. Scenarios applied comparative statics to compare alternative outbreak scenarios to a status quo food system before the onset of African swine fever in China, similar to a previous study on rice diseases in Southeast Asia[138]. This chapter applies a multi-model in series approach, linking IMPACT[54], a global partial equilibrium model, with GLOBE[105], a global general equilibrium model. The model outputs were further extended by linking IMPACT food demand projections to nutrient supply database[115] to estimate changes in nutrient supply.

Findings Model projections suggest an outbreak could lead to large global price increases for pork. Price increases could contribute to substitution into other meats, as well as spurring on increased production of pork in unaffected regions. Consequences of an outbreak of African swine fever could be observed across value chains, with impacts on key animal feed commodities such as maize, which could have consequences for food and nutrition security in and outside of China.

Scientific Contribution This work builds on previous extreme event scenario analysis in IMPACT, and extends the modelling suite to include GLOBE, a CGE model, to assess spillover effects to the wider economy, and nutrient supply analysis to better assess changes in diets. This work better integrated sector and whole-of economy modelling with more detailed food demand outcomes, highlighting a modelling approach that can be applied for assessing changes in FNS under extreme events.

Steps to Impact The underlying article has been cited more than 160 times according to SCOPUS, including in over a dozen policy documents according to PlumX Metrics. Scenario findings were well aligned with early impacts of the outbreak of African swine fever but the salience of the results was quickly superseded by the outbreak of the COVID-19 global pandemic.

1.4.4 Chapter 5: Agricultural investments and hunger in Africa modeling potential contributions to SDG2 – Zero Hunger

Based on Mason-D'Croz, Sulser, et al. (2019)[69]

Background and Key Questions Agricultural R&D (research and development) has been a major driver for increasing agricultural production, economic development, and improving food security globally. However, agricultural productivity increases have not been shared equally, and much of Africa continues to face low agricultural productivity, and serious food security challenges. This chapter explores how targeted investments in agricultural R&D could contribute to increasing agricultural productivity and achieving SDG 2 (Zero Hunger) in Africa.

Methods This study uses a top-down scenario development approach, through the coupling of a perpetual inventory model to project changes in agricultural productivity due to increasing investment in agricultural R&D proposed by the CGIAR[73]. The results of the perpetual inventory model were then used as inputs to coupled partial and general equilibrium models (IMPACT and GLOBE) to simulate how changes in agricultural productivity would impact agricultural production, demand, and food security.

Findings Scenario analysis suggested that additional investments in agriculture R&D could help accelerate progress towards SDG2 but alone would be unlikely to achieve SDG2. To

eradicate hunger in Africa by 2030 would require a broader and more ambitious portfolio of investments.

Scientific Contribution This study links together detailed sector (IMPACT) and whole-of-economy modelling (GLOBE) to work done to estimate the link between R&D investment and productivity growth. This work developed an approach to facilitate the simulation of R&D investment scenarios in economic models that merged two bodies of R&D literature based on knowledge accumulation and diffusion.

Steps to Impact The underlying article has been cited more than 120 times according to SCOPUS, including in over sixty policy documents according to PlumX metrics. The underlying approach has become the standard methodology used by the International Food Policy Research Institute to estimate potential impacts of changes in investment levels in R&D across the CGIAR, and used in discussions with larger donors such as USAID, the Bill and Melinda Gates Foundation, and the Food and Agriculture Organization. While recent political changes raise questions of whether increasing international investment in agricultural R&D for development will be politically feasible, these approaches can continue to be applicable to assess the potential consequences of cuts in investment.

1.4.5 Chapter 6: Multi-factor, multi-state, multi-model scenarios: exploring food and climate futures for Southeast Asia

Based on Mason-D'Croz, Vervoort, et al. (2016)[70]

Background and Key Questions Food systems are complex, with many outcomes driven by interactions across many varied factors. Anticipatory governance requires tools that can help decisionmakers to engage both with complexity and future uncertainty. This chapter presents an approach that facilitates the development of participatory scenarios that are simultaneously salient to regional stakeholders and explore a broader range of potential climate futures to inform regional food policy.

Methods The chapter presents a five-step process that identified factors of change, selected four primary factors (agricultural investment, enforcement capacity, land degradation, and markets), and used the OLDFAR optimization tool[139] to create four maximally diverse scenarios based on scenario drivers identified by regional stakeholders. Working with stakeholders, regional scenario narratives were further elaborated, and semi-quantified so they could be simulated using two integrated biophysical and economic models (IFPRI's IMPACT[54], and IIASA's GLOBIOM[56] models) under a range of future climates, represented by four General Circulation Models (GCMs). The scenarios were then linked to IPCC's Shared Socioeconomic Pathways to provide the global context.

Findings The chapter demonstrated a methodology for developing diverse and regionally salient scenarios to explore a wide range of alternative futures include climate change to inform regional climate and food policy. Furthermore, the chapter developed four regional narratives that were then applied to a range of regional policymaking exercises. These scenarios presented a broad range of alternative futures across climate and socioeconomic outcomes, highlighting potential environmental challenges with respect to increasing agricultural land use, and challenges to food security from reduced agricultural productivity due to climate change.

Scientific Contribution The study demonstrates that multi-factor, multi-state approaches can maintain a broader possibility space than traditional two-axis scenario methods while remaining manageable through systematic optimization tools like OLDFAR. Using a multi-model ensemble (GLOBIOM, IMPACT, and later LANDSHIFT) revealed critical uncertainties—particularly around CO_2 fertilization effects—that would be hidden in single-model approaches. This approach successfully bridges qualitative stakeholder narratives with quantitative modelling while explicitly balancing strategic elements (within policymakers' control) and contextual elements (external forces), making scenarios relevant across different decision-making scales.

Steps to Impact The underlying article has been cited more than fifty times according to SCOPUS, including in more than thirty policy documents according to PlumX metrics. This paper was part of a broader effort to embed participatory scenarios in regional climate policies. The scenarios proved highly reusable, addressing more than 75 percent of subsequently identified regional policy priorities and being successfully integrated into regional policy processes, including Cambodia's $164 million Climate Change Priorities Action Plan.

1.4.6 Chapter 7: Modelling for EAT-Lancet to assess potential environmental and socioeconomic consequences of a food systems transformation

Based on Section 4 in Rockström, Thilsted, et al. (2025)[4]

Background and Key Questions The first EAT-Lancet report proposed a great food system transformation composed of a shift to a healthy diet, increased agricultural productivity and reductions in food loss and waste[123]. This study highlighted the potential of such a food system transformation to move towards greater environmental sustainability. However, the first study did not include economics, raising questions around the affordability of a healthy diet, as well as questions around justice implications around such a transformation. In response to this, the modelling supporting the second EAT-Lancet report looked to answer what the socioeconomic and environmental implications of such a global food system transformation could be, as well as consider potential complementarities and trade-offs with ambitious climate mitigation efforts.

Methods This chapter applied a top-down scenario approach, building on previously developed food system transformation and climate mitigation scenarios[91,123,140], the shared socioeconomic pathways[84,141], and updated dietary recommendations[108]. These scenarios were simulated across a multi-model ensemble composed of ten global economic models, as well as the original input-output model used in the first EAT-Lancet report. Across the multi-model ensemble, the consequences of a food system transformation were assessed across a scenario set that allowed for a detailed decomposition analysis. This decomposition analysis assessed the individual drivers (dietary change, agricultural productivity, reduced food loss and waste, and ambitious climate mitigation) of change both in isolation and in combination.

Findings The modelling in this chapter suggested that an EAT-Lancet style food system transformation could lead to a food system in 2050 similar in aggregate size to the current food system, reducing substantially direct agricultural emissions, agricultural land-use, blue-water use (i.e., water for irrigation), as well as chemical inputs, even though these reductions may not be sufficient to fully move within safe operating spaces for nitrogen- and phosphorous- use. Additionally, the modelling suggested that such a transformation would require a substantial restructuring of global food systems, and that this would have important implications for agricultural labour, even if it might not drastically change total numbers of agricultural workers compared to the business-as-usual projection. Modelling results highlighted a less resource intensive food system, which could reduce the cost of producing a healthy diet globally, even as some regions could see an increase in food expenditure.

Scientific Contribution This analysis advances beyond the 2019 EAT-Lancet Commission by employing an expanded multi-model ensemble approach that captures uncertainty in food system responses and includes general and partial equilibrium models that simulate a wider range of potential feedback loops that could impact agricultural production, demand, trade, and prices. The decomposition analysis provided additional novel insights into how individual drivers (dietary change, productivity gains, FLW reduction, and mitigation policies) interact with each other. The research demonstrates critical complementarities between transformation components—all three drivers combined achieve better environmental outcomes than any in isolation—while also revealing important regional inequalities in both environmental responsibility and economic vulnerability.

Steps to Impact The underlying article has been cited more than 400 times according to SCOPUS, including in more than twenty policy documents according to PlumX metrics. The first EAT-Lancet report was one of the most cited scientific documents of the past five years, and the second report, which this modelling contributed to, is expected to continue being a noteworthy publication highlighting the important connections between environmental and health outcomes. Communication and outreach efforts to facilitate access to and use of

the results have already begun with substantial engagement with civil society, private sector representatives, and the policy-informing community.

1.4.7 Chapter 8: Discussion and conclusions

Drawing heavily on Mason-D'Croz et al.[36,142], Moallemi et al.[116], and Wiebe et al.[143]
Background and Key Questions The anticipatory governance research highlighted across the six case studies spans a wide range of methods, scenario approaches, and disciplinary lenses. This concluding chapter looks to zoom out and take a more holistic look at this body of research to synthesize key lessons learned. This synthesis is organized around key research questions: (1) what tools are best suited to answering different food system questions, (2) how to design high-quality and policy-salient scenarios, (3) how to apply models holistically to inform food system change, and (4) how to conduct impactful anticipatory governance research that intentionally engages with science-policy interfaces.

Findings Two key principles emerge across this body of research. First, models are better used to ask questions and test hypotheses than to predict the future of complex systems. Second, imagining, designing, and implementing futures are political processes, and it is critical to intentionally consider the political economy of alternative futures and who gets to imagine them. Building on these principles, six cross-cutting themes emerge, including the complementarity of qualitative and quantitative approaches, the need for intentional scenario design, the importance of matching models to research problems, the role of timescales in scenario design, the value of holistic approaches that embrace complexity, and the unavoidability of unanticipated consequences. The chapter also critically assesses limitations across data, scenario design, and modelling, concluding with areas for future research in anticipatory governance.

Steps to Impact This chapter reflects openly on the science-policy interface and the continuum from informing to supporting to co-creating policy, with a critical assessment of where the research in this thesis falls across this continuum. It identifies prerequisites for greater impact, recognizing that the research-to-impact pathway is an iterative, contested, and politically negotiated process. It highlights the critical role of communication and the need to build and sustain institutional relationships and trust.

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2

Ethical and economic implications of the adoption of novel plant-based beef substitutes in the USA: a general equilibrium modelling study

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ABSTRACT

Background Slowing climate change is crucial to the future wellbeing of human societies and the greater environment. Current beef production systems in the USA are a major source of negative environmental impacts and raise various animal welfare concerns. Nevertheless, beef production provides a food source high in protein and many nutrients as well as providing employment and income to millions of people. Cattle farming also contributes to individual and community identities and regional food cultures. Novel plant-based meat alternatives have been promoted as technologies that could transform the food system by reducing negative environmental, animal welfare, and health effects of meat production and consumption. Recent studies have conducted static analyses of shifts in diets globally and in the USA, but have not considered how the whole food system would respond to these changes, nor the ethical implications of these responses. We aimed to better explore these dynamics within the US food system and contribute a multiple perspective ethical assessment of plant-based alternatives to beef.

Methods In this national modelling analysis, we explored multiple ethical perspectives and the implications of the adoption of plant-based alternatives to beef in the USA. We developed USAGE-Food, a modified version of USAGE (a detailed computable general equilibrium model of the US economy), by improving the representation of sector interactions and dependencies, and consumer behaviour to better reflect resource use across the food system and the substitutability of foods within households. We further extended USAGE, by linking estimates of the environmental footprint of US agriculture, to estimate how changes across the agriculture sector could alter the environmental impact of primary food production across the whole sector, not only the beef sector. Using USAGE-Food, we simulated four beef replacement scenarios against a baseline of current beef demand in the USA: BEEF10, in which beef expenditure is replaced by other foods, and three scenarios wherein 10%, 30%, or 60% of beef expenditure is replaced by plant-based alternatives.

Findings The adoption of plant-based beef alternatives is likely to reduce the carbon footprint of US food production by 2.5–13.5%, by reducing the number of animals needed for beef production by 2–12 million. Impacts on other dimensions are more ambiguous, as the agricultural workforce and natural resources, such as water and cropland, are reallocated across the food system. The shifting allocation of resources should lead to a more efficient food system, but could facilitate the expansion of other animal value chains (e.g., pork and poultry) and increased exports of agricultural products. In aggregate, these changes across the food system would have a small, potentially positive, impact on national gross domestic product. However, they would lead to substantial disruptions within the agricultural economy, with the cattle and beef processing sectors decreasing by 7–45%, challenging the livelihoods of the more than 1.5 million people currently employed in beef value chains (primary production and animal processing) in the USA.

Interpretation Economic modelling suggests that the adoption of plant-based beef alternatives can contribute to reducing greenhouse gas emissions from the food system. Relocation of resources across the food system, simulated by our dynamic modelling approach, might mitigate gains across other environmental dimensions (i.e., water or chemical use) and might facilitate the growth of other animal value chains. Although economic consequences at the country level are small, there would be concentrated losses within the beef value chain. Reduced carbon footprint and increased resource use efficiency of the food system are reasons for policy makers to encourage the continued development of these technologies. Despite this positive outcome, policy makers should recognise the ethical assessment of these transitions will be complex, and should remain vigilant to negative outcomes and be prepared to target policies to minimise the worst effects.

All that you touch, you change
All that you change, changes you
The only lasting truth is Change.
God is Change

Octavia E. Butler, *Parable of the Sower*

2.1 Introduction

The food system has developed to supply more food to more people and at lower prices than at any point in recorded history. However, the unparalleled expansion of agricultural production has come at a cost, with substantial pressure on the environment through degradation of ecosystems and finite natural resources. The global food system is estimated to contribute 21–37% of global emissions,[1,2] with cattle accounting for an estimated 30–35% of global agricultural emissions, and with expansion of beef production identified as a key driver of land-use change and non-carbon dioxide (CO_2) agricultural emissions. Attempts to avoid warming of about 1.5°C by the end of the century will require emissions reductions across the food system.[1] In the USA, agriculture contributes about 10% of emissions,[3] with direct emissions from cattle production accounting for about 40% of agricultural emissions[4] or around 150 million tonnes (Mt) of CO_2 equivalent (CO_2eq) emissions. The Rockefeller Foundation estimated the US food system contributes about US$2.1 billion per year in externalised costs, with environmental and biodiversity costs accounting for more than $0.8 billion per year—much of which is driven by cattle emissions and land-use change.[5]

Beef production systems produce foods high in protein and many key nutrients, but which are over-consumed by many in the USA.[4] These systems play an important sociocultural role, contributing to identity formation and regional food cultures; economically, they provide employment and income to millions, even as beef production raises various animal welfare concerns.[6]

Beef production and consumption have been the target of various real and hypothetical policies and food system interventions to reduce the environmental and public health impacts of the food system.[4,7–9] Novel plant-based alternatives are potentially transformative innovations that could reduce the environmental footprint of diets, by replacing animal products with less resource-intensive alternatives, and substantially reduce the number of animals raised for food. Reducing animal production and consumption could also reduce some negative public health risks (e.g., risk of cardiovascular disease, spread of zoonoses, and foodborne pathogens).[10,11] Multiple plant-based alternatives from companies such as Meatless Farm, Very Good Food, and Impossible Burgers are produced using sophisticated processing technologies to mimic the taste, texture, and appearance of meat,[12] and are increasingly available to consumers in many countries.[13] Although these plant-based alternatives are currently more expensive than conventionally produced beef, the aforementioned companies have

been reducing their prices and aim to reach price parity with conventional beef.[14] According to one projection, by 2040, 25% of the global meat market could be plant-based alternatives.[12]

Transformative innovations can have positive and negative effects, which deserve ethical assessment. Critics of the burgeoning alternative protein industry, which includes plant-based alternatives and cellular agriculture, argue that it builds on a corporate food system that is unsustainable and inequitable.[10,15] Others see these as ethically promising innovations, which might help to solve environmental and animal welfare challenges, but with potential ethical trade-offs that must be considered.[16,17] These trade-offs could include negative effects on the producers of animal-sourced foods, and regional economies and communities based around animal-sourced food production. From an ethical perspective, it is crucial that evidence and approaches are developed to assess these trade-offs.

Here, we aimed to demonstrate an approach to assess some of the potential consequences of replacing beef demand in the USA with novel plant-based alternatives that attempt to mimic the taste and texture of beef. Many studies at the global[18–21] and national[22–26] level have assessed the potential environmental and health benefits of dietary changes. However, most of these studies, particularly at the national level,[22–26] have applied static and partial analyses and have not attempted to simulate how changes in consumer behaviour would drive a wide range of changes across the food system, or the potential ethical implications of these changes. The present study takes a dynamic and multidisciplinary approach, applying a computable general equilibrium model to simulate and assess how the food system and economy might adapt to reduced demand for beef and increased demand for plant-based alternatives, and contextualising these findings within multiple ethical perspectives.

Four scenarios are explored and are presented as deviations from a baseline scenario simulating current beef demand in the USA: **BEEF10**, in which 10% of beef expenditure is replaced by other foods, and three scenarios wherein 10%, 30%, or 60% of beef expenditure is replaced by plant-based alternatives. This range of beef reduction spans previous studies that have taxed food based on emissions[27] and health outcomes,[4] and projections on the potential market share of meat alternatives by mid-century (2040–50).[12]

Research in Context

Evidence before this study No formal literature review was done. Global analyses and high-level reports have suggested that reductions in beef consumption, particularly in high-income countries (such as the USA), could contribute to reducing the environmental pressures of food production and consumption. Furthermore, a range of nationally focused studies have presented hypothetical scenarios of a shift away from beef in the USA and have suggested that dietary changes have substantial potential to reduce the environmental footprint of US food consumption. Novel plant-based alternatives have been marketed as a technological solution that could facilitate this transition, with lifecycle assessment studies suggesting notable environmental gains. However, these analyses have primarily applied static partial analyses that did not fully assess how agricultural producers could increase exports, and how resources freed from a decreasing beef sector might otherwise be used—both of which would have consequences on the environmental footprint of US food production. Furthermore, these studies have mostly focused on environmental and public health dimensions, with less focus on the ethical implications and the disruptive potential of these novel technologies, which might have unexpected consequences on value chains (e.g., resource allocation and employment) beyond just the beef sector.

Added value of this study We build on previous static and partial analyses by way of a dynamic approach using a computable general equilibrium model of the entire US economy to simulate the interconnected nature of factor markets, economic activities, and economic outputs. Given the uncertainty in the potential adoption of plant-based alternatives, we explored various potential replacement scenarios, ranging from 10% replacement to 60%. We showed that plant-based beef alternatives should reduce the carbon footprint of the US food system, but that reductions across other environmental dimensions, such as water and cropland, will be dependent on how resources freed up from beef sectors are repurposed for other economic activities. These changes in resource availability would lead to disruptions across the US food system that negatively impact on employment for the many individuals working in beef sectors, as well as facilitating the expansion of other sectors.

Implications of all the available evidence The threat of climate change is increasing, and the magnitude of the challenge to avoid 2°C of warming will require decarbonisation across all economic activities. Plant-based beef alternatives show substantial potential to reduce the carbon footprint of food systems where they are adopted. These novel technologies, if adopted widely, would negatively impact beef sectors with concentrated losses experienced by individuals and communities dependent on these economic activities. Nevertheless, these losses could be offset in aggregate from the expansion of other sectors (e.g., poultry, pork, and biofuels) in the food system. These changes would have ethically important implications, which policy makers should monitor to avoid severe unintended negative consequences to vulnerable workers, small producers, and hard-hit communities.

2.2 Methods

2.2.1 Analytical framework

In our analytical framework to inform a multi-perspective ethical assessment of the adoption of plant-based alternatives in the USA, beef and plant-based alternative production systems are conceptualised as provisioning systems with a series of inputs, outputs, and outcomes, which matter across multiple ethical perspectives. This framework includes impact pathways—i.e., causal chains linking biophysical, social, cultural, and economic resource use and outcomes—which can be systematically explored via models (figure 2.1).

Previous ex ante assessments of plant-based beef alternatives using static projections (i.e., without dynamic sector adjustments) have suggested wider use of these technologies, versus current use, would result in reductions in natural resource use across multiple dimensions and in the numbers of animals needed for food production.

Adoption of plant-based alternatives would disrupt value chains (thus changing relationships between food production and natural resource use) and the type and quantity of agricultural workforce (labour) and capital, leading to economic dislocations of ethical relevance. The outcomes of these changes would be relevant to humans, non-human animals, and the environment, and can be evaluated from multiple ethical perspectives. For example, changes in nutrition and health, livelihoods, and safe work all matter from multiple perspectives, including human rights, as they bear on recognised rights to health, food, an adequate standard of living, fair wages, and safe and healthy working conditions.[28] From the perspective of justice (e.g., health equity and economic justice), the consequences of changes in the food system are central to human wellbeing and equitable outcomes.[29] Environmental outcomes are also relevant from multiple ethical perspectives. In addition to such outcomes being notable on the basis of the intrinsic value of the natural world (i.e., ecosystems, biodiversity, and individual living things),[30,31] climate change can violate the rights of humans and contribute to intergenerational injustice.[32] Outcomes for non-human animals, such as the conditions in which they are raised, matter from the perspective of animal rights and animal welfare.[33,34] Appendix 2.1 (p 1) includes a definition of animal welfare.

This use of multiple ethical perspectives is key to rigorous ethical evaluation. Stakeholders, advocates, and experts might bring different ethical perspectives to the evaluation of new technologies; some groups might reject the ethical perspectives embraced by others. Given this plurality of moral values, which is found within individual societies and across the global food system, the strongest ethical case for adopting a technology is not based on a particular value (e.g., health equity) or one that assumes the authority of one ethical perspective (e.g., human rights). Rather, the most robust ethical case is one that considers multiple, distinct ethical perspectives.

Figure 2.1 highlights such a multi-perspective approach to test the hypothesised benefits of plant-based alternatives and to explore some of the potential social and economic outcomes from the adoption of these technologies across various ethical perspectives.

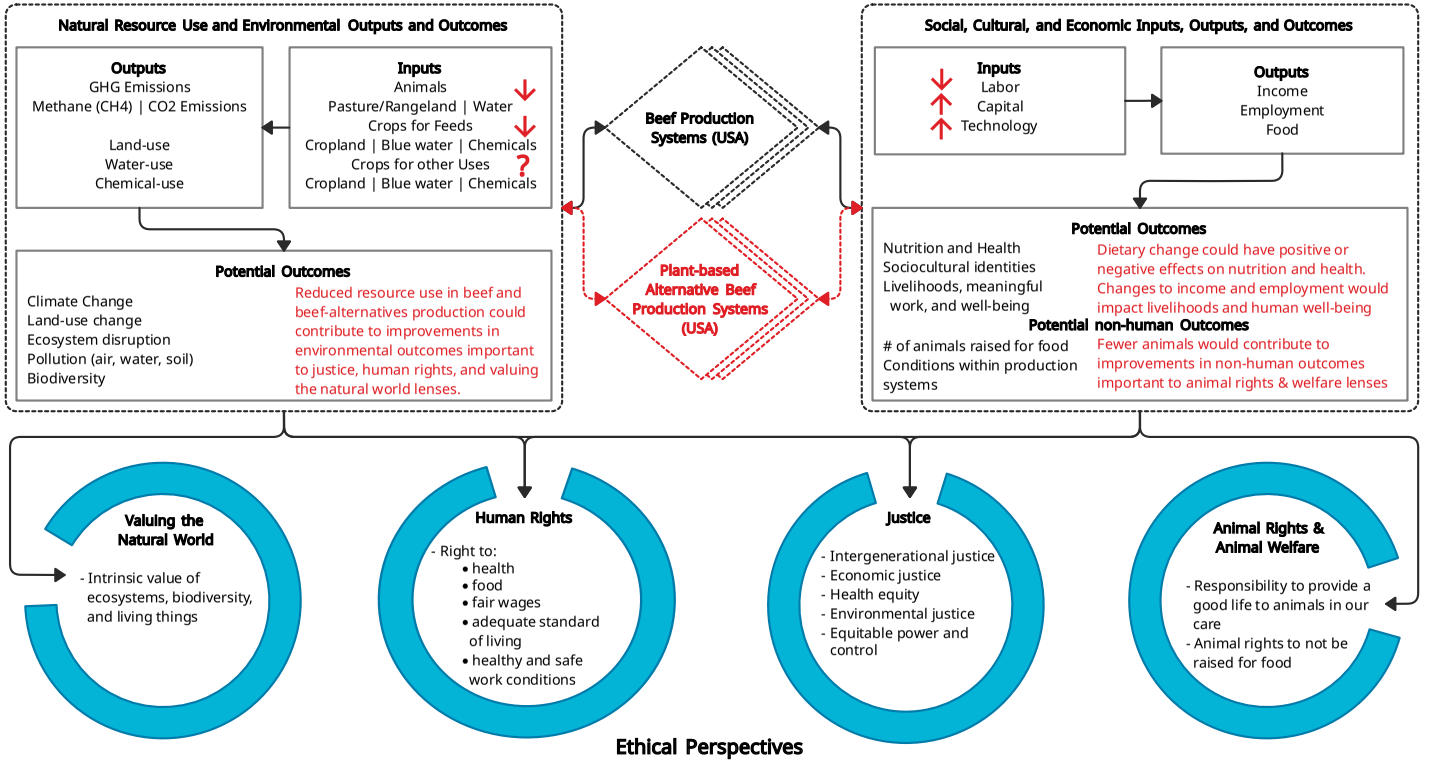

Figure 2.1: Analytical framework for a multi-perspective assessment of selected environmental and social outcomes of replacing beef with plant-based alternatives in the USA.

Notes: Here, we conceive the beef production systems as provisioning systems that connect resource use and outcomes. Each box highlights key causal chains linking inputs with ethically relevant outcomes, along with hypothesised changes in input use that can be tested (red arrows and ? icon) and potential changes in outcomes (red text) that can be assessed across ethical perspectives (blue rings).

2.2.2 Scenario specification

Projecting the future of alternative plant-based proteins is complex. Challenges include substantial uncertainty about how quickly and to what extent these technologies will be adopted, and for how long they might remain relevant. Even defining these technologies is difficult, as this novel sector has a demonstrated ability to quickly adapt production practices in response to consumer concerns around taste and nutritional content.[35,36]

To better address this uncertainty, we used four scenarios to explore the possibility space around the adoption of novel alternative meat products in the USA. We simulated three scenarios in which consumers replace current beef demand with plant-based alternatives at three different levels: 10% (**ALTP10**), 30% (**ALTP30**), and 60% (**ALTP60**) replacement. As future plant-based technologies might differ from current iterations, we will represent the adoption of these novel products as increasing demand for the plant-based constituents (grains, legumes, oilseeds, and starches) listed as ingredients by current plant-based protein companies.[25,37] Appendix 2.1 (p 2) lists specific commodities that are included in the set of potential inputs to novel alternative meat products. Additionally, we simulated a scenario wherein 10% of beef demand is replaced with other foods in a household's current consumption bundle (**BEEF10**). Given the role of the USA as a major agricultural exporter, we conducted sensitivity testing of varying levels of agricultural trade. Full details are given in appendix 2.1 (p 30).

This replacement range of 10–60% provides a plausibility space of development of the plant-based meat market that is currently small in comparison to the overall meat market (1.4% of meat category) but is a rapidly growing market.[38] The range is bounded on the high end by industry-based projections that meat alternatives could achieve market shares of up to 60% by 2040.[12] The 10% scenario was selected to facilitate future comparison with sustainable diet literature, which has targeted reductions in beef and red meat consumption using emission-based and health-based taxation.[4,27]

All four beef-demand scenarios are deviations from a baseline scenario, which simulates a business-as-usual scenario of the current economic state of the food system in the USA. A detailed description of the USAGE-Food model is given in appendix 2.1 (p 6). Changes in beef demand are the only deviation from baseline assumptions, such that all changes in model outcomes can be attributed to the change in consumer demand. In all four beef-demand scenarios, we model the change in beef demand by imposing an exogenous preference shift so that we can see how the food system would respond to a specific substitution of beef with either plant-based alternatives (**ALTP10**–**ALTP60**) or other food commodities. This substitution is applied in a symmetrical shift to ensure there is no exogenous preference shift between food and non-food expenditure.

2.2.3 Economic modelling

Although agriculture accounts for less than 2% of total US employment, the broader food system (including food manufacturing) employs 11%,[39] and accounts for more than 50% of land use and 80% of consumptive water use.[40] We aimed to understand how the introduction of novel plant-based alternatives at scale could disrupt supply chains, shifting resource availability and allocation across the economy. To do so, we modified the USAGE model,[41–43] a computable general equilibrium model of the US economy, to develop a version of the model (USAGE-Food) with more detailed countrywide representation of the US food system. The USAGE-Food model was run using GEMPACK 12.1. Using a detailed computable general equilibrium model, such as USAGE-Food, has the benefit of detailed sector representation—for example, we ran the model for 392 industries and commodities, 27 of which are food-related—which we can then aggregate to highlight how these sectors relate to the overall economy. However, focusing on expanding the sector representation required running the model without detailed regional disaggregation in this instance. Commodities and aggregations are listed in appendix 2.1 (p 21).

USAGE-Food includes two key improvements to USAGE that facilitate analysis of the US food system. First, on the production side, we disaggregated the beef value chain from other animal meat value chains (e.g., pork and lamb), thus creating an appropriate industry nesting in production functions to capture economic ties between various meat sectors and the rest of the economy. This nesting allowed us to better represent how changes in beef production would spill over to the rest of the food system. A stylised representation of nesting is given in appendix 2.1 (p 4). Second, we updated and improved the representation of food demand by specifying in greater detail the substitutability of different types of foods in the household utility function, adding more detailed nesting between food and non-food commodities, and between various meat (i.e., beef, poultry, and pork) and non-meat commodities within the food nest. To quantify these changes to the utility function we updated the constant elasticity of substitution functions to reflect a range of food demand studies of the USA[44] and global meta-analyses of food demand.[45,46]

2.2.4 Estimating environmental impacts

To estimate changes along environmental dimensions, we constructed a baseline environmental footprint for agricultural production in the USA. First, we used agricultural production data from FAOSTAT,[47] which was consistent with both USAGE and the environmental coefficients of production used in the EAT–Lancet Commission on healthy diets from sustainable food systems.[19,20]

We aggregated the environmental footprint of agricultural production in the USA to USAGE-Food agricultural commodities (table 2.1). Once this baseline was established, we estimated changes along environmental dimensions based on the changes in production

simulated in USAGE-Food. Detailed commodity mapping between Springmann and colleagues[19] and USAGE-Food is presented in appendix 2.1 (p3).

Table 2.1: Baseline agricultural resource use in the USA, by USAGE-Food agricultural commodity

	Blue water use (km^3)	**N application (000 tonnes)**	**P application (000 tonnes)**	**Greenhouse gases (Mt CO_2eq)**
Animal products				
Live cattle	…	…	…	142
Dairy cattle	…	…	…	46
Live poultry	…	…	…	25
Other live animals	…	…	…	30
Crops				
Grain farms	46	8320	1244	69
Fruit and nut farms	7	103	13	1
Vegetable or melon farms	9	229	62	6
Oilseed farms	18	205	180	13
Other crops	14	1210	137	3
Food processing				
Soya oil processing	0	0	0	10
Sugar processing	0	0	0	2
Total	94	10067	1636	347

Notes: Environmental coefficients from the EAT–Lancet Commission[19,20] were used to estimate the direct resource use of food production. Where values are blank (e.g., blue water use for animal products), it is because blue water was accounted for in the irrigation of feed crop as opposed to a direct input to animal production. CO_2eq=carbon dioxide equivalent. Mt=million tonnes.

2.3 Results

Changes in gross domestic product, household expenditure, aggregate employment, and wages were seen under all four scenarios (figure 2.2A). Across the food system, employment in and the overall value of production (output) declines across all of agriculture (0.5–4.0%) and food manufacturing (e.g., food processing and packaging; 0.2–3.2%) sectors, with neutral impacts on food services (e.g., restaurants, figure 2.2B). However, these aggregate impacts mask substantial disruption within the food system as it responds to changes in consumer food demand.

Within the food system, the beef-producing and processing sectors are most negatively affected by reductions in consumer demand for beef, with output declining by about two-thirds of the reduction in demand: a 7% reduction in the **BEEF10** and **ALTP10** scenarios, and a reduction of up to 40% in the **ALTP60** scenario (figure 2.2C). This smaller decline in production is due to there being various uses for beef products besides human consumption (e.g., pet food and cosmetics) and the role of the USA as a major exporter of beef and other agricultural goods. Our sensitivity analysis on trade assumptions can be found in appendix 2.1 (p 30).

Reductions in domestic demand for beef and beef products drive a reduction in sector output, which in turn drives down the demands by these sectors for inputs, such as agricultural workforce, capital, and animal feed. Reduced demand does not translate entirely to a reduction in output, mostly due to an increase in exports of 2.5–21.0% across the four scenarios, with the beef sector becoming increasingly export-oriented with 14–37% of output exported compared with around 12% in the baseline scenario. Full details can be found in appendix 2.1 (p 4). Across all scenarios, we saw a substantial reduction in employment in the beef value chains, which currently employ around 1 million people in cattle operations and 0.5 million in animal processing.[48]

A) Economy-wide Results	BEEF10	ALTP10	ALTP30	ALTP60
GDP	0.00	0.00	0.01	0.02
Household Expenditure	0.00	0.00	0.00	0.01
Aggregate employment	0.00	0.00	0.00	0.00
Average Wages	0.00	-0.01	-0.02	-0.03

B) Aggregate Food System Results	BEEF10		ALTP10		ALTP30		ALTP60	
	Output	Employment	Output	Employment	Output	Employment	Output	Employment
Agriculture	-0.6	-0.5	-0.5	-0.7	-1.6	-2.0	-3.1	-4.0
Food Manufacturing	-0.3	-0.2	-0.3	-0.6	-0.8	-1.6	-1.5	-3.2
Food Services	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

C) Changes within the Food System		BEEF10		ALTP10		ALTP30		ALTP60	
		Output	Employment	Output	Employment	Output	Employment	Output	Employment
Beef Sector	Live Cattle	-6.9	-7.5	-7.0	-7.6	-20.9	-22.5	-41.4	-44.1
	Beef Processing	-7.6	-8.0	-7.6	-8.1	-22.8	-24.0	-45.3	-47.1
Other Meat	Live Poultry	1.0	1.1	0.2	0.2	0.6	0.7	1.1	1.4
	Poultry Processing	1.0	1.0	0.2	0.2	0.7	0.6	1.3	1.2
	Other Live Animals	0.7	0.7	0.3	0.3	0.8	1.0	1.7	1.9
	Other Meat Processing	1.2	1.3	0.5	0.5	1.5	1.6	3.0	3.1
Selected Plant Products	Grain Farms	-0.1	-0.1	1.5	1.7	4.4	5.1	8.7	10.2
	Flour Mill	0.9	1.0	7.4	7.5	22.0	22.3	43.3	44.0
	Maize Processing	0.6	0.5	2.8	2.7	8.3	8.0	16.4	15.9
	Oilseed Farms	0.2	0.3	1.9	2.3	5.5	6.9	10.8	13.6
	Soya Oil Processing	0.5	0.5	3.6	4.4	10.7	13.1	20.7	25.7



Figure 2.2: Summary of changes in key economic variables by scenario and sector.

Notes: Results are reported as percent change from the baseline scenario simulating current beef demand. Household expenditure refers to the value of total household expenditure on final goods, but excludes savings and government spending. Output refers to the value of production. Employment refers to aggregate employment and reflects changes in employment rate across the entire economy. Sector employment reflects employment in the specified sector. Employment is expressed in USAGE in hours of agricultural workforce labour. Wages reflect the average wage across the whole of the economy. **ALTP10**=10% of beef expenditure substituted with plant-based alternatives. **ALTP30**=30% of beef expenditure substituted with plant-based alternatives. **ALTP60**=60% of beef expenditure substituted with plant-based alternatives. **BEEF10**=10% reduction in beef expenditure without any novel products. GDP = gross domestic product.

As beef-producing sectors contract, agricultural inputs (i.e., land, labour, and water) are freed up to be used in the production and provision of other commodities and services, with most of this reallocation occurring among other sectors in the food system. Under the alternative protein scenarios (**ALTP10**–**ALTP60**) much of these resources are reallocated to alternative protein value chains. Relatively large increases are seen in output and employment in grain

and oilseed processing sectors, which would supply key inputs to the production of plant-based products.

Other animal sectors expand production in response to growing demand and, because the decreasing beef sector makes many key inputs more available, production costs are decreased. Due to shifts in production cost and consumer preferences, production increases in other animal sectors across all four scenarios. In **BEEF10**, the decrease in beef demand is accompanied by increased demand for other animal-sourced foods (such as poultry and pork). This increased demand leads to an expansion of around 1% for these sectors, with an associated increase in employment and increased demand for commercial feeds (such as grains and oilseeds). In the three ALTP scenarios, the expansion of other animal sectors (range 0.2–1.7%) is driven primarily through declining production costs. In the USA in 2019, more than 8.5 billion chickens and 70–80 million pigs were reared for meat production.[49] The projected changes in production across the four scenarios could lead to an annual decline in cattle numbers of 2–12 million, with accompanying increases of 16–94 million chickens and 0.2–1.4 million pigs. Notably, at similar levels of beef replacement, replacing beef with other animal products (**BEEF10** scenario) leads to 2–5 times more chickens and pigs than when replaced with plant-based alternatives (**ALTP10** scenario).

Our results are consistent with suggestions that plant-based alternatives could reduce greenhouse gas emissions, with direct emissions from beef production declining by 7% to 41% (figure 2.3) or by 10 Mt or 61 Mt CO_2eq emissions per year, respectively, for the **ALTP10** and **ALTP60** scenarios. However, these reductions are partially attenuated due to increased production from other sectors (figure 2.2), with overall agricultural emissions declining by 2.5–13.5% or 7–40 Mt CO_2eq emissions per year. These results also suggest a potential shift in the composition of agricultural emissions, with conventional beef production in the USA estimated to have a carbon footprint of 16–40 kg CO_2eq per kg of beef.[50] This footprint is primarily composed of potent, but shorter-lived, methane and nitrous oxide, compared with estimates of the carbon footprint of novel plant-based alternatives (3–4 kg CO_2eq per kg; mainly driven by energy usage).[25,37]

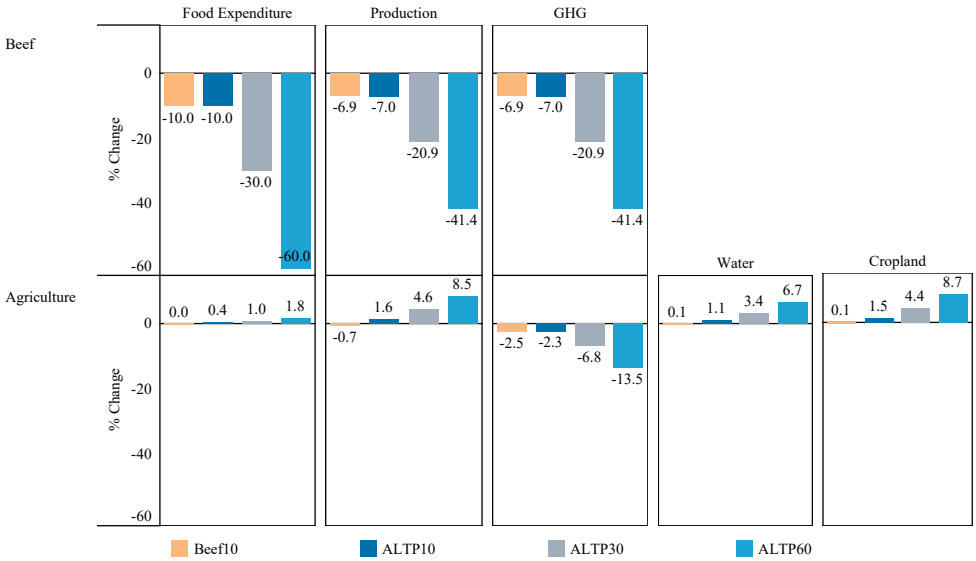

Figure 2.3: Percentage change across selected environmental dimensions from baseline in the beef sector and across all agricultural sectors under a range of scenarios.

Notes: Food expenditure is given in US$. Production is given in tonnes. Greenhouse gases are reported as annual emissions in CO2eq. Water represents changes in blue water use in km3. Cropland is reported in 1000 hectares of harvest area. Blue water and cropland are not used directly by livestock, but are used instead for crop production (some of which serves as feed). **ALTP10**=10% of beef expenditure substituted with plant-based alternatives. **ALTP30**=30% of beef expenditure substituted with plant-based alternatives. **ALTP60**=60% of beef expenditure substituted with plant-based alternatives. **BEEF10**=10% reduction in beef expenditure without any novel products. CO_2eq=carbon dioxide equivalent.

The impacts across other environmental dimensions are more ambiguous than changes in emissions. Most of the water, cropland, and chemicals (i.e., fertilisers and pesticides) associated with beef production are used in the production of feed crops (cereals and oilseeds primarily).[50] If cereal and oilseed production do not decline, then natural resource use across various dimensions is unlikely to change dramatically. Our modelling (figure 2.3) suggested there could be a small increase in water (range 0–7%) and cropland use (range 0–9%) across the four scenarios. This projected increase was due to an expansion in other agricultural sectors, given that many commercial feed crops are important inputs not only to the beef sector but to other animal sectors, novel plant-based alternatives, and a range of non-food uses (e.g., alcohol, biofuels, and starches). These crops are also part of complex global value chains with feed crops traded at higher rates than animal products.[51] Projected changes in fertiliser application followed changes in water and cropland use (appendix 2.1 p 5). Change across total agricultural land use (cropland and pastureland) would probably decline under all four scenarios, due to the large land footprint of conventional beef production.

Notably, although total changes in agricultural resource use are small, shifting from conventional beef production to plant-based alternatives should increase the overall resource efficiency of the food system, as these products—and other animal products like poultry and pork—are more efficient in converting material inputs into protein and have a smaller environmental footprint. Many of these changes suggest ethically relevant trade-offs across the various ethical lenses highlighted in figure 2.1. Table 2.2 summarises some of the ethical implications of these modelling results.

Table 2.2: Summary of selected modelled results, key points of uncertainty, and ethical implications of the replacement of beef with plant-based alternatives

	Modelled results of substituting beef with plant-based alternatives	**Key points of uncertainty**	**Considering potential outcomes from multiple ethical perspectives**
Planetary boundaries			
Greenhouse gases	Overall reduction in CO_2eq driven by reduction in non-CO_2 emissions	Will more energy-intensive food processing increase demand for electricity, with subsequent increase in CO_2 emissions from electricity generation? Will wide adoption of plant-based alternatives to non-beef animal products have less of an impact on emissions reductions, given that conventionally produced pork and poultry have comparable carbon efficiency to plant-based alternatives?	(1) Shifts in production could lead to reductions in warming potential, and contribute to climate change mitigation (justice: intergenerational, economic, health equity, environmental; VNW; human rights: health, food, standard of living); (2) a more resource-efficient food system could sustain more people with a given resource level (justice; human rights: food); (3) changes in demand and production, reductions of total resource use by the food system could reduce the environmental impact of the food system across some environmental dimensions (justice: intergenerational; VNW; human rights: health, food, standard of living, healthy and safe working conditions)
Use of agricultural inputs (land, water, chemicals)	Small changes in cropland, water, and chemical use	Will overall resource use decline after resource allocation to other uses? Reduction in pastureland likely unless other uses arise	*
Animal welfare			
Animal numbers	Fewer number of beef cattle; increased numbers of other animals (e.g., pigs and chickens)	Will plant-based beef alternatives compete with other beef (and meat) alternatives? Will plant-based beef alternatives compete with other meats? Will the wide adoption of other plant-based alternatives more significantly reduce animal numbers?	(1) Plant-based beef alternatives could lead to more chickens and pigs raised for food, who are more often raised in confinement conditions (ARW); (2) the adoption of other plant-based alternatives could more significantly reduce animal numbers (ARW)
Economy and livelihoods			
GDP	Neutral impact on aggregate GDP; growing sectors offset declining sectors	What constraints could prevent reallocation of resources between sectors? What would be the consequences of the more disruptive adoption of a wider array of plant-based alternatives?	(1) The adoption of plant-based alternatives to beef (and more broadly to other animal products) could contribute to changes in the access to resources and jobs across the economy (human rights: livelihoods); (2) the consequences of these changes would be heterogeneous, with some regions or individuals benefiting while others suffer from the changes, contributing to diverging economic, social, and health outcomes (human rights: standard of living; justice: economic)

Table 2.2: Summary of selected modelled results, key points of uncertainty, and ethical implications of the replacement of beef with plant-based alternatives (*continued*)

	Modelled results of substituting beef with plant-based alternatives	**Key points of uncertainty**	**Considering potential outcomes from multiple ethical perspectives**
Regional economic effects	Not assessed directly	What would be the regional consequences of disruptions in the food system? Where will plant-based alternatives ultimately be produced? Will there be novel sectors that could replace the economic role of animal production?	*
Animal-sourced food producers	The beef sector would contract substantially; reductions in producer prices could reduce profitability of the sector	How would beef producers adapt to a contraction in the beef sector (e.g., through diversification or new income generating activities)? Would the adoption of other plant-based alternatives reduce options for income diversification? What will be the effects on agricultural producers' livelihoods, participation in meaningful work, and identities?	(1) If animal-sourced food producers cannot successfully adapt to a contraction in their sectors, they might cease operations altogether, leading to negative effects on their livelihoods, participation in meaningful work, and identities (human rights: livelihoods); (2) increased concentration of agricultural sectors could increase power asymmetries, and disproportionately affect smaller producers (justice: economic, equitable power and control)
Agricultural labour	Wages are steady across the scenarios; labour shifts from contracting sectors to expanding sectors	Are there constraints that limit labour mobility (between regions or sectors) and contribute to regional unemployment? What would be the work conditions for workers moving to new jobs? Will already marginalised workers (e.g., migrant workers) be disproportionately negatively affected? The wider adoption of plant-based alternatives could require greater reskilling for labour to move to other jobs	(1) If labour mobility is constrained, workers in animal sectors could see negative impacts on their bargaining power, future wages, and ability to demand safer working conditions (human rights: standard of living, fair wages, working conditions), with marginalised groups more likely to be disproportionately affected (justice: economic); (2) diversification of economic activities could see shifts towards safer and more economically lucrative activities (human rights: working conditions, wages, livelihoods, health; justice: economic, health equity)

Table 2.2: Summary of selected modelled results, key points of uncertainty, and ethical implications of the replacement of beef with plant-based alternatives (*continued*)

	Modelled results of substituting beef with plant-based alternatives	**Key points of uncertainty**	**Considering potential outcomes from multiple ethical perspectives**
Public health			
Nutrition	Not assessed directly	What is the contribution of plant-based beef, and more broadly plant-based alternatives, to nutrition? What are the long-term consequences of their consumption on dietary quality and diet-related illness risk? Would declining prices for beef lead to rebound effects on beef consumption?	(1) There could be important public health consequences (positive or negative, or both) of the wide consumption of plant-based alternatives; (2) access to plant-based alternatives might not be equally available, which could have disproportionate (positive or negative) impacts across society, particularly if there are any rebound effects (justice: health equity)
Food safety and public health effects of animal production	Not assessed directly	What will be the aggregate effect of shifts in animal production on public health risks (e.g., pollution, zoonotic risk, and food-based pathogens)? What risks will these novel processes introduce into the food system (e.g., failures in industrial food processing similar to the 2022 baby formula recall)?	(1) Changes in agricultural production (what is produced and where) could contribute to changes in public health, with local and national consequences (human rights: health; justice: health equity, economic, environmental); (2) changing composition of diets would alter the food-based risks to public health with impacts likely to affect the population heterogeneously (human rights: food, health; justice: health equity)

Notes: Ethical perspectives follow from figure 2.1 and are given in brackets after each potential outcome. CO_2eq=carbon dioxide equivalent. GDP=gross domestic product. VNW=valuing the natural world. ARW=animal rights and animal welfare. *Same as above.

2.4 Discussion

Our results suggest the adoption of plant-based beef alternatives would reduce the carbon footprint of US food production, which is an ethically important outcome. However, reductions across the entire food system along other environmental dimensions (e.g., water, land, and chemical inputs) are more ambiguous. Although plant-based alternatives use less land and water per unit of production, our modelling results suggest that many of these freed resources would be reallocated to other uses across the food system. This change would allow the food system to produce more with the same inputs (increased efficiency), but does not assure that total resource use would decline.

Economically, our results suggest a large shift to plant-based alternatives would have a neutral effect on gross domestic product, with gains in expanding sectors roughly offsetting losses in decreasing sectors. However, despite the minor effect in the aggregate, the distribution of positive and negative economic effects across the economy is ethically important. Whether these changes would increase economic inequality and exacerbate existing vulnerabilities warrants further investigation. Who ultimately adopts these products might vary by demographic and economic characteristics, concentrating impacts of consumption to certain consumers.[52] Those currently involved in beef value chains are likely to experience most of the economic losses and dislocations caused by the shift towards plant-based alternatives. Large producers are responsible for most meat production and profits, even as most farms in the USA are classified as small family-owned farms, with the median cattle operation failing to break even, requiring off-farm income to supplement farm income.[53,54] It is unknown to what extent small farmers would be able to adapt to reduced beef demand by further diversification of economic activities, or if these changes would make continued involvement in the beef value chain untenable.

The economic model used in this study assumes that those employed in agricultural sectors can find employment in other economic sectors, but there can be constraints to labour mobility, particularly in the short term. Our results suggest that, although there would be substantial declines in employment in beef processing, much of this workforce could move to other animal processing sectors (e.g., pork and poultry) without substantial reskilling required. Nevertheless, it is important to recognise concerns about working conditions across animal processing sectors, with workers experiencing high rates of injury.[55,56] Furthermore, the current structure of US agricultural production[49] suggests these changes could require those employed in beef sectors moving from major beef producing regions (the Great Plains, central USA) to regions specialising in pork and poultry (southeast USA). These dislocations could have real costs that are likely to fall disproportionately on disadvantaged people and communities, and should be the focus of future research. For example, these changes could have serious implications for the rural economies reliant on cattle ranching and beef processing and put new pressure on receiving communities that might not have the infrastructure

to absorb incoming populations. Moreover, processing sectors for all animal products are heavily reliant on migrant labour, a particularly disadvantaged and vulnerable group.

Our modelling results also suggest there could be unintended consequences for animal welfare of adopting plant-based beef alternatives. The freeing up of resources used in beef production could facilitate the expansion of the pork and poultry sectors, thus swapping a relatively small number of cattle (2–12 million per year) for a much larger number of chickens (16–94 million per year) and pigs (0.2–1.4 million per year). There are two concerns here. First, the sheer numbers of animals affected, across all relevant species, could increase. Second, the welfare conditions of most pigs and chicken in agricultural production are arguably worse than those of cattle, given that the pork and poultry sector more frequently use confined feeding operations. As such, replacing beef with plant-based beef alternatives is preferable to replacing beef with other animal products, from the perspective of animal welfare. In our analysis, directly substituting beef with other animal products (**BEEF10** scenario) resulted in 2–5 times more pigs and chickens than replacing beef with plant-based alternatives (**ALTP10** scenario).

It is also important to consider the disruptive potential of the full range of alternative meat products. Plant-based alternatives to chicken and pork are increasingly coming to market and, if widely adopted together with beef alternatives, could more drastically reduce the animals in food production. Wide adoption of a range of alternatives would be economically more disruptive than our four modelled scenarios, in which only beef is replaced. For example, greater economic dislocation would be expected, since people employed in the beef processing sector would not be able to find employment in other animal processing sectors, requiring greater reskilling of the agricultural workforce to move to new activities.

In summary, the threat of climate change is increasing and plant-based alternatives could help to reduce the carbon footprint of the food system, while also reducing the number of animals needed to meet growing global food demand. If widely adopted, plant-based alternatives could restructure the food system, redefining economic and material flows within many value chains, with some economic activities expanding while others decrease. New demand for crops might spur intensification of crops that were previously less economically important (e.g., pulses as inputs to plant-based alternatives). All these changes will ultimately lead to both positive and negative effects along many dimensions, all with important ethical implications.

This study has highlighted the importance of using dynamic approaches in addition to static lifecycle assessment-based approaches when assessing the ethical implications of potentially transformative innovations. Nevertheless, the work has some limitations. First, the detailed sector representation of USAGE-Food precluded the models from being run with detailed regional disaggregation. Second, although computable general equilibrium models are powerful modelling tools, like all models, they are simplifications of reality and can struggle to represent an economy out of equilibrium and represent behaviour primarily from an economic lens. As such, future research should apply multi-model assessments to advance understanding of important ethical questions that address some of the limitations of this study, including the following four priorities.

First, exploring a wider range of potential adoption pathways of plant-based alternatives, including how these novel products could compete with conventional animal products and with other existing and future novel protein products (e.g., cultured meats). This research should consider heterogeneous demand preferences across the USA,[52] and the potential for rebound effects in consumer demand in response to price changes.

Second, extending beyond the USA to consider the potential impact of increased global demand of plant-based alternatives on agricultural producers in low-income and middle-income countries.

Third, assessing the public health impacts of shifting human diets towards plant-based alternatives, including the distribution and frequency of zoonoses and foodborne pathogens, and the burden of disease from chronic illnesses.

Finally, modelling in greater detail the regional, household, and firm-level impacts of shifts to plant-based alternatives to help to develop transition pathways that restrict negative economic effects on individuals currently involved in the beef value chain.

Although future research is needed to assess the ethical implications of plant-based alternatives more fully, the results of our multi-dimensional assessment across multiple ethical perspectives show that shifts from beef to plant-based alternatives have the potential to deliver a number of moral goods, but also reveal that a full accounting of the ethics of such a transition will be complex. Our findings suggest that plant-based alternatives could play an important role in helping to reduce the carbon footprint of the food system and have the additional benefit of increased resource use efficiency, with relatively small (albeit concentrated) negative economic impacts. These are good reasons for regulators and policy makers to encourage these technologies at this early stage of development and adoption, but only if they remain vigilant to unintended negative consequences and commit to mitigating those that are ethically concerning, including harms to disadvantaged workers and hard-hit local communities and small producers.

Author contributions

DM-D and AB wrote the manuscript. DM-D developed all figures. PD and MR modelled in USAGE-Food. DM-D, AB, PD, and MR analysed the data. DM-D, AB, PD, JBe, JF, MH, RM, TR, MR, and RF were involved in study conceptualisation. DM-D, JBo, GD, PD, JP, and MR collected data. All authors reviewed and edited the manuscript and agreed to submit the manuscript for publication. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication. DM-D, PD, and MR accessed and verified the underlying data.

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Declaration of Interest

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. We declare no competing interests.

Data sharing

The USAGE-Food model output used in this study is summarised in appendix 2.2. Mathematical descriptions of modified components of the USAGE model are included in appendix 2.1 (pp 6–29). Documentation of USAGE is available at https://www.copsmodels.com/usage.htm. Full model simulations have been made available in the form of zipped archives in a Mendeley Data Repository (http://doi.org/10.17632/dmhhfw2yzt.1). The USAGE-Food model was run using GEMPACK 12.1, which requires a licence. A model-specific and scenario-specific GEMPACK licence to reproduce the model results can be made available. Inquiries to access this limited licence as well as for more detailed training in the use of the USAGE model can be addressed to PD (Peter.Dixon@vu.edu.au) and MR (Maureen.Bleazby@vu.edu.au).

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Gaps between fruit and vegetable production, demand, and recommended consumption at global and national levels: an integrated modelling study

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ABSTRACT

Background Current diets are detrimental to both human and planetary health and shifting towards more balanced, predominantly plant-based diets is seen as crucial to improving both. Low fruit and vegetable consumption is itself a major nutritional problem. We aim to better quantify the gap between future fruit and vegetable supply and recommended consumption levels by exploring the interactions between supply and demand in more than 150 countries from 1961 to 2050.

Methods In this global analysis, we use the International Model for Policy Analysis of Agricultural Commodities and Trade, which simulates the global agricultural sector, to explore the role of insufficient production of fruits and vegetables and the effects of food waste and public policy in achieving recommended fruit and vegetable consumption. First, we estimate the average historical (1961–2010) and future (2010–50) national consumption levels needed to meet WHO targets (a minimum target of 400 g/person per day or age-specific recommendations of 330–600 g/person per day) using population pyramids; for future consumption, we use projections from the Shared Socioeconomic Pathways (SSPs), a set of global socioeconomic scenarios characterised by varied assumptions on economic and population growth. We then simulate future fruit and vegetable production and demand to 2050 under three such scenarios (SSP1–3) to assess the potential impacts of economic, demographic, and technological change on consumer and producer behaviour. We then explore the potential effects of food waste applying various waste assumptions (0–33% waste). Finally, we apply two policy analysis frameworks (the NOURISHING framework and the Nuffield ladder) to assess the current state of public policy designed to achieve healthy diets.

Findings Historically, fruit and vegetable availability has consistently been insufficient to supply recommended consumption levels. By 2015, 81 countries representing 55% of the global population had average fruit and vegetable availability above WHO's minimum target. Under more stringent age-specific recommendations, only 40 countries representing 36% of the global population had adequate availability. Although economic growth will help to increase fruit and vegetable availability in the future, particularly in lower-income countries, this alone will be insufficient. Even under the most optimistic socioeconomic scenarios (excluding food waste), many countries fail to achieve sufficient fruit and vegetable availability to meet even the minimum recommended target. Sub-Saharan Africa is a particular region of concern, with projections suggesting, by 2050, between 0.8 and 1.9 billion people could live in countries with average fruit and vegetable availability below 400 g/person per day. Food waste is a serious obstacle that could erode projected gains. Assuming 33% waste and socioeconomic trends similar to historical patterns, the global average availability in 2050 falls below age-specific recommendations, increasing the number of people living in countries with insufficient supply of fruits and vegetables by 1.5 billion compared with a zero waste scenario.

Interpretation Increasing fruit and vegetable consumption is an important component of a shift towards healthier and more sustainable diets. Economic modelling suggests that even under optimistic socioeconomic scenarios future supply will be insufficient to achieve recommended levels in many countries. Consequently, systematic public policy targeting the constraints to producing and consuming fruits and vegetables will be needed. This will require a portfolio of interventions and investments that focus on increasing fruit and vegetable production, developing technologies and practices to reduce waste without increasing the consumer cost, and increasing existing efforts to educate consumers on healthy diets.

Estrella de los pobres
hada madrina
envuelta
en delicado
papel, sales de suelo,
eterna, intacta, pura
como semilla de astro,
y al cortarte
el cuchillo en la cocina
sube la única lagrima
sin pena.

Star of the poor,
fairy godmother
sheathed
in delicate
paper, you emerge from the ground
everlasting, intact, pure
like a seed of a star,
and when you are cut
by the knife in the kitchen
the only tear you shed
is without sorrow.

Pablo Neruda, *Oda a la Cebolla*, trans. Wally Swist

3.1 Introduction

Continued progress across the food system, particularly since the green revolution, has boosted agricultural production to the point where calorie supply globally is outpacing recommended consumption levels. This has led to a decades-long decline in hunger rates, despite recent upticks caused primarily by state fragility.[1] This reduction in hunger, however, has been achieved with substantial impacts on the environment, threatening the sustainability of our gains.[2] The gains have also come at a human health cost as diets globally have become more homogeneous[3] and are increasingly characterised by cheap calories, highly processed foods, and overconsumption.[4] The population with overweight and obesity now outnumber those with insufficient caloric intake, even as more than 2 billion people experience micronutrient deficiencies.[5] Unbalanced diets are the reason many people in most countries have some form of malnutrition, due to the inadequate, unbalanced, or excessive consumption of macronutrients and micronutrients.[6] This has led to the proliferation of many of the noncommunicable diseases that are now the main cause of premature mortality globally.[7]

Increasingly, it is recognised that the global food system must move its focus from quantity towards dietary quality and health and environmental outcomes.[5,8] To this end, much attention has been focused on reducing negative dietary risk factors such as overconsumption of processed or discretionary foods, sugar, saturated fat, and red meat.[2,9] These studies also suggest public health and the environment would benefit from rebalancing towards more plant-based diets, with increased fruit and vegetable consumption crucial.[5] Several studies have also suggested that current and projected fruit and vegetable production will fail to meet healthy consumption levels[10,11] but have not directly simulated the interconnected nature of food production, demand, socioeconomic development, and food prices—a major determinant of consumer behaviour. This study aims to build on these previous studies by quantifying the gap between future fruit and vegetable supply, demand, and recommended consumption levels. First, we assess the historical gap between supply and recommended

consumption levels. We then explore future uncertainty of both supply and demand using a range of alternative socioeconomic scenarios. To better simulate the interconnected nature of technology development, population growth, economic development on both agricultural production and food demand, we simulate these scenarios in the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT), a global economic model of the agriculture sector. We then consider the potential challenges consumer waste might present in the future. Finally, we review public policy targeting fruits and vegetables and analyse them using multiple policy frameworks to determine the scope and scale of current policies in this space.

Research in Context

Evidence before this study Three recent high-level studies (the EAT–Lancet Commission on healthy diets from sustainable food systems, the Lancet Commission report on the Global Syndemic of Obesity, Undernutrition, and Climate Change, and the Global Nutrition Report) have summarised the literature on healthy and sustainable diets. All three studies highlighted the negative effects of current diets on human and planetary health and identified the need for radical change in the food system to improve diets to bridge the gap between current and recommended diets. Work done by WHO and in Global Burden of Disease assessments has consistently shown that low consumption of fruits and vegetables is a major obstacle to achieving healthy diets. Further studies have tried to assess the gap between future production of fruits and vegetables and recommended consumption levels. However, these studies projected supply in isolation from changing future food demand and did not directly simulate the inter-related nature of production, demand, and socioeconomic development. Several integrated modelling studies that have simulated future production and demand have found that economic growth alone would be insufficient to supply healthy diets or achieve food security but did not assess future gaps of fruit and vegetable production, demand, and recommended consumption levels.

Added value of this study We expand on the evidence of low fruit and vegetable consumption and production by applying a global integrated economic model of the agriculture sector to simulate how fruit and vegetable demand and production could change under a range of alternative futures with different assumptions on socioeconomic and technological change. Applying state-of-the-art scenarios and economic modelling, we explore how consumers and producers in more than 150 countries could respond to changing market conditions in these scenarios to better project the gap between future fruit and vegetable production and recommended consumption levels at the global and national levels. We explore the uncertainty of food waste for fruits and vegetables with a range of waste assumptions. We show that even under more optimistic consumer waste scenarios, many countries will probably fail to supply sufficient fruits and vegetables to meet recommended consumption levels. Finally,

we review current policies using both the NOURISHING framework and the Nuffield ladder to show the gap between public actions and what would be needed to achieve healthy fruit and vegetable consumption levels.

Implications of all the available evidence Diets—and low fruit and vegetable consumption—are associated with the most important causes of premature mortality globally. Shifting towards healthier diets rich in nutritious foods such as fruits and vegetables could lead to a win-win scenario for public and ecological health. Historical trends suggest that economic growth might help to increase fruit and vegetable consumption, but without substantial public efforts, this increase is likely to fall short of meeting the required increases. Achieving recommended consumption levels will require concentrated efforts across the food system to reorient investments and interventions to prioritise fruits and vegetables more. It will require additional investments in research and development to encourage more fruit and vegetable production, while decreasing its environmental footprint, as well as new processing, storage, and distribution technologies to reduce waste. Targeted fiscal policies such as price supports and procurement policies should also be considered to supplement public awareness efforts to incentivise consumer behaviour change.

3.2 Methods

3.2.1 Scenario analysis and selection

Projection of future fruit and vegetable availability involves substantial uncertainty, as the global food system is highly interconnected and interdependent. Future fruit and vegetable availability will be affected by many factors including economic development, population growth, changing consumer behaviour, and climate change, to name a few. In this study, we focus on assessing the impact of varying levels of socioeconomic development, while recognising that these other factors are important.

Here, we use exploratory scenarios that present plausible future pathways, based on internally consistent assumptions of various drivers, trends, and interactions into the future.[12] We chose this scenario analysis approach due to the fundamental uncertainty in projecting complex systems with interconnected and dependent variables; in such cases, the future possibility space is too large to be able to reasonably estimate confidence intervals. Stochastic analysis, which can be done in a forecasting exercise, attempts to predict the future on the basis of past behaviour and relationships. However, given that the future will potentially be very different than the past, this type of exercise will almost certainly consider a limited possibility space. Therefore, we explore future uncertainty using a range of scenarios that provide a broader envelope of plausible futures than would be possible solely by extrapolating from past behaviour. Specifically, we use the Shared Socioeconomic Pathways (SSPs), a

set of global socioeconomic scenarios developed for the Intergovernmental Panel on Climate Change.[13] We use three of the SSPs (1–3) that provide a broad envelope of plausible pathways to 2050, characterised by varied assumptions on economic and population growth. Of the three SSPs considered, SSP1 is the most optimistic scenario envisioning a more sustainable development pathway with a global population by 2050 of 8.5 billion people with per-capita gross domestic product (GDP) of US$34 000; SSP2 is a middle-of-the-road scenario, where global population grows to 9.2 billion people with per-capita GDP of $25 000; and SSP3 is the most pessimistic scenario with global population reaching nearly 10 billion people with a per-capita GDP of $18 000 (see appendix 3.1 pp 18–19). We assume IMPACT's default dietary pathways,[14] which are based on historical relationships between food demand and income growth, to allow us to estimate the future availability gap assuming business-as-usual policies and dietary transitions.

3.2.2 Economic modelling

To simulate the complex connections across the global agricultural system, we applied the IMPACT model (version 3.3). IMPACT is an integrated modelling system composed of an ensemble of economic and biophysical models, which allows it to simulate agricultural production in the face of biophysical and economic constraints. It has been extensively used in a series of global agricultural assessments and modelling exercises that have considered the impacts of policies and production shocks on the global food system.[15–17] In the class of global economic simulation models, IMPACT is the most disaggregated in terms of country and commodity representation. At its core, IMPACT is a global partial-equilibrium multimarket model that simulates national and global agricultural production, demand, and trade for 158 countries or regions and 62 commodities.[18] Of the 62 commodities simulated in IMPACT, three commodities are fruits and one commodity is vegetables. For this analysis, we additionally grouped the 158 countries and regions into seven geographical regions (east Asia and Pacific, Europe and North America, the former Soviet Union [including the Baltic states up to 1990, after which they are considered to be part of Europe], Latin America and Caribbean, Middle East and north Africa, south Asia, and sub-Saharan Africa) and two income groups (developed and developing), where appropriate. Summaries of the geographical and commodity scope of IMPACT, including a mapping of the Food and Agriculture Organization (FAO) of the UN's fruit and vegetable commodities to IMPACT commodities, are presented in the appendix 3.1 (p 10).

IMPACT simulates the interrelated nature of markets, which can respond to changes in production technologies, climate, consumer preferences, demographics, and public policy. Household demand is simulated through the interaction of a mix of exogenous (population, economic growth) and endogenous (prices) factors with consumer preferences represented by income and price elasticities following historical relationships (e.g., Engel's and Bennett's laws[17]). Similarly, producer behaviour is simulated with a mix of exogenous and endogenous factors, where producers respond endogenously to changing price levels, as well as to exoge-

nous assumptions on technological developments. Production and demand within countries are linked through trade and international commodity markets, with IMPACT finding an equilibrium such that commodity prices clear all commodity markets (i.e., global supply equals global demand). The model, therefore, can consistently simulate many of the crucial interactions between consumers, producers, and distribution networks.

IMPACT does not simulate actual consumption but it does simulate average food availability, from which we can estimate calorie availability and average consumption through post-solution application of food waste assumptions, as has been done in several recent health and nutrition assessments.[9,16,19,20] A more detailed description of IMPACT is available in the appendix 3.1, with the complete model documentation available online.[18]

3.2.3 Defining recommended consumption levels

We use two WHO targets to provide the recommended fruit and vegetable consumption levels in this analysis. The first is a minimum recommendation of 400 g/person per day,[21] similar to studies that suggest five servings of fruits and vegetables can provide the bulk of health benefits.[22] The second is an age-adjusted recommendation, which is based on health modelling used to estimate a minimum dietary risk distribution—i.e., to reduce the global risk of ischaemic heart disease, cerebrovascular disease, lung cancer, and selected gastrointestinal cancers. This more rigorous recommendation suggests 600 g per day for adults and adolescents (aged ≥15 years), 480 g per day for children aged 5–14 years, and 330 g per day for children aged 0–4 years.[23] Both WHO recommendations are broadly consistent with national recommendations based on detailed health modelling (appendix 3.1 p 1).[24]

We estimate average recommended consumption levels using population statistics or projections to estimate the average per-capita consumption level. For historical age-adjusted recommendations, we use age-specific population pyramids from the UN Population Prospects[25] and for future projections, we use population projections from the SSPs.[26] In both cases, we use age-specific numbers to calculate a population-weighted average consumption level by country that would be consistent with the WHO recommended consumption levels and the respective population pyramid. This application of age-specific recommendations allows us to take into account projected regional demographic changes.

3.2.4 Estimating fruit and vegetable availability

To estimate historical (1961–2010) fruit and vegetable availability, we use total food demand of fruits and vegetables from the FAO's commodity balance sheets.[27] The FAO reports for 17 fruit and vegetable items, with many of these representing aggregations (e.g., citrus, other). Data are reported in primary commodity equivalence (e.g., wheat flour is converted into equivalent quantities of wheat grain).[28] We then use historical population statistics[25] to estimate average fruit and vegetable availability in per-capita terms. The definition of fruits and vegetables used in this analysis follows those used by WHO and excludes pulses (e.g.,

lentils, beans, etc) and starchy roots and tubers (e.g., potatoes, cassava, etc). Future (2010–50) fruit and vegetable availability are taken from the scenario results simulated in IMPACT. IMPACT uses data from the FAO's commodity balance sheets and similarly represents agricultural production and demand in primary commodity equivalence. Due to data limitations on production, prices, and trade, IMPACT further aggregates fruits and vegetables into four commodities. Nevertheless, given that food dietary guidelines do not highly disaggregate recommended consumption levels, the model is still useful in assessing changes in production and demand with these targets.

3.2.5 Incorporating food waste into the analysis

We include food waste in our analysis, recognising that some level of waste is inevitable and a certain amount of overproduction is necessary to ensure sufficient production to achieve recommended consumption levels. Food loss and waste estimates for fruits and vegetables vary substantially in the literature,[29–31] in part due to varying definitions of what constitutes food losses and waste.[32,33] In this analysis, we define food waste as household food waste and treat other inefficiencies in the food system as food losses, which are accounted for in IMPACT in two ways: 1) post-harvest losses, which include activities at the point of primary production and are represented in IMPACT through reduced yields than what might be realised biologically; and 2) processing and storage losses, which are components of other demand and are included in IMPACT to ensure a full accounting of all primary production throughout the food value chain.[34] Consumer or household food waste makes up the difference between the food demand reported in IMPACT and average food consumption. A visual representation of the varying stages of how food losses and waste are represented in IMPACT is included in the appendix 3.1 (p 16).

Projecting future food waste is difficult, given the opposing historical relationship between higher incomes and increased waste[29,32] and growing attention to the need to reduce food waste if society is to achieve a sustainable food system.[5] To account for this uncertainty, we apply stylised waste scenarios to estimate the quantity of additional fruits and vegetables that could be needed to ensure adequate future supply. First, we use the FAO's most recent region-specific estimates from 2013,[31] which have been used in several studies on global diets, health, and sustainability.[5,9,16] These estimates range from 5% in sub-Saharan Africa to 28% in North America and Oceania (appendix 3.1 p 16). To project potential future waste, we have also included two alternate waste assumptions of 15% and 33% that are projected across all regions, similar to Siegel and colleagues.[10] This range is similar in scope to the regional differences found in the FAO estimates and allows us to consider futures where waste increases with further economic development (33% waste), as well as futures where efforts to reduce food waste are implemented (15% waste).

3.2.6 Reviewing public policies concerning fruits and vegetables

Analysis of the current state of policies was based on the World Cancer Research Fund International's (WCRF) NOURISHING database.[35] The WCRF maintains this global database of implemented government policy actions that is updated three to four times per year (when accessed, the most recent update was in October, 2018), using a two-stage search and review and verification process.[36] The database is intended to be comprehensive in its scope, although is unlikely to reflect an exhaustive list of all implemented policies due to limitations in data availability. To the authors' knowledge, the database does, however, offer the best available global information source on implemented policies related to promotion of healthy diets and is the source of policy data used in other reputable global analyses such as the Global Nutrition Report.[37] Policies related to fruits and vegetables were identified using keyword searches for "fruit" or "vegetable". Only policy examples that specifically targeted fruits and vegetables were included. We defined policies targeting fruits and vegetables as those policies that either described a minimum quantity of fruits or vegetables to be provided or described an activity or intervention specifically promoting increased consumption of fruits or vegetables. This definition might exclude some policies that broadly target healthy eating but that did not specifically mention fruits or vegetables. In many cases, policies were identified at the regional level (e.g., the EU) instead of at the country level.

We further complemented the NOURISHING framework[38] by mapping the policy options to the Nuffield ladder, an alternative policy framework used to analyse the efficacy of policies towards reducing obesity.[39] The Nuffield ladder categorises policies not on the basis of their sphere of influence but on how forceful the policies are in terms of intervening in the choice environment, ranging from "provide information" (lowest or least forceful rung) to "eliminate choice" (highest or most forceful rung). In mapping the policy options, we considered the likely effect of each option from the consumer perspective. For example, the "incentives for store-owners to locate in underserved areas" NOURISHING policy option was mapped to "enabling choice" rather than "guide choice with incentives" on the Nuffield ladder because the incentives are targeted at the store owner, whereas the outcome of the policy provides consumers with greater choices in accessing stores. A complete mapping of the policies in the NOURISHING database to the Nuffield ladder can be found in the appendix 3.1 (pp 24–25).

Table 3.1: Regional summary of fruit and vegetable availability and progress towards availability of 400 g/person per day

		1965	1990	2015	2050		
					SSP1	SSP2	SSP3
East Asia and Pacific	F&V availability (g/person/day)	194	318	834	982	924	877
	Number of countries	22 (5)	22 (7)	23 (12)	23 (15)	23 (15)	23 (15)
	Population (millions)	1862 (144)	3026 (271)	2242 (1886)	2173 (2105)	2261 (2186)	2352 (2266)
South Asia	F&V availability (g/person/day)	167	198	326	1335	956	615
	Number of countries	6 (0)	6 (0)	7 (0)	7 (4)	7 (3)	7 (2)
	Population (millions)	637 (0)	1133 (0)	1747 (0)	2108 (2025)	2373 (1980)	2720 (2032)
Former Soviet Union*	F&V availability (g/person/day)	292	349	526	678	644	624
	Number of countries	1 (0)	1 (0)	12 (10)	12 (12)	12 (11)	12 (11)
	Population (millions)	230 (0)	287 (0)	281 (270)	263 (263)	278 (270)	290 (279)
Middle East and north Africa	F&V availability (g/person/day)	436	640	735	798	771	731
	Number of countries	14 (7)	14 (11)	17 (15)	17 (15)	17 (15)	17 (15)
	Population (millions)	145 (77)	291 (251)	499 (467)	647 (594)	716 (653)	809 (732)
Sub-Saharan Africa	F&V availability (g/person/day)	178	178	206	355	301	248
	Number of countries	38 (0)	38 (0)	43 (1)	43 (14)	43 (5)	43 (3)
	Population (millions)	233 (0)	462 (0)	956 (10)	1542 (723)	1767 (519)	2055 (130)
Latin America and Caribbean	F&V availability (g/person/day)	310	322	413	544	498	462
	Number of countries	24 (6)	24 (5)	24 (13)	24 (18)	24 (16)	24 (14)
	Population (millions)	250 (53)	441 (21)	616 (442)	675 (555)	742 (584)	854 (628)

Table 3.1: Regional summary of fruit and vegetable availability and progress towards availability of 400 g/person per day (*continued*)

		1965	1990	2015	2050		
Europe and North America*	F&V availability (g/person/day)	454	601	632	700	689	708
	Number of countries	27 (11)	27 (23)	31 (30)	31 (31)	31 (31)	31 (31)
	Population (millions)	665 (393)	781 (757)	905 (898)	1053 (1053)	1027 (1027)	870 (870)
Global	F&V availability (g/person/day)	252	335	546	862	732	608
	Number of countries	132 (29)	132 (46)	158 (81)	158 (109)	158 (96)	158 (91)
	Population (millions)	4019 (665)	6419 (1298)	7243 (3969)	8457 (7314)	9162 (7217)	9946 (6934)

Notes: Numbers in parentheses represent countries that have achieved fruit and vegetable availability greater than or equal to 400 g/person per day and their respective population. Food availability excludes consumer food waste. 1965 and 1990 values are taken from the FAOSTAT commodity balance sheets[27] and 2015 and 2050 values are projections from the International Model for Policy Analysis of Agricultural Commodities and Trade using three scenarios (SSP 1–3) using default diets (based on historical trends). F&V=fruit and vegetable. *Regional groupings follow the FAO's regional classification. * The Baltic states are reported as part of the former Soviet Union up to 1990 and are included in Europe for all future projections.

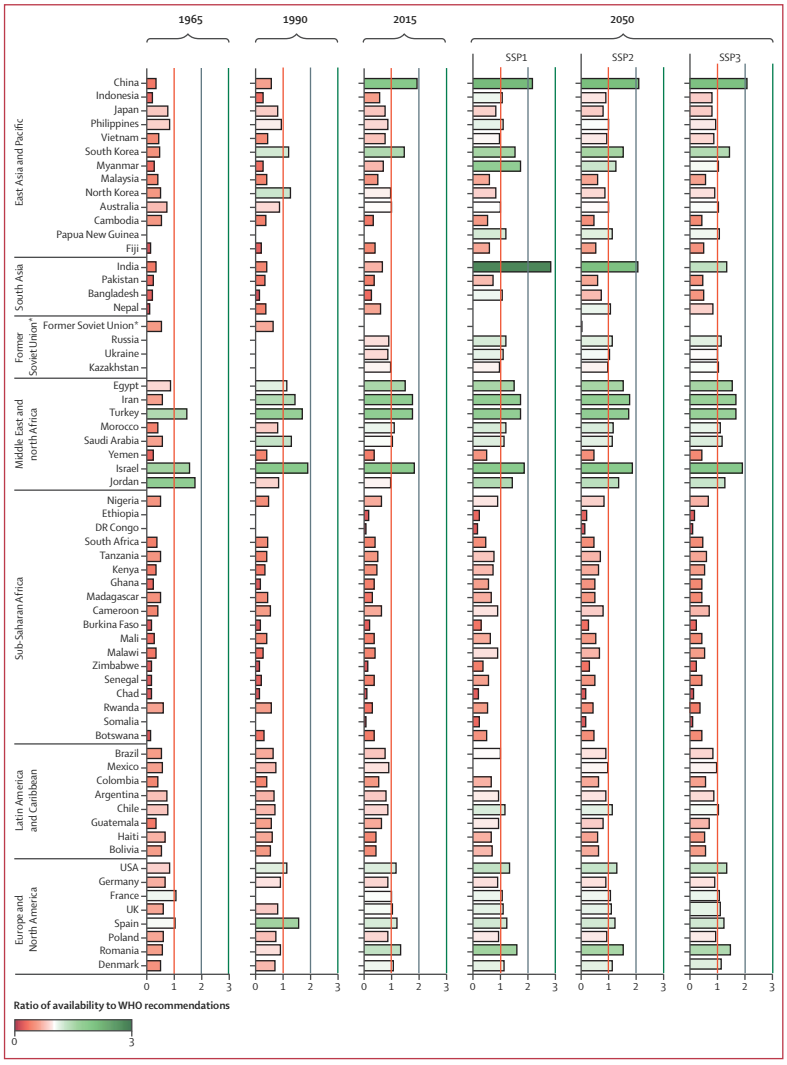

Figure 3.1: Selected country ratios of fruit and vegetable availability to WHO age-specific recommendations.

Notes: Countries shown were chosen to provide a representative group of countries from each region, including the maximum and minimum across the region. Countries in each region are listed in descending order by 2010 population. Food availability excludes consumer food waste. 1965 and 1990 values are from FAOSTAT commodity balance sheets[27] and 2015 and 2050 values are projections from IMPACT using three scenarios (SSP1–3) using default diets (based on historical trends). Vegetables follow WHO definitions excluding legumes and starchy roots and tubers. The vertical lines represent when availability (excluding waste) equals one times (red), two times (grey), and three times (green) the population weighted average recommended consumption levels. IMPACT=International Model for Policy Analysis of Agricultural Commodities and Trade. SSP=Shared Socioeconomic Pathway. *Data up to 1990 are presented for the former Soviet Union as a whole, whereas data from 2015 onwards are presented separately for Russia, Ukraine, and Kazakhstan.

3.3 Results

Statistics from the FAO show that the per-capita availability of fruits and vegetables has consistently been insufficient to supply recommended consumption levels.[27] In 1965, only 29 countries, representing about 17% of the global population, achieved average per-capita fruit and vegetable availability consistent with the minimum target of 400 g/person per day (table 3.1). By 2015, this number had increased to 81 countries, representing just 55% of the global population. Under the more stringent, age-adjusted recommendations, although progress was observed over this time, only 40 countries, representing about 36% of the global population had sufficient availability by 2015. Complete country results for both the age specific and minimum WHO recommendations are available in the appendix 3.1 (pp 23–24).

Progress has not been observed equally across all regions and many countries continue to have insufficient availability of fruits and vegetables to supply a healthy diet for all (figure 3.1). These numbers also do not take into account intracountry variation, where countries with sufficient availability often fail to achieve access for all within the country. High-income countries in Europe, North America, and the east Asia and Pacific region have made the most progress towards supplying sufficient fruits and vegetables over the past several decades. A substantial increase in availability has also been observed among the fast-growing economies of east and southeast Asia (e.g., China, Vietnam, and South Korea). Economic development, although not equally distributed, has increased the resources available to billions of people, contributing to these improvements. Far less progress has been achieved in low-income countries in Asia and sub-Saharan Africa, which have experienced less economic development and more political instability (e.g., DR Congo, Somalia, and Yemen)—one of the largest contributors to the recent uptick in the prevalence of hunger.[1]

Future economic growth will continue to be an important factor in determining global fruit and vegetable availability. In 2050, the global average fruit and vegetable availability varies from 608 g/person per day in SSP3 to 732 g in SSP2 and 862 g in SSP1 (table 3.1). Gains from future economic development are concentrated in developing regions, which are more sensitive to changes in economic growth assumptions. Several countries are projected to make substantial gains in fruit and vegetable availability by 2050, such as India and Indonesia (figure 3.1). However, many countries in Europe and the Americas fail to make considerable progress towards increasing the availability of fruits and vegetables across all three scenarios, despite being near the age-specific recommendations in 2015 (figure 3.1). Even more concerning is the number of countries in sub-Saharan Africa, parts of Asia, and the Pacific region that substantially fail to supply enough fruits and vegetables to meet recommended consumption levels by 2050 under the most optimistic economic projections. Sub-Saharan Africa is of particular concern: per-capita income growth in the region is projected between 2.2% per year under SSP3 and 4.7% per year under SSP1, but fewer than a third of the 43 countries in the region have sufficient fruit and vegetable availability to meet the 400 g/person per day minimum target in all three SSPs (table 3.1). With population in the region

projected to reach between 1.5 billion and 2 billion people by 2050, between 0.8 billion and 1.9 billion people could live in countries with average fruit and vegetable availability less than 400 g/person per day (table 3.1); under the more stringent targets, between 1.4 billion and 2.0 billion people—essentially the whole region—could be living in countries with insufficient availability (figure 3.1).

When we adjust the projections highlighted in figure 3.1 to take into account food waste, we see the insufficiency of projected supply increase. Figure 3.2 presents aggregated regional results under SSP2 using recent FAO region-specific waste estimates.[31] In 2015, this reduces the number of countries achieving an average fruit and vegetable supply of 400 g/person per day from 81 countries to 65 countries. This 16-country reduction represents a combined population of 0.7 billion people—nearly 10% of the global population. By 2030, assuming current waste levels remain unchanged, sub-Saharan Africa would fail to meet the 400 g/person per day threshold, with five additional regions (Europe, the former Soviet Union, Latin America and Caribbean, North America, and south Asia) failing to supply sufficient fruits and vegetables for the more stringent recommended consumption levels. By 2050, four regions would continue having average availability below recommended levels, with 22 fewer countries achieving this target, representing nearly 0.9 billion people living in countries with insufficient availability.

	Average fruit and vegetable availability (g/person per day)			Ratio of availability to recommended consumption											
				Excluding food waste			Including food waste								
							FAO estimate*			15%			33%		
	2015	2030	2050	2015	2030	2050	2015	2030	2050	2015	2030	2050	2015	2030	2050
East Asia and Pacific	846	958	957	1·49	1·67	1·66	1·38	1·55	1·54	1·27	1·42	1·41	1·00	1·12	1·11
Europe‡	616	643	666	1·08	1·12	1·16	0·87	0·91	0·94	0·92	0·95	0·99	0·72	0·75	0·78
Former Soviet Union	529	611	656	0·94	1·07	1·15	0·82	0·94	1·01	0·79	0·91	0·97	0·63†	0·72	0·77
Latin America and Caribbean	418	462	513	0·75	0·82	0·90	0·68†	0·74	0·81	0·64†	0·70	0·77	0·50†	0·55†	0·60†
Middle East and north Africa	744	779	796	1·35	1·39	1·41	1·19	1·23	1·24	1·15	1·18	1·19	0·91	0·93	0·94
North America	659	716	726	1·16	1·26	1·27	0·84	0·91	0·92	0·99	1·07	1·08	0·78	0·85	0·85
South Asia	331†	540	1002	0·60†	0·97	1·77	0·56†	0·90	1·65	0·51†	0·82	1·51	0·40†	0·65†	1·19
Sub-Saharan Africa	211†	253†	318†	0·40†	0·47†	0·58†	0·38†	0·45†	0·55†	0·34†	0·40†	0·49†	0·27†	0·32†	0·39†
Developing countries	540	637	772	0·98	1·14	1·37	0·75	0·87	1·04	0·83	0·97	1·16	0·65†	0·76	0·92
Developed countries	621	660	680	1·09	1·16	1·19	0·93	0·98	1·02	0·93	0·98	1·01	0·73	0·77	0·80
Global	552	640	760	0·99	1·14	1·34	0·82	0·95	1·12	0·85	0·97	1·14	0·67†	0·76	0·90

Ratio of availability to stringent, age-adjusted recommendation

0 2

Figure 3.2: Regional summary of ratios of average fruit and vegetable availability to recommended consumption levels including and not including various levels of food waste.

Projections are considered under Shared Socioeconomic Pathway 2. Availability is population-weighted average for each region. Recommended consumption levels are 330–600 g/person per day, depending on age. FAO=Food and Agriculture Organization of the United Nations. *FAO waste estimates vary by region and range from 5% in sub-Saharan Africa to 28% in east Asia and Pacific and North America. †Fails to achieve the 400 g/person per day minimum recommendation. ‡Includes Baltic states.

Under both alternative future waste assumptions (i.e., 15% and 33%), we see erosions in the gains projected for many regions (figure 3.2). Assuming 33% waste, by 2050, average global supply fails to meet recommended consumption levels, with all but two regions—east Asia and Pacific and south Asia—falling below recommended levels and sub-Saharan Africa and Latin America and the Caribbean falling to less than 400 g/person per day on average. Under the 33% waste scenario, only 19 countries, representing 3.6 billion people would have sufficient fruit and vegetable availability to meet recommended consumption levels compared with 60 countries representing 5.1 billion people under the no waste scenario. Even under the more optimistic assumption of 15% waste, four regions would fall below recommended levels by 2050, with sub-Saharan Africa still supplying less than 400 g/person per day on average (figure 3.2). We show what the availability gap could look like assuming a more sustainable dietary pathway in the appendix 3.1 (p 21), and even under this more sustainable dietary pathway many countries continue to supply insufficient fruits and vegetables on average.

Of the 764 policies in the World Cancer Research Fund International's NOURISHING database, only 168 specifically target fruit and vegetable consumption. Almost two thirds of these policies focused on behaviour change, most of which are food-based dietary guidelines, corresponding to the lowest or least forceful rung on the Nuffield ladder (figure 3.3). There were only 55 examples of policies targeting fruits and vegetables in the food environment (48 examples) and food supply (six examples), including examples from just four countries (Canada, Fiji, the UK, and the USA) of fiscal policies to reduce the cost of fruits and vegetables, corresponding to the more forceful rung on the Nuffield ladder of "guide choice through incentives" (figure 3.3). Furthermore, these national fiscal policies are often highly targeted and not comprehensive in coverage. For example, Canada's fiscal policies are subsidies targeted to increase access to healthy foods in isolated communities in northern Canada.[35] This analysis highlights the relative dearth of policy options currently implemented to promote increased fruit and vegetable production and consumption.

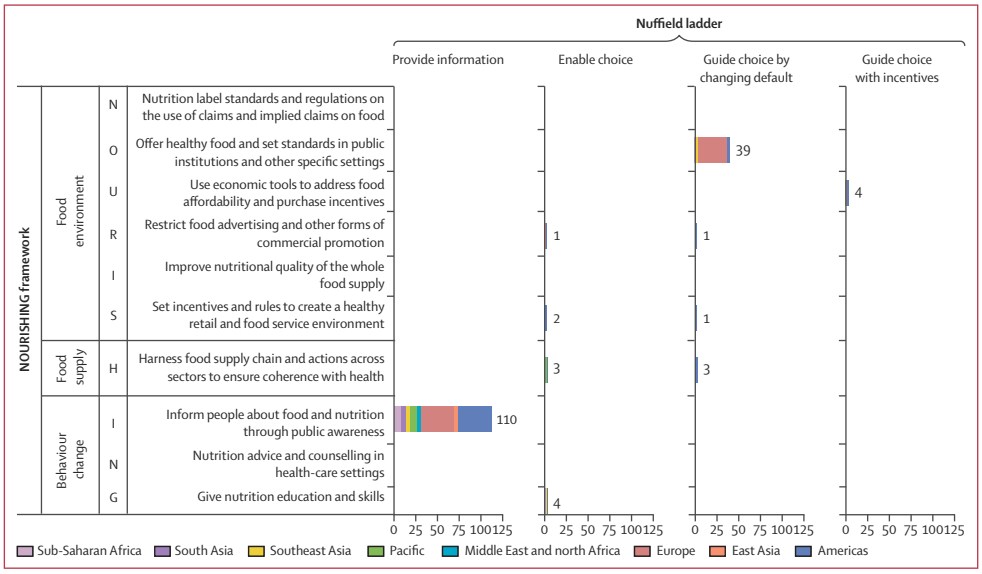

Figure 3.3: Summary of policy interventions in the NOURISHING database related to fruits and vegetables grouped by region and mapped to the Nuffield ladder.

Notes: Figure shows the number of countries for which the NOURISHING database describes either a minimum quantity of fruits and vegetables to be provided or some other activity that specifically promotes increased consumption of fruits or vegetables. No country examples were found for three Nuffield ladder policy options—guide choice with disincentives, restrict choice, and eliminate choice—which are therefore not presented on the figure. Some policies pertaining to general healthy eating, without specific mention of activities regarding promotion of increased consumption of fruits or vegetables, are excluded from this count. Regional policies are converted to country counts by assuming 28 countries are included in the EU, 15 countries in the Caribbean Community group, and 22 countries in Pacific Island Nations and Territories group.

3.4 Discussion

Low fruit and vegetable consumption is an important and long-running challenge and has many inter-related causes, such as insufficient supply, poor access, low affordability, and high levels of waste.[40] Reviewing historical data, we see there has been progress at increasing the availability of fruits and vegetables, although it has lagged behind progress made towards reducing hunger over the past several decades. Our results suggest we are likely to see continued progress but with substantial regional variation, with many regions failing to achieve adequate fruit and vegetable availability, hindering progress towards the second Sustainable Development Goal, Zero Hunger.

Our analysis builds on methods used in recent global assessments of the food system. We expand the analysis of food security using the SSPs by exploring in greater detail the impacts of projected agricultural production and demand on representative diets and compare them to WHO recommendations on healthy diets. This analysis consistently models the interaction of projected trends in population growth, economic development, agricultural productivity, and

changes in consumer behaviour. To do this we have used IMPACT, an integrated economic model in combination with socioeconomic and waste scenarios. Global economic models such as IMPACT rely on aggregated national statistics (FAOSTAT) and simulate complex economic behaviour in fairly stylised ways. For example, IMPACT represents all production in terms of homogeneous commodities (e.g., bananas instead of, say, Cavendish bananas) and simulates demand using a single representative consumer for each country. The global and national statistics used to build and calibrate these models are limited, with data often reported in aggregate (e.g., citrus, other). Fruit and vegetable recommended consumption levels are also highly aggregated, with many cases not differentiating fruits and vegetables, and where there are disaggregated targets, they are fairly coarse (e.g., leafy greens, orange vegetables). There is substantial variation on both the production and demand side within countries and commodity groups that global datasets and global models such as IMPACT cannot directly comment on. Downscaling the implications of global scenarios that inform general trends to better assess the specific impacts on different types of producers and consumers is an important area of future research.

We focused on the potential impacts of varying socioeconomic assumptions using the SSPs. The SSPs are long-run scenarios of the global economy and do not include other drivers that are important to global food security, such as extreme events, ecological collapse, state fragility, and transformative technologies. Climate change, which is also not included, is likely to lead to lower yields, higher food prices, and decreased availability of fruits and vegetables, particularly in lower income countries.[16] Nevertheless, changes in economic development[17] and food policy[41] are likely to have a greater impact than climate change up to the mid-21st century. The three scenarios we used provided a broad range of socioeconomic assumptions. However, there can be many representations of each SSP, which would affect the final results. Additionally, model selection incurs uncertainty in results. Ideally, this type of analysis could be completed using multi-model ensembles and various representations of the SSPs as has been done for land-use[14] and climate change.[15]

The scarcity of global data on waste makes this a major point of uncertainty in trying to estimate average consumption globally. We elected to use a range of waste scenarios to give a sense of how far projected fruit and vegetable availability could be from average consumption. We recognise that this invariably means that the projected gap from these scenarios is somewhat crude. However, it serves to highlight the importance of increasing production of fruits and vegetables to ensure that supply is more than sufficient to satisfy recommended levels, as well as emphasising the need for further research on food waste and its impact on food value chains.

Economic development has been and will continue to be an important contributor to future progress. However, economic growth alone will be unlikely to lead to sufficient availability of fruits and vegetables in all regions, particularly when taking into account the effects of food

waste. Globally, fruit and vegetable availability in 2050 under SSP1 could be more than 40% higher than under SSP3. This increase is driven almost entirely in lower-income regions such as sub-Saharan Africa and south Asia, with availability in developed countries substantially less sensitive to future economic growth assumptions. This suggests that policies that target poverty and broad economic growth might have important co-benefits in spurring increased demand and access to fruits and vegetables in lower-income countries. For higher-income countries, however, additional economic growth will probably have less of an impact, as economic constraints are less binding. Nevertheless, there is substantial variation within countries in terms of access and affordability with fruits and vegetables continuing to be relatively more expensive than other foods. Targeted policies on the consumption side, such as price subsidies, could increase the affordability of fruits and vegetables, leading to population-wide health benefits.[20]

Producing exactly the amount of fruits and vegetables required to satisfy WHO recommendations will ultimately be insufficient given the impact of food waste. However, we found that even with zero waste, many countries will need to increase their fruit and vegetable production to achieve adequate supply, a finding consistent with recent literature comparing production to dietary recommendations.[10,11] Increasing production will probably require prioritisation of investments in research and development around fruit and vegetable production, which has been relatively ignored.[42] Given that most fruits and vegetables are used relatively near the point of production, these investments should be targeted to promote production in regions where projected supply is inadequate, such as sub-Saharan Africa, parts of Asia, and the Pacific. Investments in agriculture have been broadly shown to have substantial potential to increase incomes and food security, particularly in Africa.[43] Therefore, investments in this sector could carry additional co-benefits in contributing to several Sustainable Development Goals (SDGs; e.g., SDG 1: no poverty and SDG 2: zero hunger), especially when we consider the importance of small-scale producers in fruit and vegetable production in these regions.[44]

Approaches to increasing fruit and vegetable production must also be assessed on their potential environmental impacts. Fruit and vegetable production is more resource-intensive compared with other crops.[5,6] Increased consumption of fruits and vegetables could increase environmental pressure, unless it is accompanied by other shifts towards more sustainable production and consumption. Fruits and vegetables are also relatively perishable, with some estimates suggesting they contribute more than 40% of total food losses and waste.[30] Food waste and food losses decrease consumption directly and indirectly by increasing the cost of fruits and vegetables. Under SSP2 and the high waste scenario, we projected 139 countries, representing 5.6 billion people, with insufficient fruits and vegetables by 2050—an increase of 1.5 billion people compared with the no waste scenario. Efforts to reduce waste are crucial to achieving sustainable food systems but, if improperly targeted, could make fruits and vegetables more expensive. Ideally, policies could be coordinated to decrease unhealthy and resource intensive components of modern diets while promoting healthy options. However,

in practice, such coordination is challenging, which might lead to difficult trade-offs between environmental and health objectives in the short and medium term that are not fully taken into consideration in the discussion of win-win scenarios for environmental and health outcomes of diet changes.

Increasing the supply of fruits and vegetables is crucial to achieving recommended consumption levels; however, this is unlikely to be achieved without changing consumer behaviour, as low consumption continues even where availability is not a constraint. Public policies targeting consumer behaviour could help to shift consumption patterns. However, to date there has been little public policy activity in this space, and the activity that exists is primarily informational in nature. Provision of information is important and quantified food-based dietary guidelines provide valuable scientific targets. More countries need to develop them, particularly in Africa where only seven countries have done so.[24] However, in isolation, informational policies are likely to be slow and ineffective at increasing fruit and vegetable consumption.[39] For example, in the USA, 5 years after a 2007 update to fruit and vegetable consumption targets, only 6% of surveyed consumers were familiar with the new consumption targets and only an additional 30% were familiar with the previous targets established in 1991.[45]

Due to few policy interventions to date, it is difficult to know which policies could be most successful. However, lessons can be learned from policy interventions to reduce smoking, and current efforts to reduce fat and sugar consumption. These experiences would suggest that informational policies are more likely to be effective if supplemented by more forceful policy options along the Nuffield ladder that more actively and directly restructure the choice infrastructure within which both consumers and producers act, such as taxes and subsidies.

Increasing productivity of the fruit and vegetable sector could reduce the resource intensity of fruit and vegetable production, permitting more production at a lower cost to consumers and the environment. Reducing waste in fruit and vegetable value chains also can reduce the environmental footprint of their production and, if properly implemented and fully taking into account the benefits and costs,[33] could save consumers money. Many of these interventions could be in the shape of investments in research and development to develop new and improved processing, storage and distribution technologies but could also include changes to labelling regulations (e.g., use-by dates) and, more broadly, the promotion of new markets for by-products to encourage a more circular economy.

Author contributions

DM-D, JRB, TBS, MH, and KW conceived the paper. DM-D, TBS, SD, and NC were responsible for socioeconomic modelling. DM-D and JRB were responsible for figures and tables. DM-D and JRB wrote the paper, with comments and edits from all authors.

Data Sharing

Country-level results and interactive data visualisations used in this analysis are available at http://dx.doi.org/10.17632/d7m5h5zvw7.1.

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4

Modelling the global economic consequences of a major African swine fever outbreak in China

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Modelling the global economic consequences of a major African swine fever outbreak in China.

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ABSTRACT

African swine fever is a deadly porcine disease that has spread into East Asia where it is having a detrimental effect on pork production. However, the implications of African swine fever on the global pork market are poorly explored. Two linked global economic models are used to explore the consequences of different scales of the epidemic on pork prices and on the prices of other food types and animal feeds. The models project global pork prices increasing by 17–85% and unmet demand driving price increases of other meats. This price rise reduces the quantity of pork demanded but also spurs production in other parts of the world, and imports make up half the Chinese losses. Demand for, and prices of, food types such as beef and poultry rise, while prices for maize and soybean used in feed decline. There is a slight decline in average per capita calorie availability in China, indicating the importance of assuring the dietary needs of low-income populations. Outside China, projections for calorie availability are mixed, reflecting the direct and indirect effects of the African swine fever epidemic on food and feed markets.

No man is an island entire of itself; every man
is a piece of the continent, a part of the main;
if a clod be washed away by the sea, Europe
is the less, as well as if a promontory were, as
well as any manner of thy friends or of thine
own were; any man's death diminishes me,
because I am involved in mankind.
And therefore never send to know for whom
the bell tolls; it tolls for thee.

John Donne, *Meditation XVII*

4.1 Introduction

African swine fever (ASF) is a virulent disease of pigs that originated in Africa and has been reported in other continents from the 1950s.[1] It has recently spread into Eastern Asia and was recorded for the first time in China in August 2018. At the time of revising the paper (February 2020), the disease has spread to all mainland provinces and several million pigs have been culled in an effort to halt its spread.[2,3] Industry estimates suggest 150–200 million pigs (30% of the Chinese population) have been infected by mid-2019,[3] while some press reports indicate that once under-recording is considered the figure may be as high as 50–70%.[4,5]

ASF is a notifiable haemorrhagic disease caused by an *Iridovirus* (*Asfarviridae*).[6] Its natural hosts in Africa are wild members of the pig family where it is transmitted by soft ticks and does not cause clinical disease.[7–9] Different strains of the virus strike farmed and feral pigs and their European wild boar relatives, with the strain present in China being particularly virulent and causing nearly 100% mortality.[10] Disease control consists of culling infected herds and imposing strict quarantine procedures; there is no current vaccine or treatment.[11–13] The disease is spread by contaminated products and by the animals themselves. The presence of wild boar populations or free-roaming feral pigs, as found in many areas of China, and the common practice in China of feeding untreated swill to pigs are particular risk factors.[8] There is no direct biological risk to humans from ASF.

It is important to explore the potential consequences of a major epidemic in China and to consider potential ramifications as it spreads. The repercussions could potentially affect not only pork consumption and the incomes of pork producers, but also feed markets, the demand for pork alternatives or substitutes,[5,14] and the diets of consumers in areas directly and indirectly affected by the disease.

This study uses economic modelling of the global food system to examine some of the potential consequences of a major disruption of pig production in China. The modelling approach first considers the direct and a number of indirect consequences of the disruption of the sup-

ply of pork on the prices of pork and other food types. Second, the model is used to explore the sensitivity of the results to different assumptions about supply and demand responses. Five scenarios, where pig production in China remains constant (S^0) or is reduced by 20, 40, 60 or 80% (S^{20} and so on), are explored.

When we conceived this project, these scenarios spanned the possible range of epidemic severities. At the time of revising this paper (February 2020), it appears the last two scenarios best match the unfolding outbreak, but we present results from the full range of scenarios because these provide information about the effects of possible future less serious epidemics.

4.2 Methods

4.2.1 Model

We studied the effect of ASF in China on food system dynamics using two linked global models: IMPACT, developed by the International Food Policy Research Institute,[15,16] and a dynamic version of GLOBE.[17] These two models were used to assess the potential effects on the broader global economy and average incomes across regions and countries that are linked to China through international trade. The IMPACT model has been used to explore other supply shock scenarios (for example, the effects of a major disease of rice in Southeast Asia[18] and extreme weather events affecting particular regions[19] or the global food system[20]).

Briefly (see appendices 4.1 and 3.3 for a fuller explanation), IMPACT is a partial equilibrium economic model that represents the production and consumption of 62 agricultural commodities in 158 political units (which are composed of one or more sub-regions where political units encompass several water basins). Consumer diets are determined by income and food prices summarised by functions (with constant price elasticities) describing how they affect demand; while producer behaviour is determined analogously by commodity prices and input costs. Population and income are treated as exogenous, with crop yield growth rates having both exogenous and endogenous components. IMPACT is linked to crop and hydrological models (that can themselves be driven by global climate models) to determine changing yield patterns. Different countries are linked by international trade and IMPACT simulates the operation of the global economy, finding world prices for all included commodities that clear international markets. IMPACT does not directly project future diets, but dietary patterns and calorie intake can be estimated under different scenarios and compared with WHO (World Health Organization) guidelines for a healthy diet (assumed to be ~2500 kcal for men and ~2000 kcal for women) as was done in Springmann et al.[21]

The IMPACT model includes only agricultural goods and markets and does not incorporate links between agriculture and the rest of the economy. To capture these links, we use a separate global model (GLOBE) that operates at the level of national economies, incorporating production and demand for all commodities, and trade between countries. This model sim-

ulates the operation of commodity and factor markets in all countries and finds equilibrium commodity prices and wages of factors of production that clear both domestic and world markets together. This dynamic computable general equilibrium (CGE) model is calibrated with a global dataset maintained by the Global Trade Analysis Project at Purdue University.[22]

In our analysis, the IMPACT model is used to determine the effects of a shock on the agricultural sectors. The results are then 'soft linked' to the GLOBE CGE model,[23] which is used to analyse the effects of the changes in agriculture on the rest of the economy, tracing the direct and indirect links between the agricultural and non-agricultural sectors. The CGE model captures links between commodity markets and factor markets, showing how a shock in agriculture affects incomes, supply, demand, and prices across the economy.

4.2.2 Scenarios

Our main analysis is a comparison of a reference scenario with a series of alternative scenarios in which we assume that the number of pigs in China is reduced by 20, 40, 60, and 80% in a single year. In the face of great uncertainty (at the time the project was conceived) about the possible severity of an epidemic, we choose these five alternatives to span a full range of possibilities. The reduction includes pigs killed by the disease and those slaughtered (but not consumed) to prevent the spread of the epidemic. Pork prices in China cycle with a period of approximately four years,[24] which seems to be associated with inaccurate expectations about future profits. We think it likely that the appearance of the epidemic reset profit expectations and we make no attempt to model the cycle. There has been a reduction in China's pig herd (although less, only 2%, in pigs slaughtered) since about 2013 due to tightening environmental regulations, but this has been relatively gradual and very different from the dramatic declines beginning in 2018.

The assumed income elasticity is 0.18, which is broadly consistent with income elasticities estimated by the US Department of Agriculture[25] (0.24 for urban and 0.13 for rural households). IMPACT's default own-price elasticity of demand for pork is −0.23. This is within the range of price elasticities reviewed by Chen et al.,[26] although on the inelastic side as IMPACT elasticities are calibrated for long-run as opposed to short-run behaviour. This elasticity represents an average Chinese consumer and is a simplification of the diversity of demand outcomes (preferences, incomes, available food budgets, and prices) within the country. This simplification allows us to estimate average changes but will not allow us to capture some of the potential distributional and compositional effects that might occur from production and price shocks that would impact different consumers to varying extents. We explore the sensitivity of the results to the value of the own-price elasticity for pork by halving or doubling the assumed value, which we expect to include the likely range of uncertainty about that parameter.

4.3 Results

4.3.1 Effects on pork prices, demand, production and trade

China currently (2018) produces about 55 million metric tons (Mt) of pork per year, from more than 700 million slaughtered pigs.[27] Our simulations assume a reduction of pigs that leads to a decline in pork production in China of between 10 and 40 Mt in the four scenarios representing increasingly severe ASF epidemics (figure 4.1a). This represents cuts of 9–34% in global production (120 Mt in 2018) compared to a reference scenario without an ASF epidemic (figure 4.1a and appendix 4.1 Table 1). This decline in production would lead to increases in world pork prices of 17–85% (figure 4.1b). For $\boldsymbol{S}^{\mathbf{60}}$ and $\boldsymbol{S}^{\mathbf{80}}$, pork prices rise above beef prices, a major inversion of past price trends for the two commodities last observed in 1996,[28] when bovine spongiform encephalopathy was linked to Creutzfeldt–Jakob disease and led to a sharp decline in beef demand.[29,30]

Higher pork prices drive down pork demand in all regions, with average global per capita demand declining by 0.7–2.4 kg yr^{-1} (4–16%) (figure 4.1c and appendix 4.1 Table 2). In China, the percentage reduction is slightly smaller than the global average (3–13%) although the actual drop in demand (1.4–5.3 kg yr^{-1}) is above the global average. Much of the global decline (60%) happens outside China with the greatest effects (for $\boldsymbol{S}^{\mathbf{80}}$) observed in Europe (7.9 kg yr^{-1}), with notable drops in North America (4.5 kg yr^{-1}), Latin America (2.4 kg yr^{-1}) and the rest of East Asia and Pacific (2.2 kg yr^{-1}).

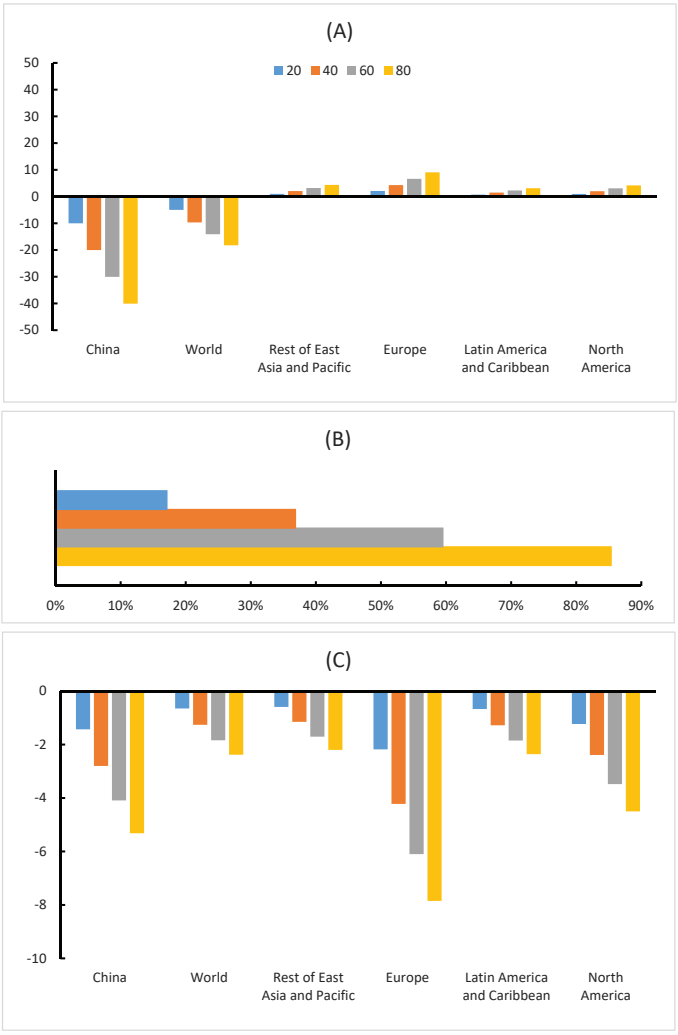

Figure 4.1: Summary of changes from the reference scenario in pork markets in China and selected regions.

Notes: a–c, Changes in pork production in China and selected regions (**a**), world pork prices (**b**) and average per capita food demand in China and selected regions (**c**).

Higher pork prices spur more production (5–22 Mt) in regions outside China. This response makes up for about half of the losses in China so that overall global production falls by only 5–18 Mt (4–16%). Europe, the rest of East Asia and Pacific, North America and Latin America are the regions that contribute the most in this global response with increases in pork production of 6.6, 4.4, 4.2 and 3.1 Mt, respectively.

The reference scenario assumes own-price elasticities based on historical trends and which vary from country to country. To explore uncertainty in how sensitive consumers would be to changes in pork prices, we implemented all scenarios under elasticities half and double the reference assumption. Global pork production and pork prices are negatively correlated with this elasticity (appendix 4.1 Figs. 1 and 2), effects that would be stronger if the changes were applied globally, not just in China.

China is the world's largest pork importer and has seen steady growth in imports over the past decade.[31] Currently, China imports account for about 5% of domestic demand,[27] as China has tended to encourage feed imports to achieve greater self-sufficiency of meat production.[31,32] The changes described in figure 4.1 suggest that trade will play an important buffering role in reducing the shock to Chinese consumers, albeit at the expense of pork consumers elsewhere. Pork imports into China increase by 8–32 Mt. The regions highlighted in figure 4.1 that see the largest increases in production as well as declines in per capita demand are the primary sources of China's additional imports, as pork in these markets gets reallocated to respond to the shock in China.

4.3.2 Knock-on effects on other commodities

Higher pork prices will not only impact consumers and producers of pork. They will also have secondary effects as consumers substitute pork with relatively cheaper alternative food types (for example, other meats and plant-based alternatives). Changes in food prices also spur the reallocation of resources in the agricultural sector in response to changing demand patterns. Key inputs to the pork sector in China are reallocated to other uses, whereas the pork sector in other regions takes a larger share of feed inputs as they expand to respond to increased demand for imports into China. This could impact the historical preference in China for grain imports over meat imports,[31,32] at least in the short run until livestock value chains adjust and recover.

As consumers shift to pork substitutes, global production increases to meet this demand (figure 4.2a). However, their prices are projected to rise, which reflects limitations in animal value chains to quickly increase production. Note that these price changes are considerably smaller than those observed for pork (figure 4.1), with beef and poultry seeing price rises of 1.5–6.0% and 1.6–6.7%, respectively; global production increases by up to 0.1 Mt for beef and 0.4 Mt for poultry (mostly in North and South America) in the case of the most severe epidemic. The ASF epidemic in China causes major disruption to livestock value chains in China and abroad, forcing feed markets to adjust. Figure 4.2b,c summarises these spillover effects for key pork substitutes and feed inputs to the livestock sector in China and globally. Changes in feed inputs may negatively or positively affect animal productivity, but we do not model these indirect effects here.

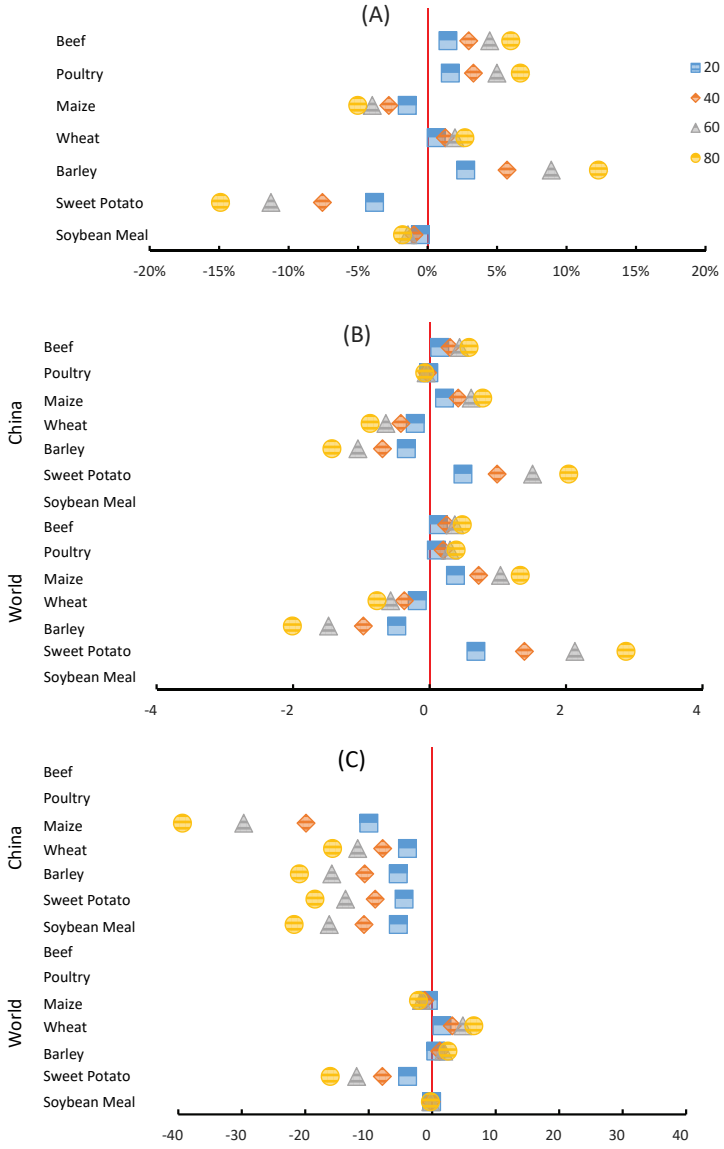

Figure 4.2: Summary of changes from the reference scenario in selected commodity markets in China and globally.

Notes: a–c, Changes in world prices (% change) for selected commodities (**a**), household food demand (mt) (**b**), and animal feed demand (mt) (**c**).

Larger disruptions are seen in feed markets than are observed in global food demand (figure 4.2a) as lower pork production in China reduces the demand for feed crops used in the pig meat industry. Globally, this reduction is partially offset by increased pork production in other regions and increased beef and poultry production both in China and abroad. Nevertheless, the price declines observed for key feed inputs (maize, soybean meal and sweet

potatoes) are similar in size to the increases for meat substitutes. In the worst scenario (S^{80}), maize and soybean meal prices decline by 5% and 2%, respectively. Sweet potatoes, another important feed input into the pork sector,[33] see the largest price declines of nearly 15% in S^{80}, due to limited domestic and global capacity to use additional sweet potatoes. These price rises may be ameliorated if other uses for sweet potato such as bioethanol production emerge in China. The increase in production of livestock products outside China leads to a substantial reallocation of feed globally. Demand for maize for feed in China declines by as much as 47 Mt compared to the reference scenario. Globally for the same scenario, maize feed demand declines by only 11 Mt, with the majority of maize previously destined for the Chinese livestock sector being reallocated to livestock production in other countries. Soybean meal sees a similar trend, whereas the deficit in sweet potato demand is not as readily absorbed by increased livestock production in other regions, explaining the much larger price declines. Price rises for other globally important feeds (wheat and barley) are also observed. These price rises are driven by increased demand for both throughout the world, but particularly in Europe where wheat and barley are disproportionately used in the livestock sector.

The changes in demand for different feedstocks are reflected in shifts in agricultural trade patterns. The most dramatic is a marked decrease in exports of maize from North America. This maize is redirected to support livestock sectors in North America, although there is also an increase in maize exports to Africa (and of sweet potato from China), which affects food security and welfare as discussed below.

4.3.3 Effects on food and nutrition security

We estimate the sum of the spillover effects on different components of people's diets and their effects on calorie consumption. Higher prices for meat and those cereals that serve as animal feeds (for example, wheat) lead to declines in calorie availability in most regions (figure 4.3a). The projected changes in food prices increase food expenditure in China (as a share of average income in the reference scenario) by as much as 9% in the most severe scenario. This increase leads to the average per capita calorie availability in China declining by more than 50 kcal per day or 1.6% of the reference scenario. Aside from China, we see many countries in East and Southeast Asia as well as Europe with declines in calorie availability of more than 1%. In high-income countries where baseline calorie availability is already high, such declines will tend not to have negative health impacts. However, in middle-income countries in Southern and Eastern Europe (for example, Poland and Romania), rising food prices may be of greater concern (figure 4.3b). In East and Southeast Asia, a similar pattern can be seen with higher-income East Asian countries able to absorb the reduction in calories, while the effects in lower-income countries such as Vietnam and the Philippines are of greater concern. The largest absolute change in hunger is found in India (more than 2 million additional people at risk of hunger) and is driven primarily by the secondary price impacts, particularly the increase in the price of wheat, which is an important food staple.

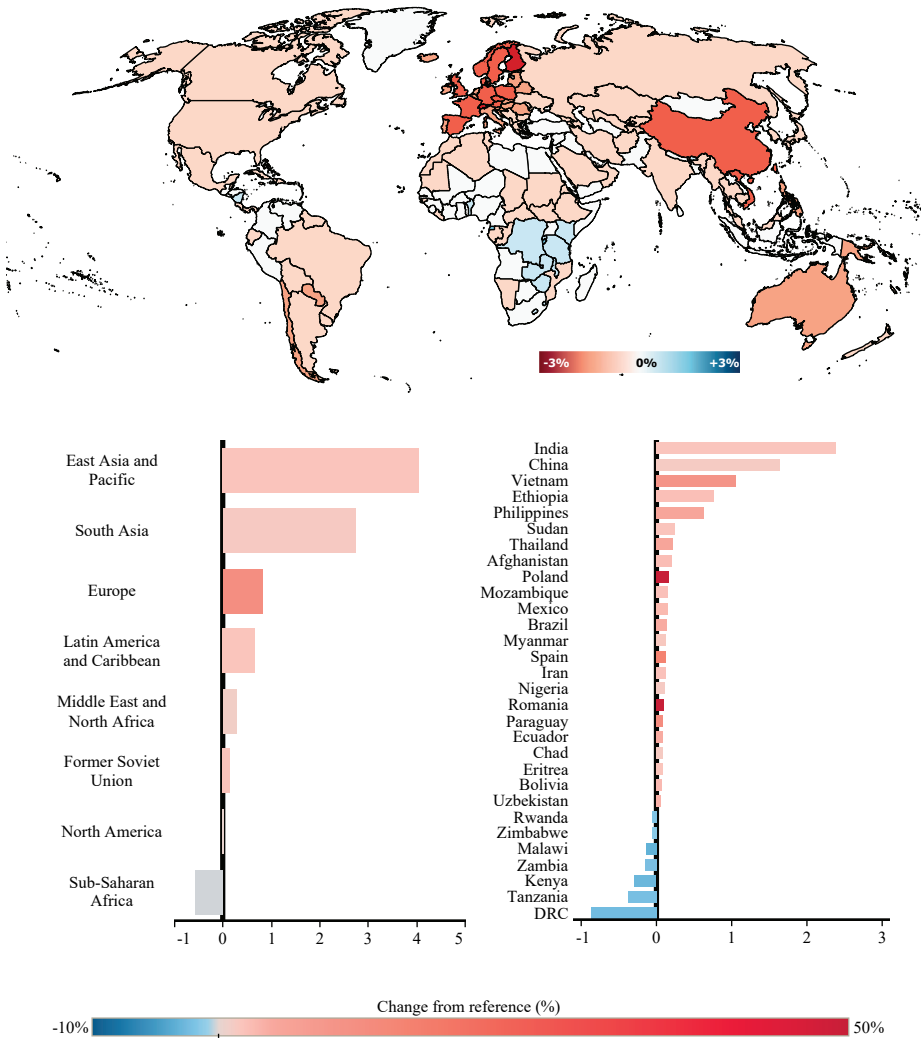

Figure 4.3: Effect of the ASF epidemic on calorie availability and risk of hunger.

Notes: a, Percentage change from the reference scenario in average calorie availability in S^{80}. **b**, Changes in the population at risk of hunger in absolute (bar length) and relative (colour scale) terms by region (left) and selected countries (right) in S^{80} compared to the reference. DRC, Democratic Republic of the Congo.

Several countries, particularly in Eastern and Southern Africa and Central America, see an increase in calorie availability. In these countries, maize is a dietary staple and they benefit from the lower prices caused by reduced demand for maize as an animal feed. However, this picture is complicated by the preference of consumers in these countries for white rather than yellow maize, which while not uniform across the whole region can be observed by price premiums for white maize.[34,35] Internationally and domestically, white and yellow maize prices tend to track each other; nevertheless, there is evidence that local and global markets are not well integrated, and that transmission of world prices locally is muted and often with

a time lag.[36,37] Eastern and Southern Africa also consume a considerable amount of sweet potatoes and obtain a further benefit from the large price declines in this crop. As for maize price transmissions, there is reason to be sceptical of these gains, given shallow international sweet potato markets. Nevertheless, both China and Africa are net exporters to Europe,[27] and increased availability of sweet potatoes for export could displace some African exports, increasing domestic supply in the region. Overall, the number of people at risk of hunger in sub-Saharan Africa may decline by more than half a million people in the most severe ASF scenario. However, while countries such as the Democratic Republic of the Congo and Tanzania are beneficiaries, those such as Mozambique and Ethiopia would see increases in the population at risk of hunger (figure 4.3b). These projections of varying effects on different countries should be treated as indicative—further analysis considering the national dietary and cultural context, as well as integration between local, regional and international markets, is warranted.

The ASF epidemic may also affect dietary diversity and nutrient intake, particularly in China, with negative health implications (table 4.1). Further details are given in appendix 4.1 but, in particular, the model projects possible reductions in the B vitamins and zinc. Among macronutrients, the projections show a relatively large reduction in total and saturated fat consumption, which may in some people affect their intake of critical fat-soluble vitamins.

Table 4.1: Changes in selected macronutrients and micronutrients in China

	Baseline		**% change under ASF scenarios**			
Nutrient	**AR[a]**	**RNS[b]**	S^{20}	S^{40}	S^{60}	S^{80}
B vitamins						
Folate (B9, μg[c])	1.1	403	0	−0.1	−0.1	−0.1
Niacin (B3, mg[d])	1.8	27	−0.4	−0.8	−1.3	−1.6
Riboflavin (B2, mg)	1.4	2	−0.3	−0.7	−1.0	−1.3
Thiamin (B1, mg)	1.8	2	−0.6	−1.2	−1.8	−2.3
Vitamin B12 (μg)	0.8	2	−0.8	−1.5	−2.3	−2.9
Vitamin B6 (mg)	2.6	3	−0.3	−0.6	−0.8	−1.1
Minerals						
Iron (mg)	1.0	21	−0.1	−0.2	−0.4	−0.5
Phosphorus (mg)	2.6	1925	−0.2	−0.5	−0.7	−0.9
Potassium (g)	1.0	5	−0.1	−0.2	−0.4	−0.5
Zinc (mg)	1.2	17	−0.4	−0.8	−1.1	−1.5
Fat[h]						
Total fat (g)	—	91	−0.7	−1.3	−1.9	−2.5
Saturated fat (g)	—	27	−0.8	−1.6	−2.4	−3.1

Table 4.1: Changes in selected macronutrients and micronutrients in China (*continued*)

	Baseline		% change under ASF scenarios			
Nutrient	**AR**	**RNS**	S^{20}	S^{40}	S^{60}	S^{80}
Fat-soluble vitamins						
Vitamin A (µg[e])	1.9	1330	0.2	0.3	0.5	0.7
Vitamin D (µg[f])	0.5	1	0.1	0.2	0.2	0.3
Vitamin E (mg[g])	0.7	11	0	−0.1	−0.1	−0.1
Vitamin K (µg)	4.5	299	0	−0.1	−0.1	−0.1

Notes: [a]Adequacy ratios in the absence of ASF; the ratio of average daily availability of a nutrient to the requirement for a representative consumer. Data from https://impactnutrients.ifpri.org/nutrientModeling/.

[b]Reference nutrient supply: average nutrient supply in the reference scenario (units) per person per day.

[c]Micrograms of dietary folate equivalents.

[d]Milligrams of niacin equivalents.

[e]Micrograms of retinol activity equivalents.

[f]Does not account for vitamin synthesized in the presence of sunlight.

[g]Milligrams of α-tocopherol.

[h]There are no recommended daily allowances for fat, which prevents the calculation of an adequacy ratio. Recommendations for fat intake are that total fat should contribute 25–35% of total energy intake, and saturated fat should contribute less than 10% of total energy intake. In the reference scenario China's share of calories from total and saturated fat was 24% and 7% respectively.

Demand for food is relatively inelastic, so the production shock in Chinese pig production tends to increase global food expenditures. In the absence of any countervailing intervention by governments, consumers will be relatively worse off, especially in countries and regions where pork is a major part of the diet. As IMPACT is a partial equilibrium model, it cannot be used to explore the effect of changes in prices and production on overall household income. To begin to investigate the effect on household incomes and changes in welfare, we use the output from IMPACT as input to the GLOBE computable general equilibrium model. We found that household welfare in China declined by between 0.12 and 0.78% for S^{20} to S^{80}, with household income declining by 0.3 to 1.8%, respectively (see also appendix 4.1 Table 3). For the worst-case ASF scenario, this is a socio-economically important and perhaps politically relevant decline.

Outside China, we find that only a few regions benefit from increased commodity prices (figure 4.4). These are major meat-exporting regions, with the largest gains 0.01–0.09% observed in high-income countries in Oceania (Australia and New Zealand). Most other regions see small declines in welfare. In all cases, these shifts are many orders of magnitude smaller than those observed in China.

		S20	S40	S60	S80
East Asia and Pacific	China	-0.12	-0.28	-0.49	-0.78
	Other East Asia	0.00	0.00	-0.01	-0.01
	High Income Asia	0.00	-0.01	-0.01	-0.02
	High Income Oceania	0.01	0.03	0.06	0.09
South Asia	India	0.00	0.00	0.00	0.00
	Other South Asia	0.00	0.00	0.00	0.00
Latin America and Caribbean	Central America	0.00	0.00	0.00	-0.01
	South America	0.00	0.00	0.00	0.00
Sub-Saharan Africa	West Africa	0.00	-0.01	-0.01	-0.02
	East Africa	0.00	-0.01	-0.01	-0.02
	Southern Africa	0.00	0.00	0.00	0.01
Middle East and North Africa		0.00	-0.01	-0.01	-0.02
Europe		0.00	0.00	0.00	0.00
North America		0.00	0.00	0.00	0.01
Former Soviet Union		0.00	-0.01	-0.01	-0.02

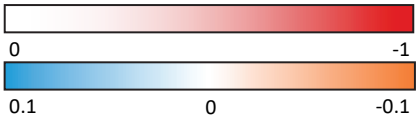

Figure 4.4: Percentage change in average household welfare by region and scenario.

Notes: The heat chart uses two colour schemes reflecting the fact that the impacts in China are ten times higher than in other regions. Changes in China are in red and range from 0 (white) to −1% (red). A different scale is used for other regions where blue reflects welfare improvements (up to 0.1%) and orange reflects welfare reductions (up to −0.1%).

4.4 Discussion

Approximately half of global pig production occurs in China. The presence of a disease as deadly as ASF in East Asia will have major ramifications for the global food system and food security.[6] Our projections of the effects of a major production shock in the Chinese pig industry using a global partial equilibrium economic model of the food sector provide an indication of the capacity of the national and global food system to absorb the perturbation without large effects on prices and consumption. This resilience comes about through international trade and consumers switching to non-pork foods. The effects of an ASF outbreak in China are not limited to China, but are experienced in other countries and affect other food types. While we modelled a shock and a response that occurred within a year, delays in restocking and an epidemic that lasts for a greater period of time are likely to lead to more severe effects.

Recent data on pork prices in China show increases of the order of 50% during 2019 (figure 4.5), which may have contributed to inflation in China recently exceeding government targets. These are consistent with our projections, although we think it is too early to do a formal comparison and validation of the model. There is still considerable uncertainty about the extent of the epidemic, and some of the economic data are still preliminary.

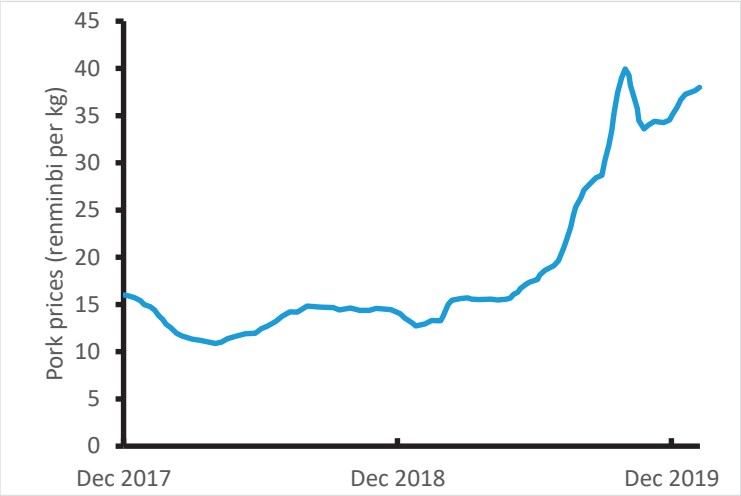

Figure 4.5: Changes in Chinese pork prices from 31 December 2017 to 6 February 2020.
Notes: The data are from the Professional Pig Community (https://www.pig333.com/).

It is important to explore whether this conclusion is a consequence of model assumptions that may not reflect real-world food systems accurately. Models such as IMPACT assume that markets regularly equilibrate. If there are frictions or disruptions, so that markets clear more slowly or trading flows adjust less rapidly, then the initial effects of the outbreak may be larger and more spatially contained. IMPACT also tends to overestimate the degree to which domestic markets in low-income countries are tied to world markets and hence some of the effects of the ASF outbreaks on sub-Saharan countries may be less than projected.[36–38] In addition, IMPACT uses data from the Food and Agriculture Organization and these are based on national statistics, which have been found in some studies to be inconsistent, particularly with respect to pork.[39]

Several aspects of real-world food systems may influence the effects of an ASF outbreak. First, the release of frozen meat in 2019 is thought to have tempered pork price rises in China,[5] and this approach could be taken again. Such policy decisions would probably be captured by a simple reduction in the size of the production shock in proportion to the amount of stocks released. Pork production and consumption vary across the country.[40] Per capita consumption is lowest in the north and east and highest in the south and west: the region with least consumption is the western province of Xinjiang (3.8 kg yr^{-1}), with its large Muslim population, and highest in the southern provinces of Sichuan and Chongqing (>30 kg yr^{-1}). Since the outbreak began, the Chinese authorities have introduced and sometimes relaxed different regulations about inter-province pig trade that will have affected price transmission and local prices, but these are not modelled here.

Second, it is possible that the presence of ASF affects not only supply but also demand. In previous outbreaks of livestock diseases, demand of affected commodities was reduced in part due to a loss in trust in the quality and safety of the commodities.[41,42] There is evidence of this already occurring in China.[5] This impact can linger beyond the initial outbreak and can take some time (a decade or more) before consumers fully return to previous levels.

Third, governments often respond to production shocks by imposing tariffs or export restrictions. These policies are typically motivated by a wish to protect local producers or consumers (or a political imperative to be seen to be doing something), with their effectiveness depending on trading partners. Import restrictions on live animals or animal products are likely to be introduced as quarantine measures. In general, trade restrictions will tend to reduce the capacity of the global food system to buffer production shocks, although genuine quarantine measures can help contain the disease.

Finally, the current ASF outbreak is occurring at a time of tension in global trading relationships, especially between China and a major source of pork imports, the United States. Tariffs on US pork imports into China have recently increased from 12% to 62%, although this has not disincentivised some major purchases.[43] In July 2019, net tariffs were at 81%, although the politics are fluid, which adds an additional layer of geopolitical uncertainty to the way the global food system will be affected by the disease outbreak.

The outbreak of the coronavirus (COVID-19) that is developing as we revise the paper (February 2020), and which affects humans (and conceivably pigs), adds another level of uncertainty that is as yet impossible to assess, although possibly it may have reversed a small decline in pork prices at the end of 2019 (figure 4.5).

Since the beginning of the project, the outbreak has expanded rapidly to other countries. ASF has now been recorded in 2019 from Mongolia (January), Vietnam (February), Cambodia (April), North Korea (May), Laos (June), Philippines (July), Myanmar (August), Timor-Leste (September) and South Korea (November) and may be in Indonesia (November). Further modelling of a broader epidemic in Asia would be informative, as well as in Europe, which has suffered a number of smaller-scale outbreaks. In Europe, the pig industry is more intensive and more vertically integrated,[44] in part due to challenges from other diseases, and containment should be easier compared to Asia with its large smallholder sector.[45] Nevertheless, the disease is causing major concern in Europe, with Denmark building a fence along its southern border to prevent wild boar entering from Germany. A serious ASF outbreak in Europe could undermine the Common Agricultural Policy and "dramatically shake European identity and cohesion".[46]

An ASF outbreak will have both macroeconomic and welfare economic consequences. Agriculture currently makes up 7–8% of Chinese gross domestic product (GDP)[47] with the pork sector contributing 10–15% of gross agricultural value added.[27] The pork sector is probably worth more than US$100 billion and the worst outbreaks we simulated would reduce Chinese GDP by approximately 1%. For context, this reduction is a little less than the effect of the 2008 Sichuan earthquake, but of the order of 20 times greater than recent avian flu outbreaks or the SARS (severe acute respiratory syndrome) outbreak centred on southern China in 2002–2003. In the same regions, the early 2000s avian flu outbreak depressed Vietnam GDP by 0.3–1.5% (US$0.1–0.6 billion).[48] Further analysis of the costs of the epidemic, in particular of mass culling, and of alternative mitigation strategies would be welcome.

Although analysis with the GLOBE model suggests that average household incomes will decline by less than 2% in the worst case, predominantly smallholder farmers in the lower deciles of the income distribution will be affected by ASF.[49] Some farmers will be insured against epidemic risk, but the majority will have no or inadequate insurance. Thus, it is likely that the government would need to provide income support. Furthermore, the impacts on the mental health of farmers and their families are likely to be substantial.

China will probably import more pork and less pig feed with consequences for trading partners. Pork producers in exporting countries will benefit, although consumers will experience higher prices in domestic markets. Feed producers will look for new markets, resulting in increased exports of commodities such as maize and sweet potato to emerging economies in sub-Saharan Africa and elsewhere. In this case, there is a risk that local agriculture may be undermined, especially if exports are supported by direct and indirect subsidies and other market distortions.

In the longer term, the current ASF outbreak will spur investment in research and innovation with the possibility of vaccine development.[13] A less optimistic possibility is that the disease becomes endemic with periodic resurgences buffeting the food system. This possibility would reduce the attractiveness of pig production for investment and tend to increase food prices. Consumers could respond by switching to meat substitutes, chicken or ruminant meats. Given the different consequences for human health and the environment of the production and consumption of these different food types, there are possibilities for both positive and negative indirect effects of continuing ASF outbreaks.

Author contributions

The project was conceived by HCJG, SR and DMD; all authors contributed to its execution and write up with DMD leading on the IMPACT analysis, DW on the GLOBE analyses, JRB on the nutrition aspects and HCJG and DMD on writing the paper.

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Data sharing

Full documentation for IMPACT and GLOBE is available in Appendix 3.3 and 4.4 respectively. Model output from this study can be found in Appendix 4.2 and 4.3 or the Mendeley Data repository at https://doi.org/10.17632/zgrngg5hp5. Source data are provided with the published paper.

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5

Agricultural investments and hunger in Africa modeling potential contributions to SDG2-zero hunger

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ABSTRACT

We use IFPRI's IMPACT framework of linked biophysical and structural economic models to examine developments in global agricultural production systems, climate change, and food security. Building on related work on how increased investment in agricultural research, resource management, and infrastructure can address the challenges of meeting future food demand, we explore the costs and implications of these investments for reducing hunger in Africa by 2030. This analysis is coupled with a new investment estimation model, based on the perpetual inventory methodology (PIM), which allows for a better assessment of the costs of achieving projected agricultural improvements. We find that climate change will continue to slow projected reductions in hunger in the coming decades—increasing the number of people at risk of hunger in 2030 by 16 million in Africa compared to a scenario without climate change. Investments to increase agricultural productivity can offset the adverse impacts of climate change and help reduce the share of people at risk of hunger in 2030 to five percent or less in Northern, Western, and Southern Africa, but the share is projected to remain at ten percent or more in Eastern and Central Africa. Investments in Africa to achieve these results are estimated to cost about 15 billion USD per year between 2015 and 2030, as part of a larger package of investments costing around 52 billion USD in developing countries.

Is it lack of imagination that makes us come
to imagined places, not just stay at home?
Or could Pascal have been not entirely right
about just sitting quietly in one's room?
Continent, city, country, society:
the choice is never wide and never free.
And here, or there … No. Should we have stayed at home,
wherever that may be?

Elizabeth Bishop, *Questions of Travel*

5.1 Introduction

The Second Sustainable Development Goal (SDG2) builds off the progress achieved under previous hunger eradication efforts (e.g. Millennium Development Goals[1]) and presents the ambitious target of ending hunger globally by 2030.[2] Achieving this goal will require a multi-pronged effort that recognizes that the "last mile" to eradicate hunger will be the most difficult.[3] The next push will have to confront more binding environmental and resource constraints[4,5] even as food demand continues to increase due to a growing population[6] and their growing demand for richer diets.[5,7,8] Climate change further complicates eradicating hunger by reducing agricultural yields, driving up food prices, reducing food availability, and increasing negative health outcomes.[9–11]

Since the 1960s, increasing agricultural productivity has been critical for reducing poverty and hunger globally.[12–14] However, Africa South of the Sahara (SSA) has benefited less than other regions from past investments and continues to have low agricultural productivity by global standards.[15] Closing agricultural productivity gaps alone will not be sufficient to ensure food supply can keep pace with growing demand.[16] Therefore, achieving SDG2 will require specific attention be given to agriculture in Africa and will have to take into account the particularities of the region and encompass a range of important regional crops beyond just the key staple cereals that fueled the Green Revolution.[14]

In this paper we present scenarios of agricultural productivity enhancements based on current and envisioned CGIAR efforts focused on the developing world. We then estimate the costs of achieving these projected improvements in the agriculture sector applying methodologies developed in the field of R&D investment and productivity gains.[17–21] We then estimate the impacts of achieving these improvements on agricultural productivity, average incomes, commodity prices, food demand, and hunger using an augmented version of IFPRI's IMPACT modeling system,[22] which was extended to include GLOBE,[23] a global general equilibrium model, to capture the macroeconomic impacts of increased agricultural productivity.[24] Finally, we compare these results to several recent reports on reducing or eradicating

hunger to highlight potential points of uncertainty with respect to the contributions of public investments in agriculture towards SDG2.

5.2 Methods

5.2.1 Current levels of agricultural investment

We begin by providing rough approximations of current levels of investment in agriculture to provide context on agricultural investment scenarios explained in greater detail in following sections. The private sector is by far the largest investor in agriculture[25,26] along with being the largest investor in measures to address climate change.[27]

A dataset newly released by the United Nation's Food and Agriculture Organization (FAO) shows that, in recent years, farmers in developing countries have invested approximately 153 billion USD annually on agricultural capital—similar to the $156 billion estimate of investments made by farmers in developed countries (table 5.1).[I] Further details on private investments in Appendix 5.1. Government investments in agriculture have been smaller than private investments globally, with this difference being more pronounced in developed regions where government investments are about a third the level of private investments, compared to developing regions where it is about half. Public spending on agricultural research and development (R&D) (not shown in table 5.1) is also an important component of government spending. Beintema and colleagues[28] show that in 2008, it accounted for almost $32 billion globally (about 25 percent of annual government investments in 2010–2012), with Africa and West Asia contributing about 11 percent of global investments.

As shown in table 5.1, globally, development flows to agriculture (ODA to agriculture) are much smaller than private and governmental investments in agriculture, while dedicated funds for climate change adaptation and mitigation in agriculture are even smaller. However, ODA flows to agriculture are significant across Africa. In SSA there is a reliance of public budgets on ODA support with over three billion annually from ODA compared to less than two billion from government investments.

Although ODA for adaptation to and mitigation of climate change in the agricultural sector is quite small compared to other sources of finance, development assistance is the most easily tracked of any source of climate finance. Consequently, much discourse and analysis focuses on international public finance of climate change. Private sources of finance for climate change, whether domestic or international, remain largely hidden, which greatly limits our understanding of the overall financing of climate change adaptation and mitigation efforts.[29]

I While these investment numbers are estimates of total amounts subject to different methods of imperfect data collection, they do provide a fair indication of equivalence and relative magnitude.

Work by Buchner and colleagues[27] shows that if we consider financing (public, private, domestic, and international) to adapt to and mitigate climate change across sectors, we see that the private sector is, again, the largest source of funds. In 2014, about $391 billion was spent on the financing of adaptation to and mitigation of climate change; most was spent in the country of origin, with the bulk of investments made in East Asia and the Pacific, Western Europe, and the Americas. About $12 billion was invested in countries in SSA. Most public and private finance has funded mitigation efforts and the generation of renewable energy. The amount of private finance for climate change adaptation and mitigation allocated toward agriculture, forestry, and land use is unknown, but about six billion in ODA (of $148 billion of public finance) was allocated to these sectors, with about an even split between mitigation and adaptation. Public finance for climate adaptation and mitigation encompasses national, multilateral, and bilateral actors, with contributions from international organizations representing only a small fraction of the assistance.[27]

Table 5.1: Average annual agricultural investments/spending in millions of constant 2005 US dollars, by source

Region	Private investment[1] (2010-12)	Government investment[2] (2010-12)	Development flows[3] (2013-14)	ODA for climate adapt./mitig.[4] (2013-14)	Multilateral climate funds[5]
Africa	10 027	3104	3163	1443	97
Northern Africa	1941	1140	59	15	0
South of Sahara	8086	1964	3104	1428	97
Eastern Africa	2306	591	1267	652	42
Central Africa	388	138	29	7	3
Southern Africa	1553	479	45	23	3
Western Africa	3838	756	1114	369	47
Other developing	142 635	71 286	5057	2034	227
Developing countries	152 662	74 390	8219	3477	324
Developed countries	155 969	54 082	—	—	—
World	**308 631**	**128 472**	**8219**	**3477**	**324**

Notes: [1] Private investment is gross fixed capital formation.[30]

[2] Government investment in agriculture is approximated as one half of government spending on agriculture, from the SPEED database.[31]

[3] Development flows to agriculture.[30]

[4] ODA for climate adaptation and mitigation through agriculture and forestry.[32]

[5] Agricultural spending by climate funds.[33]

Source: author-compiled following a method similar to that used by the FAO.[25]

5.2.2 Modeling framework

To explore the role of increased agricultural productivity for food security in Africa, we use IFPRI's IMPACT system of models.[34] IMPACT has been used extensively in projecting future agricultural production and demand and changes to food security globally and regionally.[35–39] It has been used to explore alternative agricultural productivity futures,[40,41] including the potential impacts of climate change on agriculture.[10,36,42] IMPACT is linked to spatially explicit crop and hydrology models to integrate natural resource constraints on agricultural production.[22,43] Additionally, IMPACT represents the global agriculture sector with a high level of geographic disaggregation and broad commodity coverage as compared to other similar models,[44,45] which makes it a good tool to analyze the potential of investing in African agriculture across a range of commodities.

The IMPACT system of models has, at its core, a highly disaggregated, global partial equilibrium multi-market model that simulates 62 agricultural commodity markets in 158 countries and regions. This multi-market model is directly linked to grid-based biophysical models (crop and hydrology models) that provide inputs on the impacts of changes in temperature and water availability at 0.5-degree resolution that are aggregated to summarize effects on agricultural production in 320 sub-national geographic units (Food Production Units or FPUs), which are the intersection of national boundaries with water basins. The DSSAT crop-modeling suite[46,47] provides estimated yields of crops at the grid-cell under varying management and climate scenarios. Crop land and crop allocation are determined at the FPU level using stylized land markets that simulate cropping choices based on changes to marginal revenue of crop production, such that total cropland and specific crop areas respond over time to changing crop productivity and prices. Water availability is modeled with the IMPACT suite of water models at the grid level and aggregated to FPUs, with water demand determined through crop/livestock life cycles, cropping patterns, and competition with non-agricultural sectors at FPU levels. IMPACT solves for equilibrium prices that clear world commodity markets by equating global supply and demand annually out to 2050. Food demand is simulated for all countries and regions based on changes in average income, population, and prices. Food demand then serves as an input to estimations of changes in food security, such as the population at risk of hunger[48] and malnourished children.[49] For more details on IMPACT see Appendix 5.1, which summarizes Robinson et al. (2015)[34].

As a partial-equilibrium model, IMPACT does not endogenously model the feedbacks between the agriculture sector and the broader economy. Investments in agriculture, particularly in developing countries where agriculture contributes a large share of total GDP, would be expected to have significant economic spillovers.[12,50] To better assess the potential of investments in agriculture to spur economic growth, the IMPACT framework was augmented to include an iterative link to GLOBE,[51] a global computable general equilibrium model.

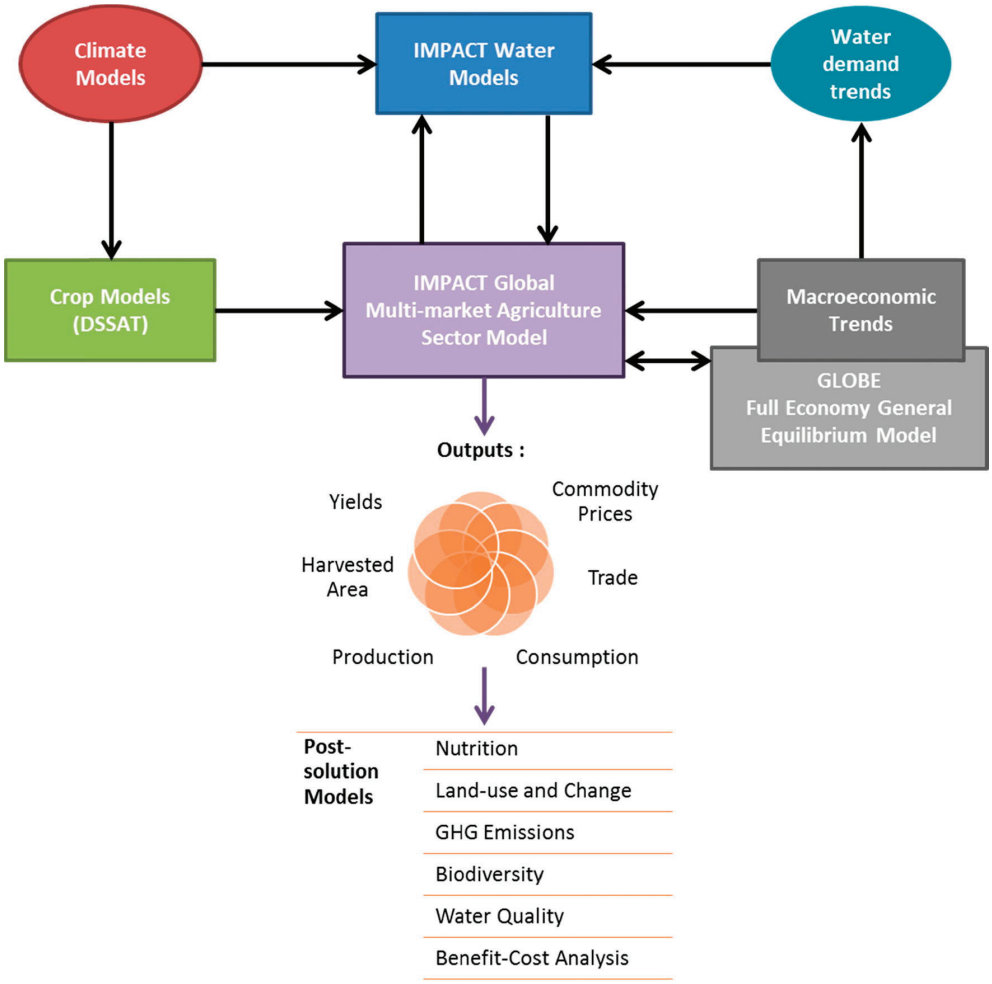

Figure 5.1: The extended IMPACT modeling framework.[24]

The extended dynamic version of GLOBE employed here was initially calibrated to the GTAP 8.1 database[52] and represents global economy-wide production, demand, and trade for 24 sectors in 15 geographical regions. This version incorporates capital accumulation, population growth, labor force growth, and technical progress, and features a stylized representation of the technical substitution possibilities among different energy sources in production using a state-of-the-art KLEM (Capital [K], Labor, Energy, Materials) technology specification. For more details on GLOBE see Appendix 5.1.

Changes in agricultural productivity from IMPACT are passed to GLOBE as factor productivity shifters that generate equivalent impacts on agricultural producer prices. Price changes lead to knock-on effects for non-agricultural sectors, ultimately leading to changes in real household incomes, which are then passed to IMPACT that incorporates these income dynamics into its food demand system. To bridge the varying levels of geographic aggregation

between the two models we exploit the fact that the household real income deviations from the baseline are highly correlated with the initial shares of value added generated by food production. Using the fully disaggregated GTAP database we estimate the food value-added shares in GDP for 135 countries to downscale changes in real income from GLOBE to IMPACT. For more details on the coupling of IMPACT and GLOBE see Appendix 4.4.[51]

5.2.3 Scenario assumptions

To explore how additional investment could affect agriculture and hunger in Africa, we ran three scenarios:

1. A "no climate change" scenario with current baseline model productivity assumptions[10,11] and a constant 2005 climate, called **NoCC**.
2. A scenario with baseline productivity assumptions and strong climate change impacts, called **CC**.
3. A productivity enhancement scenario under climate change, called **COMP**, where productivity gains from additional investments in agriculture were added to the **CC** scenario.

Baseline socioeconomic assumptions

The baseline socioeconomic assumptions start with the "middle of the road" scenario (SSP2) of the Shared Socioeconomic Pathways (SSP), a set of global scenarios developed for the IPCC's Fifth Assessment Report.[53–55] The SSP2 scenario corresponds to the medium variant of IIASA-VID-Oxford population projections, where global population reaches 8.3 billion by 2030 with an economy of US$143 trillion.[6,56,57] SSP2 is a useful contextual scenario both at the global and regional scale and has served as a point of reference for several regional scenario exercises, which downscaled the SSPs in East[58] and West Africa.[59]

Under SSP2, expected changes in population and economic growth vary substantially by region (table 5.2). Population growth is concentrated in the developing world, where population grows at more than one percent per year adding, by 2030, almost 1.4 billion people globally (0.5 billion in Africa), compared to about 0.1 billion in developed countries. Economic growth is also fastest in developing countries, with an average annual growth rate of five percent compared to two percent in developed countries. Africa grows at the developing country average (5.2 percent), with Western and Eastern Africa growing somewhat faster at 6.5 percent per year. Central, Northern, and Southern Africa grow below the regional average at 5.0, 4.7 and 3.9 percent respectively. Robust economic growth across Africa pushes up average incomes, with the regional average annual income nearly doubling to $5000 by 2030. Nevertheless, by 2030, average annual incomes in Africa would still be below the developing country average, with only Southern Africa exceeding the developing country average.

Table 5.2: Regional changes under SSP2 for key socioeconomic indicators in 2010, 2020, and 2030

	Population (million)			GDP (trillion USD)			Avg. annual income (000 USD/person)		
Region	**2010**	**2020**	**2030**	**2010**	**2020**	**2030**	**2010**	**2020**	**2030**
Africa	1032	1279	1538	2.8	4.5	7.7	2.7	3.6	5.0
Northern Africa	223	260	293	1.2	1.8	2.9	5.2	6.9	9.9
South of the Sahara	863	1086	1326	1.7	2.9	5.0	2.0	2.7	3.8
Western Africa	304	386	479	0.5	1.0	1.9	1.7	2.5	3.9
Eastern Africa	321	407	498	0.3	0.6	1.1	1.0	1.5	2.3
Central Africa	127	162	200	0.2	0.4	0.6	1.9	2.4	3.1
Southern Africa	58	63	68	0.5	0.8	1.1	9.0	12.3	16.6
Other developing	4508	4903	5205	26.6	48.4	76.1	5.9	9.9	14.6
Developing countries	5778	6460	7058	31.4	56.0	88.2	5.4	8.7	12.5
Developed countries	1102	1167	1222	36.1	45.3	55.0	32.8	38.8	45.0
World	**6879**	**7626**	**8280**	**67.6**	**101.3**	**143.1**	**9.8**	**13.3**	**17.3**

Notes: USD are reported in constant 2005 terms.

Source: SSP population[6,57] and GDP[56] downloaded from the SSP database.[60]

Baseline climate change assumptions

The second scenario (**CC**) adds climate change to the baseline socioeconomic assumptions. Work done in the Agricultural Model Intercomparison and Improvement Project (AgMIP) has explored various dimensions of uncertainty around climate change impacts on agriculture. First, there is uncertainty on future GHG concentration levels, which will depend on economic growth and technological development. There is also uncertainty to the effects of increasing GHG levels in the atmosphere on changing temperatures and precipitation patterns and the ultimate impact of these changes on crop yields.[61–63] We use the **CC** scenario not as a projection of climate change impacts, which ideally would include multiple climate models to give a range of potential outcomes, but more as a benchmark to provide context of the potential benefits of increased agricultural investment. As such, we designed the **CC** scenario to be a more "extreme" climate scenario to explore diverse alternative climates similar to other modeling exercises.[36,44,64]

The IPCC's Fifth Assessment report[65] provides a range of future climate scenarios called Representative Concentration Pathways (RCPs). Through 2030, there are limited differences in atmospheric concentration of GHGs across the four RCPs ranging from concentration levels between 445 ppm and 480 ppm in 2030 compared to approximately 375 ppm in 2005. Radiative forcing by 2030 ranges from 2.9 W/m^2 to 3.3 W/m^2 compared to 1.9 W/m^2 in 2005. The RCPs begin to diverge more significantly by mid- and end-of century (figure 5.2). In the **CC** scenario, we have chosen to apply RCP 8.5, the most severe of the RCPs, and which a rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO_2 eq) by 2100.[66,67]

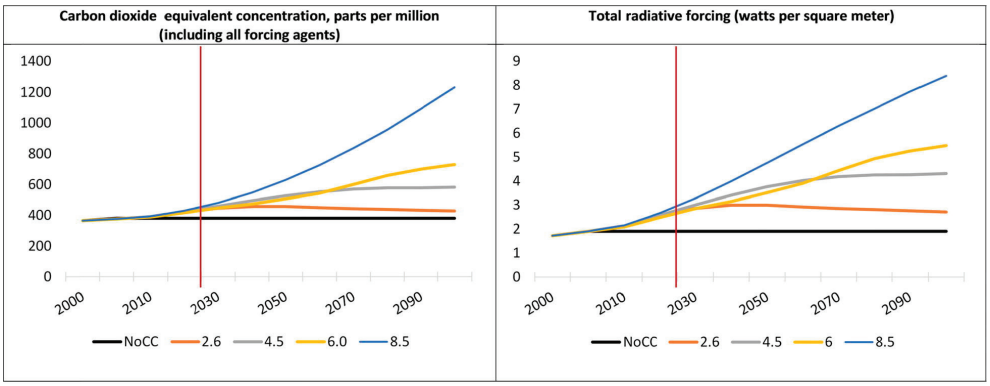

Figure 5.2: CO_2 equivalent concentration and radiative forcing for IPCC's four RCPs and a **NoCC** (constant 2005 climate) scenario.

Notes: NoCC=no climate change or constant 2005 climate; the red line represents the 2030 endpoint for achieving the SDGs.

Source: Figure based on Robinson and colleagues;[22] data downloaded from the RCP Database version 2.0.5.[68] RCP 2.6:[66,67]. RCP 4.5:[69–71]. RCP 6.0:[72,73]. RCP 8.5:[74].

Climate models vary in how they simulate the effects of a given GHG concentration pathway on temperature and precipitation. In this report, we focus our analysis on the climate realization from the Hadley Center's Global Environment Model (HGEM).[75] We selected HGEM because this climate model projects the most severe global consequences to agriculture from climate change with respect to changes in temperature and precipitation under RCP 8.5 (figure 5.3) and thus represents the most negative global climate scenario of those scenarios that were available from the freely available dataset of the ISI-MIP fast track initiative.[76] At the other extreme, the "No-Climate-Change" (**NoCC**) case presents a future climate with no additional climate change.[II]

II To test the sensitivity of the climate model selected, we simulated scenarios under an additional climate model from the Institut Pierre Simon Laplace's Earth System Model[77] and found that our results were robust across this alternative climate realization.

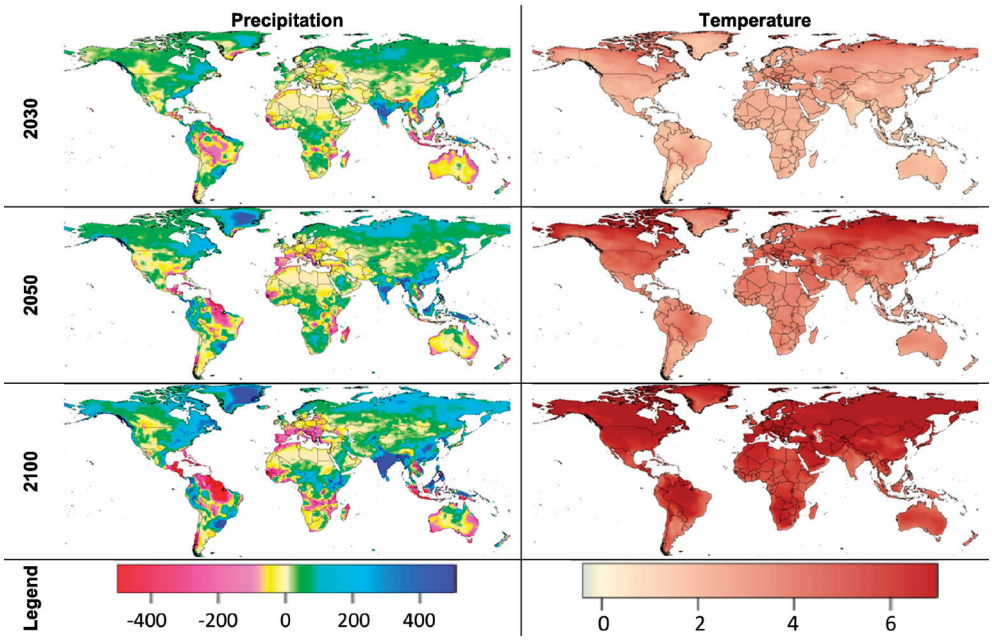

Figure 5.3: Change from 2000 in annual precipitation (mm) and maximum temperature (°C) for HGEM using RCP8.5 by 2030, 2050, and 2100.

Notes: Downscaled for use in the crop models.

Source: climate data from CMIP and ISI-MIP,[61,76,78]

In the **NoCC** scenario, aggregate crop productivity in Africa is assumed to increase by 38 percent between 2010 and 2030.[10] The changing temperatures and precipitation represented in figure 5.3 would lead to a negative biophysical shock that would decrease 2030 yields in Africa by about seven percent, excluding possible economic adaptations. The negative effects of climate change in Africa are higher than for the average across developing countries or the global average (five and six percent respectively).

Comprehensive agricultural investment scenario assumptions

The third scenario presented is a comprehensive investment scenario (**COMP**) for agriculture and the rural sector, which combines investments in agricultural research, resource management, and infrastructure in developing countries. This scenario is drawn from related work[24] assessing the potential impact of various investment levels across the CGIAR on agricultural development and sustainability.

The **COMP** scenario was selected for this analysis for three main reasons. First, it responds to the question of what outcomes could be achieved through increased public funding to agricultural R&D. The CGIAR has a long history of successfully converting research into agricultural and economic development[79,80] and this scenario builds on this network having been developed jointly with experts across the CGIAR system and embodies an optimistic,

but plausible, scenario of the potential for improvements to the agricultural sector in a future with higher investments. Second, the investments represented in this scenario are well suited to responding to the problem of underinvestment in public goods technologies, in which the CGIAR specializes. Tassey[81] identified the four primary causes of underinvestment as: (1) technical complexity; (2) long time horizons between investments and returns; (3) challenges of scale and scope of research; and (4) leakages. The CGIAR specializes in the provision of global goods technologies and the heart of its mission is to work on the types of research most likely to see underinvestment. It also plays a critical role in developing and helping diffuse technologies by building regional research capacity that, in turn, should increase the region's ability to absorb new technologies.[82] Third, with limited knowledge of what the future will bring, we believed it was better to look at a scenario that would help prepare for the future,[83,84] instead of trying to predict the "best path forward." Given the broad future uncertainty, we also believed it reasonable to follow portfolio theory and consider a broad and diversified mix of investments.[85,86] The **COMP** scenario is just such a mix, encompassing investments across the agriculture sector.

All the interventions specified in **COMP** are assumed to begin after 2015, with the scenario projection horizon going to 2050. The 2030 results presented in the following sections show the outcomes of these interventions at the midpoint of the overall scenario. While we focus on investments in Africa, the analysis includes investments in all developing regions, recognizing the importance of spillovers in technology and market effects to eliminating hunger in any one region and the difficulty and high cost of trying to do so in isolation.

The **COMP** scenario considers the role of improving agricultural productivity throughout the developing world, focusing on the potential gains in reducing yield gaps from increased CGIAR investment in agricultural R&D. The target yield improvements were quantified through consultations with CGIAR scientists on plausible yield gains from increases in research budgets. These yield gains were quantified for the developing world at the country level, differentiated across irrigated and rainfed systems, and incorporated knowledge on varying regional production levels and local research and extension capacity.

Figure 5.4 summarizes the target improvements in crop productivity globally and specifically in Africa. Agricultural productivity in Africa lags significantly behind the rest of the world and, therefore, the productivity gains possible in this region are significant in percentage terms. Africa in general is projected to be catching up with the rest of the world in the coming decades and productivity gains are generally projected to increase at a faster rate than the global average. Assuming some level of convergence may be optimistic, given that African cereal yields have not grown at a rate significantly faster than the global average since 1990,[30] however it is consistent broadly with the SSP2 narrative, which projects economic convergence (table 5.2).

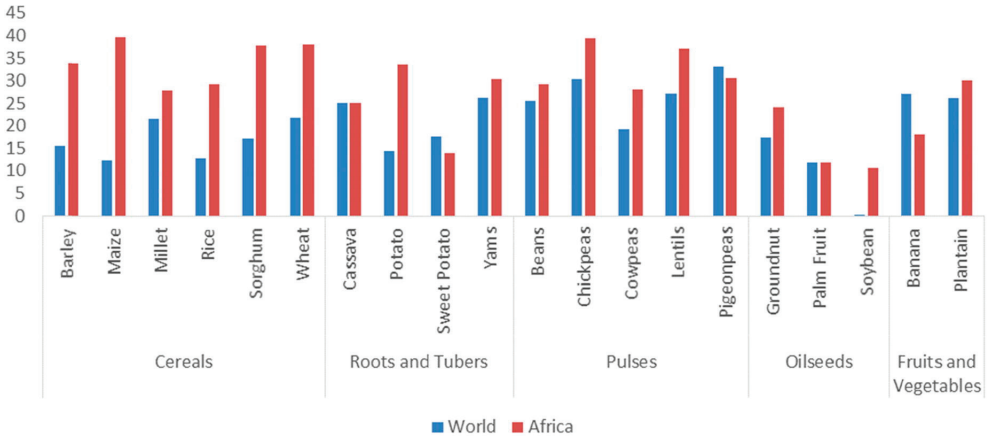

Figure 5.4: Target crop productivity improvements in Africa and globally by 2030 (percent change from the baseline climate change scenario, HGEM).

Notes: These figures summarize productivity improvement assumptions in the **COMP** scenario. All productivity targets were specified at the country level and disaggregated by irrigated and rainfed management. The World value includes Africa.

COMP also considers the critical role of water in sustainable intensification of the global food system. Expanding the area equipped for irrigation is a powerful option in terms of both increasing crop yields as well as reducing the risk of production volatility due to changing weather. At the same time, however, water can be a scarce resource and the expansion of irrigation in a sustainable fashion requires investments in water use efficiency. Water use efficiency investments in all targeted regions increases efficiency by 15 percentage points. Table 5.3 summarizes the targeted increases in irrigated area, water use efficiency, and soil water availability.

Table 5.3: Scenario target increases by 2030 in irrigated area and soil water availability, by region (percent increase relative to baseline)

Region	Irrigated area	Water use efficiency	Soil water availability
Africa South of the Sahara	30	30	15
North Africa and West Asia	5	25	5
Africa and West Asia	13	27	14
Other developing countries	5	25	6
All developing countries	6	25	8
World	**5**	**20**	**6**

High transportation and marketing costs reduce the potential revenues that producers can make while increasing the prices that consumers face. The **COMP** scenario also includes investments in improvements to transportation (roads, rail, and ports) and energy infrastructure (expansion and improvement of electrical network), which are major constraints to transportation and storage of agricultural production. These scenario assumptions were

represented as declines in the price wedges between the farm-gate price and the prices consumers face.

5.2.4 Estimating scenario investment costs

Potential investment costs are assessed quantitatively for the **COMP** and baseline scenarios (**NoCC** and **CC**) with the understanding that the timing of investments is inherently different according to the targeted driver of agricultural production (e.g. crop yields versus irrigation expansion). Infrastructure investments in irrigation, as well as investments in improving marketing efficiency, require more up-front spending to expand and improve irrigation and transportation networks, whereas investments to increase agricultural yields through increased TFP require a longer-term stream of research and development activities (See Appendix 5.1 for more details on investment calculations).

Infrastructure investments are estimated using unit costs of construction and maintenance. However, given the challenges of capturing the "lumpy" development of new technology, where progress can be observed in fits and bursts, with advances in basic science pushing continued gains in applied science for a period of time,[81] we decided to structurally model the process of converting R&D investments into agricultural productivity gains. To do this, we follow a long literature of translating R&D investments into changes on sector productivity[18,87–96] and chose to employ the perpetual inventory methodology (PIM), considered "the workhorse of R&D stock estimation" techniques.[97]

The PIM includes not only the building of the stock of knowledge, but also acknowledges the process of "creative destruction" as new methods of production make the old obsolete.[98] We follow Esposti and Pierani,[18] who link the parameterization of the PIM (in particular the decay rate and R&D elasticities) with the type of research being modeled (basic, applied, and developmental research). Additionally, we recognize different regional and institutional returns to R&D investment[19] and disaggregate agricultural R&D by region and source of public investment (CGIAR or National Agricultural Research Systems (NARS)). This allowed us to represent the variation of regional and institutional capacity, as well as in what types of research each institution specializes (i.e. CGIAR tends to work more on basic research). We further apply lessons from Alston and colleagues[17] to explicitly incorporate spillovers into the process of the building of stock of knowledge.

Baseline investments

The additional public investments included in the baseline for Africa and West Asia[III] are projected to be more than $9 billion per year, with about $7.5 billion in direct government investments in agriculture (excluding infrastructure and the CGIAR; columns 2–5 in table 5.4). This will require government investments in agriculture to more than double currently

III Due to data constraints, it is not possible to separate West Asia from the aggregated numbers for West Asia and North Africa (WANA).

estimated levels (table 5.1) by 2030, a significant increase, but one that is plausible given the low levels of investments compared to other developing regions and the economic growth projected for Africa under SSP2 (table 5.2). Globally, the additional investments assumed in the baseline are more than $86 billion per year, with about $34 billion coming from direct investments in agriculture, which can be categorized primarily as either investments in R&D or in irrigation and water resource use.

In IMPACT, improvements in agricultural productivity are embedded in growth rates, which represent historical trends on agricultural yield growth and biological yield potential.[22] To assess the future costs of the projected yields, we have calculated the required investments in agricultural R&D to achieve given changes in agricultural productivity using PIM. The CGIAR contributed about three percent of total public R&D funding in developing regions; however, in SSA it contributes about twelve percent.[28,99] The projected investment costs for Africa are $2.7 billion per year, with CGIAR investments projected to follow historical trends and keep pace with GDP growth from 2010 to 2050 (4.1 percent compared to 4.4 percent for GDP). Investments grow faster than GDP to 2030 (6.3 vs. 4.7 percent) to account for research lags between initial investments and productivity growth. NARS investments are also projected to increase across the region from $1.6 to $2.4 billion by 2030, an increase of over 50 percent.

In 2010, Africa and West Asia accounted for about 10 percent of the world's irrigated area, about 32 million hectares. Total irrigated area in IMPACT is projected to increase in the region by approximately six million hectares by 2030, with this increase split evenly between SSA, and North Africa and West Asia. In SSA this is an increase of over 33 percent, whereas for North Africa and West Asia, the increase is about 13 percent over 2010 levels. In addition to expanding irrigated areas throughout the region, the baseline scenario considers that new water resource management technologies will be implemented over time. There is significant variation globally on the efficiency of water management systems due to irrigation technologies (e.g. drip vs. furrow[43,100]) and crop management (e.g. no-till[41]). The baseline scenario assumes improving regional water use efficiency based on historical trends, which leads to a 4 percent decline in water use intensity per hectare (m^3/ha). Using cost data on water projects[101] and FAO's AquaStat Database,[102] the average annual cost of investments to achieve this level of improvement to the irrigation system amounts to about $4 billion per year from 2010 to 2030. The majority of the investments is dedicated to irrigation expansion, particularly in SSA. Improvements in soil management were estimated to be more than $1.5 billion per year with SSA requiring about 58 percent of costs for Africa and West Asia.

Table 5.4: Projected average annual baseline costs between 2010 and 2030 (billion 2005 USD)

	Agricultural R&D		Other direct investment in agriculture			Indirect Investments in agriculture	
Region	**CGIAR (1)**	**NARS (2)**	**Irrigated area (3)**	**Water use (4)**	**Soil mgmt. (5)**	**Infrastructure (6)**	**Total (7)**
Africa South of the Sahara	0.68	0.85	2.98	0.13	0.88	0.17	5.7
North Africa and West Asia	0.06	1.12	0.81	0.07	0.64	0.90	3.6
Africa and West Asia	0.74	1.97	3.79	0.20	1.52	1.07	9.3
Other developing countries	0.41	3.38	3.77	2.02	2.10	24.50	36.2
All developing countries	1.16	5.35	7.56	2.22	3.62	25.57	45.5
Developed countries	—	13.26	0.56	0.17	—	26.92	40.9
World	**1.16**	**18.61**	**8.12**	**2.39**	**3.62**	**52.49**	**86.4**

Notes: CGIAR investments focus on developing countries, and soil management investment data are available only in developing countries.

The economic growth projected as a part of the baseline SSP2 assumptions is significant across the developing world, particularly for SSA. This growth will require investments in expanding and maintaining transportation and energy infrastructure, which are critical for not only the agriculture sector, but the economy as a whole. Following Rosegrant and colleagues,[103] we estimate global infrastructure investments to be about $52.5 billion per year. In Africa and West Asia, the investment levels will be much smaller than in other regions at about $1.1 billion per year, which may seem counterintuitive due to lower levels of infrastructure in the region. However, a significant share of infrastructure investment is focused on maintenance and preventing deterioration. The low levels and quality of existing infrastructure throughout Africa and West Asia lead to lower investment costs in the region as investments are focused on new construction instead of maintaining older infrastructure.

Comprehensive agricultural sector investments to help end hunger in Africa

The **COMP** investment portfolio represents a broad array of additional investments across different parts of the agricultural system. If these investments were to occur simultaneously, we would expect the total additional cost for all developing countries to be about $52 billion per year from 2015 to 2030 (table 5.5), an amount comparable to assumed baseline infrastructure investments. The additional direct investments in agriculture (excluding infrastructure) account for about $26 billion per year, of which about $8 billion per year would be in Africa

and West Asia. The total investment cost for Africa and West Asia, including infrastructure, is almost $15 billion per year (29 percent of total investment across all developing countries).

Table 5.5: Total additional cost of comprehensive investment scenario (billion 2005 USD)

Region	Agric. R&D (1)	Irrigation expansion (2)	Water use efficiency (3)	Soil & water mgmt. (4)	Infrastructure (5)	Total (6)
Africa South of the Sahara	0.67	2.76	0.41	1.76	4.52	10.1
North Africa and West Asia	0.01	0.83	0.61	1.28	2.06	4.8
Africa and West Asia	0.67	3.59	1.02	3.04	6.57	14.9
Other developing countries	0.07	4.34	9.25	4.19	19.36	37.2
All developing countries	0.74	7.93	10.27	7.23	25.94	52.1

Notes: Additional investments are specified only in developing countries.

To achieve the additional productivity enhancements projected in the **COMP** scenario illustrated in figure 5.4, total CGIAR investments in agricultural R&D would start to diverge from the baseline in 2015, increasing to more than $3.1 billion by 2030, almost double the investment level in 2030 in the baseline scenario ($1.7 billion) (figure 5.5). This amounts to an average annual investment of $0.74 billion per year in additional investments in CGIAR research. These investment increases will not be uniform across regions, with nearly 90 percent of additional investments ($0.67 billion per year) needed in SSA.

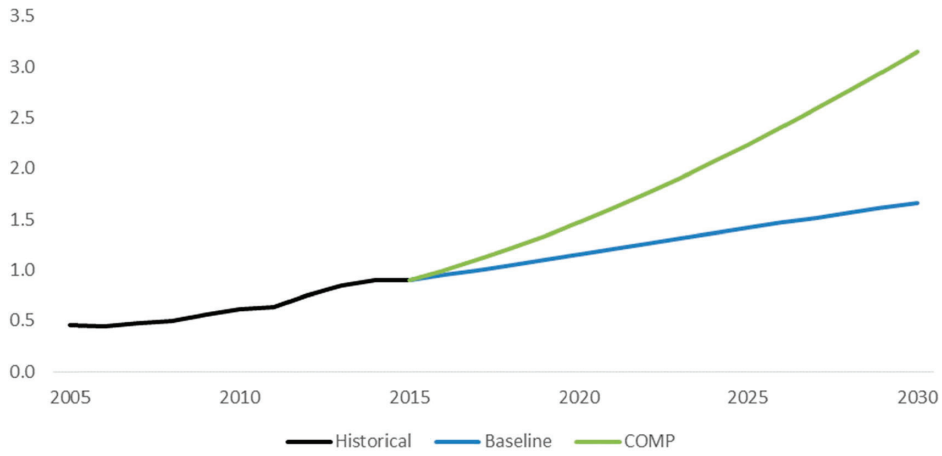

Figure 5.5: CGIAR investment streams in the **COMP** and Baseline scenarios (billion 2005 USD).

Plausible investments in agricultural research to boost yields by 2030 will not be sufficient to eliminate hunger in Africa. Additional investments to improve the productive capacity of agriculture and boost the sector's efficiency will be required. These investments are also critical towards improving the sustainability of the agriculture sector ensuring that gains achieved by 2030 can be maintained moving further into the 21st century. The additional agricultural investments considered in this analysis include investments to improving the capacity of water resource management (more efficient irrigation technologies, implementation of soil water management technologies), as well as further expansion of irrigation beyond the assumed expansion in the baseline.

The additional investments needed to expand irrigation, and improve water resource management throughout the developing world are significant, more than $25 billion per year (columns 2–4 in table 5.5), nearly doubling baseline investments for irrigation expansion (table 5.4). About $7.7 billion, or about 31 percent, of this additional investment will be in Africa and West Asia. Most of this investment in Africa and West Asia will be in irrigation expansion ($3.6 billion, 47 percent) and soil management ($3 billion, 40 percent). Within this region almost two thirds of the investments are concentrated in SSA.

Agricultural markets throughout the developing world suffer from market inefficiencies due to poor infrastructure. To reduce these inefficiencies, and thereby reduce transportation and marketing costs it is necessary to invest in building new infrastructure as well as improving and maintaining current infrastructure. These investments enhance productivity along the value chain, increase the speed of moving commodities to markets while also improving storage capacity, all of which improve market efficiency by better matching supply and demand over time. In this scenario, infrastructure investments focus on expanding and improving energy and transportation infrastructure. The cost of infrastructure investments is based on Rosegrant and colleagues,[103] where infrastructure investments across the developing world in road network expansion and improvement, rail expansion, and increased electrification were estimated to cost almost $26 billion per year between 2015 and 2030. Investments in Africa and West Asia account for about $6.6 billion (25 percent) of the total infrastructure investments with the majority dedicated to the improvement of road connections.

5.3 Results

The developing world is projected to experience important improvements in overall well-being and reduced hunger in the **NoCC** scenario. The investment scenarios described above, combined with other drivers, will play a significant role in this positive trajectory. Economic growth is particularly important with average incomes in the developing world more than doubling between 2010 and 2030 in the baseline scenario. Africa experiences fairly optimistic growth in per capita incomes of more than three percent per year during this period. Although, we should note that changes in average incomes can still mask significant diversity of income and poverty levels at the household and individual level. Climate change (**CC**) is

projected to slow global income growth by about 1 percent over this period and have stronger effects in the developing world, especially in Africa and South Asia.

5.3.1 Income

Coupling the GLOBE and IMPACT models allows endogenous determination of the aggregate income effects of changes in agricultural productivity. The **COMP** scenario, combining high investment in agricultural R&D, irrigation expansion, improvements in water use efficiency and soil water management, and reduced marketing margins, sees significant increases in income and manages to more than offset the negative effects of climate change on incomes by 2030. Globally, average incomes increase by almost $500 per person (about three percent) in 2030 compared to the **CC** scenario without added investments. Developing countries generally benefit more, with Africa seeing average incomes increasing by more than five percent (over $200 per person). The regional average masks variation within Africa, with larger growth observed in West Africa ($300 per person) compared to Central Africa ($60 per person) (table 5.6).

Table 5.6: Comparing average income (per capita GDP, thousand USD) in 2010 and 2030 by region and scenario

Region	2010	2030		
		NoCC	CC	COMP
Africa	2.7	5.0	4.9	5.1
Northern Africa	5.2	9.9	9.8	10.2
South of Sahara	1.9	3.8	3.8	4.0
Western Africa	1.7	3.9	3.8	4.1
Eastern Africa	1.0	2.3	2.3	2.3
Central Africa	1.9	3.1	3.1	3.2
Southern Africa	9.0	16.6	16.5	17.3
Developing countries	5.4	12.5	12.4	12.9
World	**9.8**	**17.3**	**17.2**	**17.6**

5.3.2 Agricultural productivity

Agricultural productivity is projected to increase by about 32 percent in the developing world between 2010 and 2030 in the absence of climate change (**NoCC**). Climate change reduces this potential productivity growth by four percentage points (with variation by crop and region) as yields respond to changes in temperature and precipitation and, in turn, to changing prices. The additional investments in agriculture in the **COMP** scenario have significant effects on yields, with gains more than offsetting the negative effects of climate change and increasing global crop productivity in 2030 by 40 percent compared to 2010. This is 12 and 8 percentage points above the **CC** and **NoCC** scenarios, respectively. Africa gains significantly in this scenario with crop productivity increasing by 51 percent over 2010 levels, from 47 to 56 percent, depending on the region (figure 5.6).

5.3.3 Commodity prices

The interplay of food prices and income ultimately determines the ability of consumers to purchase the quantities of food they demand. Growing population, increasing incomes, and climate change are all factors that will likely lead to higher food prices. By 2030, prices are projected to increase between 10 and 30 percent from 2010 levels under a baseline without climate change (figure 5.7).

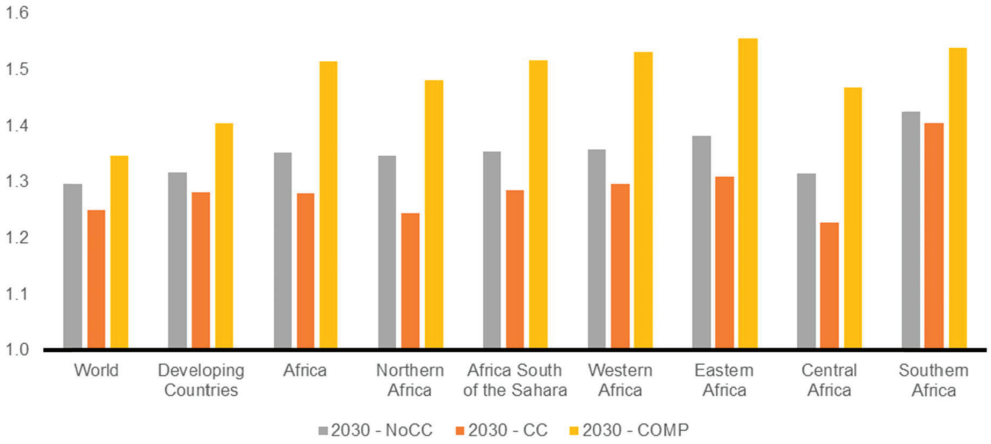

Figure 5.6: Average aggregate crop yields in 2030 (indexed, 2010 = 1.0) by region and scenario.

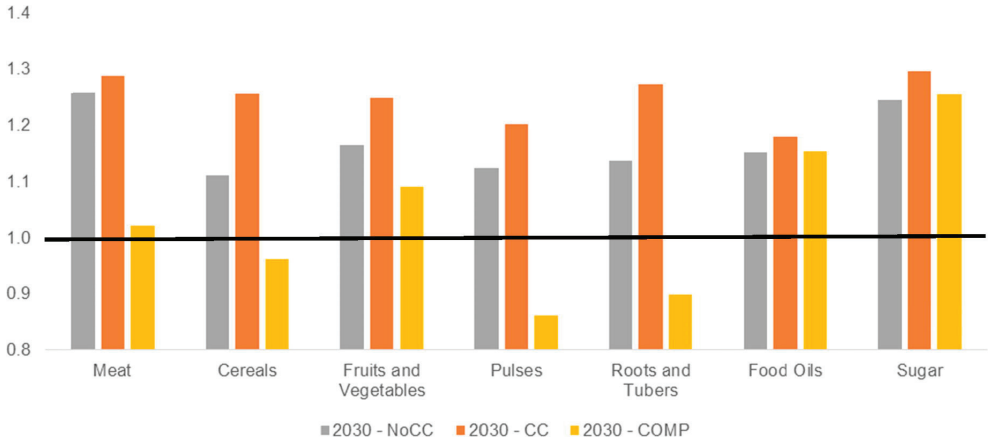

Figure 5.7: World prices in 2030 (indexed, 2010 = 1.0) by commodity group and scenario.

Notes: The black line represents 2010 price levels.

Climate change, on average, increases prices an additional 3 to 15 percentage points, with cereals and roots and tubers seeing the largest price increases due to climate change. In the **COMP** scenario, the increases in agricultural productivity are able to not only offset the price increases caused by climate change, but also, in several cases, are able to more than match the added demands caused by population and income growth. For example, average prices for

meats, cereals, pulses, roots and tubers fall to or below 2010 levels. Processed commodities like food oils and sugar, which were not targeted in this scenario, see smaller price declines, but still return to levels projected without climate change.

5.3.4 Food availability and hunger

The average kilocalorie availability across the developing world increases from about 2700 kcal per person per day in 2010 to almost 3000 per day by 2030, or the recommended daily intake of an active 20 to 35-year-old male.[104] Africa starts from a lower base than the developing country average with 2500 kcal per person growing to 2700 by 2030. Northern and Southern Africa are above the developing country average, both achieving over 3000 kcal by 2030 with or without climate change. Eastern and Central Africa lag behind the rest of Africa with initial kilocalories per person around 2100 in 2010 and staying below 2500 in 2030 in both scenarios with and without climate change.

Increasing incomes combined with lower food prices due to productivity improvements in the **COMP** scenario help to drive down food insecurity (along the dimension of food supply) globally with calorie availability increasing by 15 and 13 percent relative to a baseline without climate change in developing countries and Africa, respectively (figure 5.8). The largest gains are in Central and Western Africa, where kilocalories increase by six percent compared to the **NoCC** scenario. Higher consuming Northern and Southern Africa see smaller gains (two to three percent) with Eastern Africa in between at four percent.

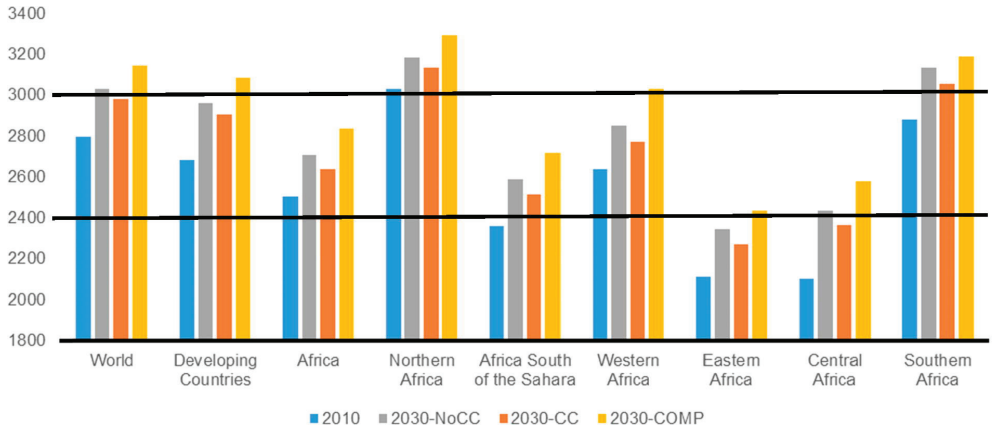

Figure 5.8: Average food supply (kilocalorie per person per day) in 2010 and 2030, by region and scenario.

Notes: The line at 1800 represents the daily minimum requirement. The black line at 2400 represents recommended daily consumption of an active 20–35-year-old female and the line at 3000 represents the recommended daily consumption of an active 20–35-year-old male.[104]

What does it mean to achieve SDG2 and eliminate hunger? Few would argue with the goal, but actually defining it in practical terms (let alone achieving it in absolute terms) is more challenging. Changes in average income, prices, and food availability are useful targets for broadly driving down hunger but will still miss parts of the population. For example, some people remain hungry even in rich countries due to gaps in social protection measures and other factors. Therefore, we follow one of the scenarios analyzed in the FAO's *Achieving Zero Hunger* report,[105] which adopted "a prudential threshold of five percent of the population."

The general trend towards increasing calorie availability leads to a decline in the prevalence of hunger as measured by the share of the total population in the developing world. However, in raw terms, this decline is less noted in Africa where rapid population growth keeps the number of people at risk of hunger in 2030 near 2010 levels even though shares are declining.

This is particularly true for Northern and Eastern Africa where the number of people at risk of hunger increases in 2030 compared to 2010 even without taking into account the negative effects of climate change (figure 5.9).

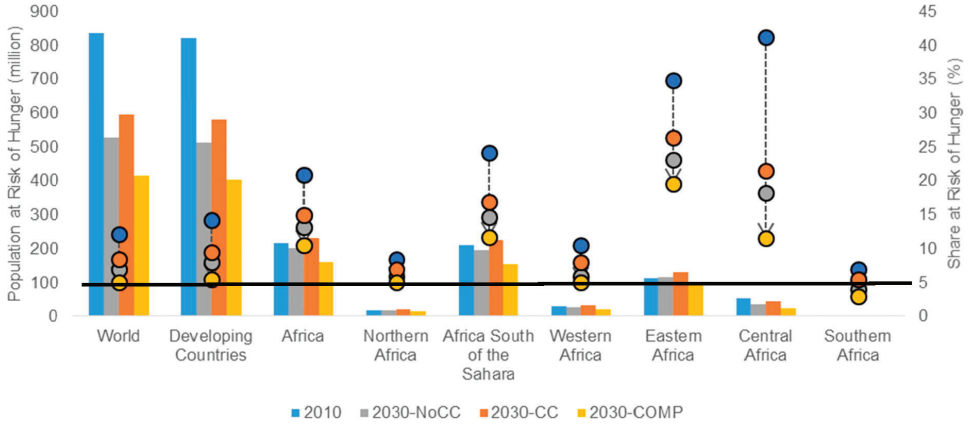

Figure 5.9: Prevalence of hunger in millions of people and as a share of the total population (%).

Notes: Clustered bars represent the number of people at risk of hunger in each region (left axis). The enlarged dots represent the share of the region's total population at risk of hunger (right axis). The dotted lines reflect the change in the share at risk of hunger over time and across scenarios. The solid black line represents a target threshold of five percent of the population at risk of hunger (right axis).

Once climate change is included, the population at risk of hunger in 2030 is greater than 2010 levels in Northern, Western, and Central Africa, with only Southern Africa seeing a decline in the population at risk of hunger from 2010. Nevertheless, it is important to note that in all regions the share of the population at risk of hunger is declining. Particularly large reductions are observed in Eastern and Central Africa where the share falls from 35 and 41 percent in 2010 to 26 and 22 percent in 2030, respectively.

Under the **COMP** scenario, these trends toward declining rates of hunger are accelerated and help drive down the prevalence of hunger across the three most food insecure regions (Western, Eastern, and Central Africa) that contribute almost 90 percent of those at risk of hunger in Africa and almost a quarter of the global population at risk in 2010. By 2030, the added investments in agriculture help to halve the number of people at risk of hunger and drive down the share of the world's population at risk of hunger from over 12 percent to just over 5 percent. In Africa, these additional investments lead to the share at risk of hunger falling from 21 percent in 2010 to about 10 percent by 2030, a reduction of about 55 million people, compared to a 16 million increase by 2030 in the **CC** scenario. Three sub-regions (Northern, Western, and Southern Africa) achieve the target of five percent at risk of hunger, but the share at risk remains above 10 percent in Eastern and Central Africa, despite significant reductions. In total, 16 of the 48 African countries modeled in IMPACT approach or surpass the five percent target by 2030, with another six countries at or below 10 percent at risk of hunger. Without the additional investments in **COMP**, only 12 countries would achieve the five percent target, with another five countries below 10 percent at risk of hunger.

5.4 Discussion

5.4.1 Model results in context

Numerous estimates have been made of the cost of achieving various development goals, such as ending hunger, though methods and targets are often specified differently and therefore careful interpretation is necessary when comparing across studies. Estimates vary for different reasons related to the specific questions being asked; the objective of the study; sectors covered; whether climate change is considered; the methods, models and assumptions used; geographical coverage; and numerous other factors.

Because different studies ask different questions and employ different methods, estimates are not always directly comparable. Here we compare and contrast our results with those from a 2015 study by FAO, IFAD, and WFP (referred to here as the *Achieving Zero Hunger* estimates) as well as with joint IISD and IFPRI work.[106]

Estimates of the additional investments needed are largest for the 2015 *Achieving Zero Hunger* analysis and smallest for Laborde and colleagues[106] with the results presented in this paper in-between. This is largely due to differences in the questions being asked and the methods used to answer them (table 5.7). The *Achieving Zero Hunger* analysis eliminates hunger in all countries by eliminating poverty. Laborde and colleagues[106] instead consider the minimum public investment needed to end hunger. Both of these studies consider investments in and outside of agriculture and do not include the impacts of climate change. Our analysis, instead of costing the eradication of hunger, attempts to estimate the potential hunger reduction from investments only in the agriculture sector and includes the potential impacts of climate change on hunger eradication efforts.

In the 2015 *Achieving Zero Hunger* report, the Rome-based UN agencies[105] posited that poverty and hunger could be eradicated in all developing countries by 2030. To do so would involve additional public investment in social protection combined with public and private efforts to raise investment levels in productive sectors—especially in rural areas and particularly in agriculture. Over the period 2016–2030, the additional poverty gap transfers as well as increased investments in productive sectors would need to total US$265 billion per year on average. This represents 0.3 percent of global GDP in 2014. It would fund social protection and additional targeted pro-poor investments with rural areas receiving most (US$181 billion) of the annual investments. Hunger would be reduced to below five percent prevalence rates in all developing countries considered by raising incomes of the poor above the poverty line. Climate change impacts are not considered in the *Achieving Zero Hunger* analysis.

The joint analysis by IISD and IFPRI estimates the minimum cost of ending hunger by 2030, defined as reducing the population consuming less than the Minimum Dietary Energy Requirement (MDER) to five percent or less. This study found the cost to be $11 billion annually from 2015 to 2030, four billion of which would be required from donors.[106] The pathway for ending hunger focuses on additional investments in social safety nets, farm support, and rural development. The target recipients are vulnerable households and the impacts of climate change are not included. The model used was the MIRAGRODEP model—using a mixture of multisector CGE modelling and bottom up estimates based on household survey data for seven countries in Africa. The split between donors and private financing was determined using a co-funding rule; this involved regression of government spending on ODA to determine the relationship which is assumed to stay the same into the future.

Table 5.7: Comparing present analysis to other estimates of the cost of eradicating hunger

	Present analysis	**Achieving Zero Hunger[105]**	**Ending Hunger: What would it cost?[106]**
Question asked and time frame	What are the impacts on hunger from increases in agriculture investments in developing countries by 2030?	What additional transfers and investments are needed to eradicate poverty and hunger in all countries by 2030?	What is the minimum cost of ending hunger for vulnerable households in all countries by 2030?
Sectors for investment	Increased investments in agricultural R&D, irrigation expansion, water use efficiency, soil management, and infrastructure	Public investments in poverty gap transfers, irrigation, genetic resources, mechanization, agro-processing, infrastructure, institutions, and agricultural R&D	Investment in social safety nets, farm support, and rural development
Climate change impacts included	Effects of climate change are considered	Climate change impacts are not included	Climate change impacts are not included
Estimated annual costs	$52 billion annually from 2015–30 ($15 billion of which is in Africa)	$265 billion annually from 2016–30 (most of that is in Africa south of the Sahara excluding South Africa)	$11 billion annually, of which $4 billion is from donors (most investment in Africa)

The results presented in this paper are estimates of possible outcomes of different levels of investment on a range of indicators, including agricultural productivity and hunger. Under baseline productivity scenarios, direct investments in agriculture (excluding infrastructure) across developing countries average $20 billion annually from 2010 to 2030. Including infrastructure, the total baseline investments across developing countries is about $45.5 billion. Under the **COMP** scenario, additional investments are $52 billion annually from 2015 to 2030 and are allocated to agricultural R&D, expanding irrigation, improved water use efficiency and soil management, and improved transportation and energy infrastructure. Most of the additional investments needed in agricultural R&D takes place in SSA while investments in some other sectors are more evenly spread among regions.

The impacts of additional investments under **COMP** are increased average incomes, improved agricultural productivity, decreased food prices, and improved food security. The prevalence of hunger would be reduced to five percent on average across developing countries. In addition to reducing hunger, other goals are also achieved, such as increased agricultural productivity, and increased incomes. Incomes in Africa increased by about five percent compared to the baseline in 2030, and agricultural productivity was more than 1.5 times as high as it was in 2010. Nevertheless, despite the share at risk of hunger declining to the five percent threshold in the developing world as a whole and in several African sub-regions, Africa in aggregate persists at a level closer to 10 percent with progress lagging in Eastern and Central Africa. This suggests that additional investments in agriculture could be important pieces of a broad portfolio of investments and interventions, but will need to be supplemented by additional social safety net and pro-poor investments similar to those suggested by Laborde and colleagues[106] if the goal of achieving SDG2 is to be achieved.

5.4.2 Caveats and critical assessment

In this paper, we explore the potential contributions of a scenario of higher future investments within the CGIAR with a particular focus on the impacts on the population at risk of hunger. We have taken a novel approach attempting to integrate the R&D and agricultural productivity literature directly to a global economic modeling framework to better link projected economy-wide gains in agricultural production to the kinds of investments needed to achieve these gains. Our modeling efforts include a broad multi-model ensemble designed to capture key feedback dynamics between agriculture and other sectors of the economy by integration of GLOBE into the IMPACT framework. The inclusion of this linkage allowed for a better assessment of some of the potential benefits of investments in agriculture in Africa, which suggested an estimated reduction of 1.2% (2 million) fewer people at risk of hunger in Africa than would have been estimated without income feedbacks from GLOBE (for more detailed comparison of results with and without connection to GLOBE in Appendix 5.1).

Our objective with this multi-model ensemble was to expand the scope of analysis, but we recognize that results are in part dependent on the models selected. Research from AgMIP

suggests that there can be significant differences in outcomes between models even when assuming the same scenario inputs.[61,63] A multi-model ensemble that included multiple similar models (crop, economic, climate), would allow us to explore model uncertainty at each coupling point. Baseline productivity growth and investment levels, as well as future food demand are directly tied to scenarios of economic growth. This analysis only used SSP2, and we would expect the magnitude of the challenge of eradicating hunger would vary significantly based on the socioeconomic scenarios used. Nevertheless, given recent results from work by Hasegawa and colleagues,[107] which explores future hunger across a broader range of economic and climate scenarios, and including land-use and trade policies that were not included in this analysis, we believe our conclusion that increased investments in agriculture are necessary but insufficient to achieve SDG2 would be robust in such an exercise.

The potential gains from agricultural R&D are also susceptible to uncertainty in future state capacity and fragility. The SSPs focus their narratives on long run trends in the global economy, which, while helpful for exploring scenarios around climate change and long run drivers in the food system like agricultural R&D, do not include other drivers that are important to global food security. For example, extreme events, both social and environmental, will almost certainly complicate progress towards SDG2. These events and crises can displace millions while destroying capital (human, physical, natural, social) and limiting the capacity of societies to effectively function. Poor governance and weak and corrupt states can prevent the effective application of science, technology, and best practices. The recent uptick in global food insecurity can be attributed in large part due to state failure and internal conflicts.[108,109] Peace and stability, broadly, are prerequisites for development, without which gains from research are unlikely to be achieved.

Uncertainty in this analysis also stems from the fact that global economic models rely on aggregated national statistics and must represent detailed economic behavior in a fairly stylized way. The global food system is rapidly transforming with the development of more complex and integrated processing value chains.[110] We believe that by coupling a highly disaggregated agricultural partial equilibrium model like IMPACT to GLOBE was an important advance to better assess economy-wide impacts of investments. However, we also recognize that the kinds of investments we considered are focused more on primary production, even as we tried to simulate certain investments like improved infrastructure that would see their impact more generally throughout the value chain. Future research linking global models like IMPACT and GLOBE to more granular analysis of value chains could highlight important complimentary interventions that could ensure there is full capacity throughout the value chain for the increased production modeled in this work. Hunger in this analysis, as well as those we've compared to provide context define hunger in terms of calories. For a better assessment on changes to food security, which should be the ultimate goal for policymakers, more research will be needed to move beyond calorie supply, and to consider dietary and nutritional quality. Both IMPACT and GLOBE simulate economic behavior of a single

representative consumer. National averages can mask significant distributional differences within countries and there would be significant gains from trying to bridge scales of analysis through linking to more detailed value chain and disaggregated household analyses.

On the side of cost estimation, we had to work in a data sparse environment with limited long-run data on investments, which complicates the empirical estimation of returns to R&D.[18] We applied a methodology with a structural theory of how investments in R&D are converted to changes in sector productivity, the PIM. However, this approach has its drawbacks in that the parameters needed to represent research lags and knowledge decay are not observed directly and are difficult to estimate as they are endogenous with respect to investment decisions.[97,111] Baker and Shittu[112] highlighted the importance of better understanding endogenous technical change, and further research is still needed to better understand the way that research institutions respond to changes in R&D investment levels and how basic research and absorptive capacity can increase or decrease with respect to investment decisions. Better understanding these relationships will be critical for closing the modeling feedback loop, to begin to consider the potential effects of income changes and economic development on R&D investment streams.

Additionally, with our focus on public investments through the CGIAR, we assumed that private and other public investments (e.g. NARS) stayed at baseline levels and would not adjust to higher spending in the CGIAR. However, it is unlikely that the rest of the agricultural R&D ecosystem would not adjust their behavior. More research would be needed to explore this. It is possible that these increases could crowd out other investments, decreasing non-CGIAR investments, which in turn could diminish regional capacity to fully benefit from research done in the CGIAR. Alternatively, it could spur complementary research investments, leading to an even greater impact from additional investments. From a policy perspective, the latter case is obviously preferred, so applied research in this realm would be useful to ensure greater impacts and efficacy.

5.5 Conclusions

In this research, we used a quantitative foresight modeling system (IMPACT) to examine the potential impact of increasing investments in agricultural R&D, with a particular focus on the potential impact of climate change. Agricultural research, resource management, and infrastructure improvement can help address the challenges of meeting future food demands, but it is unlikely that hunger can be eliminated by focusing on the agricultural sector alone. Complementary efforts will be required outside of agriculture. The costs of investments focused on the agricultural sector are in line with historical trends and should be manageable with increasing growth in global and regional economies. Nevertheless, reducing hunger in Africa will be a challenge moving forward. To make progress towards this goal we should recognize the following:

1. **Climate change has impeded and will continue to impede progress on reducing hunger.** Climate change could increase the number of people at risk of hunger in 2030 relative to a scenario without climate change. In Africa, the combined effects of population growth and climate change mean that the number of people at risk of hunger is projected to increase even relative to today's levels, i.e. more than offsetting reductions projected in 2030 due to increased incomes and other factors. Reducing hunger will be particularly challenging in Eastern and Central Africa.
2. **Increased investment in agriculture in Africa and the rest of the world can accelerate productivity growth for important crops and livestock and counteract the effects of climate change.** Increased investments in agricultural research, resource management, and infrastructure can more than offset the negative effects of climate change, increasing crop productivity in 2030 by 40 percent globally and by over 50 percent in Africa compared to 2010 levels.
3. **Increased investments in agricultural R&D will result in large declines in the share and number of hungry people in Africa.** Increased productivity growth in agriculture boosts food supply, reduces food prices, and increases incomes. This increases access to food and helps reduce the share of people at risk of hunger in 2030 to five percent or less in Northern, Western, and Southern Africa. However, the share is projected to remain at 10 percent or more in Eastern and Central Africa even with investments in agricultural R&D.
4. **Additional investments in Africa to achieve these results under climate change are estimated to cost about $15 billion per year between 2015 and 2030**[IV] (compared to the baseline scenario). While the costing methodology in this research produced estimates that differ from other research on this topic, the research questions and approaches make these studies mutually reinforcing, despite their apparent contrast. The joint IISD and IFPRI work by Laborde and colleagues[106] targeted vulnerable households only and did not consider the impacts of climate change and produced lower estimate for annual cost. The FAO's *Achieving Zero Hunger* report[105] estimated a costlier goal of raising incomes and eliminating poverty more generally. In all cases, the research implies necessary increases over current levels of government and international spending on agriculture in Africa.
5. **Increased investment outside of the agricultural sector is likely needed to end hunger in Africa by 2030.** While agriculture is an important cornerstone for most of Africa, its overall importance is declining as economies grow. Investments in the agricultural sector will help build the foundation for a more prosperous and stable Africa, but complementary investments throughout value chains within the food system and in the non-agricultural sector will be necessary for resilient economies and achievement of the SDGs, especially for eliminating hunger. Future work will examine the scope for further progress in ending hunger through investments outside of the agricultural sector, such as clean water and sanitation, health, education, and the manufacturing and services sectors.

[IV] As part of a larger, global package of additional investments costing around USD 52 billion, compared to the baseline scenario, in developing countries as a whole.

Author contributions

DMD, TBS, KW, MWR, and SL wrote the paper. DMD, TBS, ANP, DW, SR, TZ, SD, and RR quantified scenarios for the models. DMD, TBS, DW, NC, and SD analyzed scenario results. All authors were involved with research design.

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Declaration of Interest

Several authors are or were employed by the International Food Policy Research Institute, which is a member of the CGIAR. Non-IFPRI authors declare no interests.

Data sharing

Supplementary data to this article can be found online at https://doi.org/10.1016/j.worlddev.2018.12.006.

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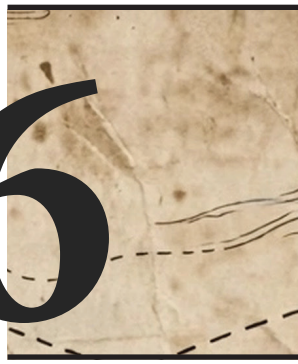

6

Multi-factor, multi-state, multi-model scenarios: exploring food and climate futures for Southeast Asia

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ABSTRACT

Decision-makers aiming to improve food security, livelihoods and resilience are faced with an uncertain future. To develop robust policies they need tools to explore the potential effects of uncertain climatic, socioeconomic, and environmental changes. Methods have been developed to use scenarios to present alternative futures to inform policy. Nevertheless, many of these can limit the possibility space with which decision-makers engage. This paper presents a participatory scenario process that maintains a large possibility space through the use of multiple factors and factor-states and a multi-model ensemble to create and quantify four regional scenarios for Southeast Asia. To do this we explain: (1) the process of multi-factor, multi-state building, done in a stakeholder workshop in Vietnam; (2) the scenario quantification and model results from GLOBIOM and IMPACT, two economic models; and (3) how the scenarios have already been applied to diverse policy processes in Cambodia, Laos, and Vietnam.

There is a need for reasoned argument, with oneself and with others, in dealing with conflicting claims, rather than for what can be called 'disengaged toleration', with the comfort of such a lazy resolution as: 'you are right in your community and I am right in mine'. Reasoning and impartial scrutiny are essential. However, even the most vigorous of critical examination can still leave conflicting and competing arguments that are not eliminated by impartial scrutiny… [However], the necessity of reasoning and scrutiny is not compromised in any way by the possibility that some competing priorities may survive despite the confrontation of reason. The plurality with which we will then end up will be the result of reasoning, not of abstention from it.

Amartya Sen, *The Idea of Justice*

6.1 Introduction

Policy-makers and planners in all sectors related to socioeconomic development, environmental change, and the water-food-energy nexus are faced with unprecedented challenges as they plan for a rapidly changing world.[1] The challenges of fundamental uncertainty and the impossibility of gaining full knowledge about system dynamics are compounded by human cognitive biases[2] and the diversity of world views and interests that exists among system actors.[3]

Forecasting a 'most likely' future and planning accordingly is often impossible and potentially dangerous in complex systems. Yet, decision-makers must respond to current pressures while also engaging with future uncertainty in a meaningful way to devise robust and flexible policies that will function in a variety of future contexts.[4,5] In response to these needs, new tools and methodologies have been developed, which incorporate an improved understanding of the decision-making process when faced with uncertainty. Such tools and methodologies can create a varied possibility space, where decision-makers can consider the potential effects of future stressors, such as climate change, socioeconomic development, environmental degradation, and political instability. The development and use of multiple scenarios is one approach to create this possibility space and apply it to planning.[6–9] Well-designed scenarios have the potential to combine many factors of change into comprehensible and integrated narratives.[10,11]

Many methods to develop and use scenarios to inform decision-making exist. The challenge is to ensure a highly diverse set of scenarios to supply decision-makers with a broad range of alternative futures in which to test policies.[11] This is challenging, as scenario development, even when involving diverse stakeholders, can be limited in scope. To create a broad possibility space, we must start with a broad range of perspectives, expertise, and opinions of how the future may unfold. To ensure this breadth is maintained, an extended group of stakeholders should be involved throughout the scenarios' development and use.[12] However, this diversity can threaten to overwhelm scenario development before it even starts. In order for

the scenarios to be applicable in models and useful to decision-makers, this diversity must be channeled into a manageable number of alternative futures.

Quantifying scenarios for use in models risks losing scenario richness, as models will need to streamline and summarize the scenario narrative.[13] Funneling scenarios through a single model especially risks reducing the range of possibilities in the quantification of the scenarios through a single interpretation of future stressors.[14] Despite this, models are powerful tools that allow quantitative ex-ante scenario analysis, a feature valued by decision-makers. Therefore, to maintain scenario diversity while providing valuable quantification, scenarios should be simulated across a multi-model ensemble.

This paper presents a participatory scenario development process conducted for Cambodia, Viet Nam, and Laos, which focuses on the exploration of a large scenario possibility space. We discuss the challenges and tradeoffs associated with creating and maintaining this possibility space through a case study. This case study presents how four regional socioeconomic scenarios were created in an interactive and inclusive scenario development process. We then describe how multiple models were used to quantify these scenarios and link them to the IPCC community's Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs).[15,16] Finally, we summarize the results of these quantified scenarios, and describe how they have guided policy and investment plans in Southeast Asia.

6.1.1 Case study: scenarios for policy development in Southeast Asia

In November 2013, in Ha Long, Viet Nam, 30 stakeholders from government agencies, NGOs, academia, the private sector, and the media, from Cambodia, Laos, and Viet Nam explored key regional drivers of change as part of a regional scenario building process. This process, one of 7 regional efforts led by the CGIAR Research Program on Climate Change, Agriculture, and Food Security (CCAFS),[7,17] was done in collaboration with the United Nations Environment Programme's World Conservation Monitoring Centre (UNEP WCMC). It had the objective of creating diverse, stakeholder-driven scenarios to test and develop regional policies and investment strategies on climate-resilient agriculture and food systems, while exploring potential environmental tradeoffs. Taking a regional approach allowed for the creation of a common framework that could be applied to different policy development processes at regional and national levels. The regional scale also served as an ideal bridge between the global and national perspective, and is often the most appropriate scale of analysis for transboundary environmental and development issues. The decision to focus the regional work on Cambodia, Laos, and Viet Nam was made for several reasons. Limiting participation to stakeholders from a few countries ensured there was a wide range of stakeholders representing each country, allowing for a robust and multi-disciplinary discussion. These three countries share extensive land borders, and have coordinated across boundaries in the past as a part of ASEAN and the Mekong River Commission. These past experiences facilitated conversations surrounding the creation of integrated regional scenarios. While key

regional actors like Thailand and China were not present, the role they play in the region was discussed in the development of the scenarios.

The scenarios were quantified in two spatially explicit partial-equilibrium global agricultural economic models and one high resolution land-use, land cover model, and linked to global socioeconomic and climate scenarios (SSPs/RCPs).[16,18] This linking to global scenarios was done with a focus on coherence, ensuring the scenarios were compatible with the global context, but sufficiently independent to target regional policy concerns.[19] The scenario outputs then provided valuable plausible futures with quantified results, which policy-makers used to weigh the costs and benefits of different policies and investment plans. To date these scenarios have been used in the 3 participating countries to inform an investment proposal process in Vietnam, to improve Cambodia's agricultural climate adaptation plan, and to inform Laos's social development program.

6.2 Methods

6.2.1 Definition of regional scenarios

The scenario development process started with pre-workshop interviews to prepare participants to consider factors of change and scenarios. The scenarios were then created following a five step process where participants (1) identified factors of change; (2) selected four primary factors of change based on uncertainty and relevance; (3) identified factor-states; (4) combined the factor-states into four diverse scenarios using the OLDFAR model; and (5) clarified the internal logic of the scenarios through scenario narratives and semi-quantification.

Step 1: identifying and clustering factors of change

To ensure inputs were drawn from all stakeholders and not only the most vocal, all participants were asked to pair up, and in five minutes list (on individual pieces of paper) factors of change affecting food security, rural livelihoods, and the environment. Participants repeated this exercise six times, each time with a different partner, ensuring a large number of factors were identified. All the factors were then collected and randomly redistributed to the participants. The participants were then asked to place all factors in a publicly visible space (e.g. stuck to a wall) and cluster similar factors. By the end of this step, the factors of change were aggregated transparently from nearly 150 to a more manageable 34.

Step 2: selecting and defining primary factors of change

Of these 34 factors, participants voted for their 3 most uncertain factors and their 3 most relevant factors as they pertain to food security, rural livelihoods, and the environment. This consensually narrowed the number of factors to four primary factors of change, while ensuring the factors maximized relevance and uncertainty for decision-makers.[20] The four primary factors identified were (1) Agricultural Investment, (2) Enforcement capacity and regional collaboration, (3) Land degradation through land-use change, and (4) Markets. Once the

primary factors were established, a consensus understanding of what each factor would encompass had to be documented. This was done in a plenary discussion where participants defined the primary factors, ensuring the factors represented key regional issues, without being focused on specific policies (e.g. five year economic plan, deforestation legislation, etc.) to encourage greater flexibility of use in scenario development. As a part of this process, the 30 remaining factors were clustered together as sub-factors under the most relevant primary factor ensuring all relevant issues were included in the scenario semi-quantification. Figure 6.1 summarizes the results of the factor voting, and the coloring of the text in the original figure reflects how the sub-factors of change were clustered within the four primary factors.

		Relevance								
Uncertainty	**Votes**	0	1	2	3	4	5	7	12	13
	0	Capacity, Environ. regulation, Overfishing, Waste Management, Industry	Ag. labor, Technology		Ag. changes, Pollution	Urbanization		Education	**Land degradation**	
	1	Knowledge, Floods		Econ. Growth			Deforestation			Improved Ag production
	2	Health, Mining, Inequality	Biodiversity				Strength of governance, Population		Ag. Land	
	3	Food Availability, Invest in Environment								
	4	Infrastructure, Migration	Disaster							
	5							**Ag. Investment**		
	7	**Regional Cooperation**								
	9	Water								
	10		Conflict							
	20							**Markets**		

Primary Factors of Change:
Agricultural Investment, Enforcement capacity and regional collaboration, Land degradation through Land-use change, Markets

Figure 6.1: Results of factor ranking and clustering.

Notes: Each workshop participant voted for their 3 most relevant and their 3 most uncertain factors. The four primary factors were chosen to maximize votes on both dimensions (lower right corner of the table). The coloring illustrates how all of the other factors were clustered as sub-factors of change within each of the four primary factors of change.

Step 3: identifying factor-states

Participants were separated into four groups (one for each factor) to identify plausible, "extreme", and mutually exclusive future states (e.g. low vs. high growth), for their respective factor. Extreme states were necessary to ensure the scenarios are significantly different from each other, as well as the present. When necessary more than two extreme states were allowed, as was the case for agricultural investment and markets, where three extreme states were identified. Table 6.1 summarizes the extreme states for each of the four primary factors of change.

Table 6.1: Southeast Asia primary factor-states

Agricultural investment	Enforcement capacity and regional collaboration	Land degradation through land-use change	Markets
1. High public and private investment	1. Strong enforcement and regional collaboration	1. Low degradation	1. Common regulated market
2. Unbalanced, high private investment only	2. Weak enforcement and regional collaboration	2. High degradation	2. Unregulated market
3. Low public and private investment			3. Protectionist and closed market

Step 4: combining the factor-states and creating scenario skeletons

A selection of one factor-state from each factor of change from table 6.1 produces a scenario skeleton, which can be represented by a numerical string. For example, a scenario with high private investment in agriculture, weak enforcement capacity and regional collaboration, high land degradation through land-use change, and unregulated markets would be represented by the string: (1, 2, 2, 2). Not all of the factor-states in table 6.1 are compatible with each other. To turn these skeletons into full scenarios, participants developed a compatibility matrix to determine factor-state compatibility, a standard method to examine the plausibility of factor-states through pairwise comparisons.[21–26] In these pairwise comparisons, the participants ranked the factor-state combinations as: (0) not possible; (1) uncertain/disagreement; or (2) possible. For example, participants were asked "is weak enforcement and regional collaboration compatible with a common and regulated regional market: 0. Not possible, 1. Maybe possible, 2. Definitely possible". These three grades allow for identifying compatibility between factor-states, without grading likelihood, something we wanted to avoid to ensure the scenarios provided a wide range of plausible futures.

Once the compatibility matrix was created, 21 of 36 scenario skeletons were still plausible. There are 5985 possible ways to choose a subset of 4 scenarios from these 21 plausible scenarios; however, not all of these subsets are equally diverse. The number of combinations was too large to do the selection manually; thus, it was decided to use OLDFAR to select a subset of six diverse scenarios. OLDFAR is an ideal tool for this task as it goes beyond the pairwise checks of a compatibility matrix or simple difference metrics (i.e. Euclidean or Manhattan distance between scenario strings), by using a robust optimization that maximizes diversity

through third- and fourth-order comparisons.[27] This ensured a wide possibility space across all of the potential 6 scenarios. Participants were then asked to vote for 4 of these 6 scenario skeletons to develop into complete scenarios. This transparent and democratic selection process helped build legitimacy and ownership of the final scenario set, and the result of this final scenario selection is summarized in table 6.2.

Table 6.2: Southeast Asian scenario skeletons

Scenario	Agricultural investment	Enforcement capacity and regional collaboration	Land degradation through land-use change	Markets
The Land of the Golden Mekong	High public and private investment	Strong enforcement and regional collaboration	Low degradation	Common regulated market
Buffalo, Buffalo	Unbalanced, high private investment only	Weak enforcement and regional collaboration	High degradation	Unregulated market
The Doreki Dragon	Unbalanced, high private investment only	Strong enforcement and regional collaboration	High degradation	Common regulated market
Tigers on a Train	Low public and private investment	Strong enforcement and regional collaboration	Low degradation	Protectionist and closed market

Step 5: building regional scenario narratives

In this step, participants clarified the internal logic of the scenarios through defining the scenario narratives and semi-quantification. The scenario skeletons (see table 6.2) provided the general framework for the narratives (table 6.3), with additional content derived from considering the sub-factors of change listed in figure 6.1. Participants developed diverse and coherent narratives, while exploring the interactions and combined effects of factors of change, a strength of this method.[10] Key to this narrative building was to first imagine what a future world defined by the selected extreme factor-states would be like, and then backcast (look backwards from the future) a series of events that would tie together this future to the present. This process defined the dynamics of change of the scenario, and ensured participants imagined novel and diverse futures, with their own challenges and opportunities, before connecting them to the present.[28]

Table 6.3: Scenario narrative summary

The Land of the Golden Mekong
Unification of Southeast Asia on political, economic and environmental issues gradually becomes a reality. Aging population and insufficient low-skill labor availability poses a challenge, leading to increasing migrant competition in the working class. This is a challenge for the region to manage increasing migration and urbanization. Ultimately, institutions, which are strong and inclusive, can manage the development process, leading to significant improvements in food security, livelihoods, and the environment. Climate resilience is therefore improved, although biophysical vulnerabilities remain, especially in the form of extreme events.
The Doreki Dragon
ASEAN facilitates the development of a regional market, which spurs the growth of big businesses across the region. The agriculture sector industrializes through the use of GMOs and other advanced technologies. However, through this process large producers dominate at the expense of small shareholder farmers, who become laborers on industrial farms, or are forced to the cities to find work. Rapid urbanization and industrialization leads to greater environmental degradation. This leads to a very unequal society, where food security is a major concern in the lower classes, and climate resilience is decreasing.
Buffalo, Buffalo; water flows uphill
Initially, ASEAN cooperation increases. However, by 2020 problems arise, with major corruption scandals weakening national governments. The private sector in response to energy and food prices starts to increasingly acquire land, putting pressure on smallholder farmers. Food production declines, leading to more migration and societal conflict. By 2050, unsustainable agricultural intensification has led to concentration of agricultural land, and a focus on processed foods. There are issues of inequality and access to food. Poor environmental management leads to deforestation and conflicts within ASEAN. Though attempts continue to be made to improve conditions across sectors, general environmental and socioeconomic situation of the region declines.
Tigers on a Train
Regional collaboration within Southeast Asia increases, but is coupled with increasing protectionism against outside economic influences. High food prices in the near future leads to targeted investments in agriculture, which spur the sector to industrialize with a focus on value added products. This focus on agriculture ebbs over time. Protectionist policies lead to tensions with China and by 2050, threatens to cripple the regional economy. Climate resilience and food security are threatened through increasing inequality, and a lack of investment in a sustainable agricultural development in the final decades of the scenario.

To develop scenarios that could be used and reused by various groups of decision-makers, it was necessary to discuss with participants (1) the role of decision-maker agency to ensure the scenarios contained strategic (within the control of the scenario end-user) and contextual (outside the end user's sphere of influence) elements;[11,29] and (2) the importance of avoiding purely utopian or dystopian scenarios.

A careful consideration of the role of control and context is critical. Completely strategic scenarios, focusing only on change within the control of decision-makers will fail to consider the effects of changes occurring outside their field of influence. At the other extreme, exclusively contextual scenarios may be too abstract, and advocate a purely adaptive approach to policy-making. Broadly, these regional scenarios skewed towards the strategic, as most of the factors of change were within the scope of control of some of the scenarios' intended users. However, this was balanced by including a few purely contextual elements such as climate change and global markets, which were simulated by the global models in which the scenarios were quantified. Additionally, as the intended scenario users are at the national and sector

levels (i.e. government ministries, donor groups, private sector groups, etc.), with limited control of issues outside their domain, this meant that the same scenario element that might be strategic for one group of scenario users could be considered contextual for other users.

Once completed, different scenarios can be considered more or less desirable. It is important, however, to avoid imagining "perfect" or "perfectly imperfect" futures to ensure the scenarios would be plausible and useful. Utopian futures fail to consider the downsides and unintended consequences of generally positive changes, such as the policy challenges of increasing expectations raised by societal improvements. Dystopian futures, on the other hand, fail to consider human agency, and the many ways in which people attempt to overcome challenges and identify new opportunities that may emerge. To avoid utopian/dystopian scenarios, participants were asked to consider the unique challenges and opportunities each future scenario would present policy-makers. For example, in 'The Land of the Golden Mekong', a generally optimistic scenario, potential challenges with demographic change and migration were explored, whereas in 'Buffalo, Buffalo', a more pessimistic scenario, included narrative elements describing attempts to mitigate the negative trends in the overall scenario (table 6.3).

Once the scenario narratives were established, participants provided semi-quantitative information for each of the sub-factors of change, by identifying the direction and magnitude of change at different times throughout the scenarios' time horizon. To ensure these decisions were well understood by the modeling teams, participants highlighted the logic behind these decisions as well as where there was uncertainty or disagreement amongst the participants.

6.2.3 Agricultural economic models

All models are simplifications of reality, and full predictability of complex systems like the earth's climate and the global economy over extended time periods is not feasible.[6,30–32] Quantifying the regional scenarios across a multi-model ensemble allowed for greater exploration of the possibility space around the regional scenarios, by highlighting potential uncertainties where the models disagree,[9] and providing a metric of robustness when in agreement. Nevertheless, agreement across an ensemble of models will not ensure the results are accurate,[33] and model results should still be treated as conditional projections as opposed to predictions, and serve to spur thought about the future.

Balancing the benefits and costs of quantifying scenarios across a multi-model ensemble is critical when the goal is to help inform decision-making. For this exercise, two economic models that had participated in the Agricultural Model Intercomparison and Improvement Project (AgMIP) were selected.[34,35] This facilitated issues of harmonizing scenario drivers across the models. The two economic models used were IIASA's Global Biosphere Management Model (GLOBIOM)[36] and IFPRI's International Model for Policy analysis of Agricultural Commodities and Trade (IMPACT).[37] Both models are global partial economic models focused on the agriculture sector, with significant levels of geographical disaggregation,

allowing the regional scenarios to be simulated within a global context. Table 6.4 summarizes features of these two models.

Both models assume low levels of commodity differentiation and perfect competition. The two models differ in how they link between global and regional agricultural markets. In IMPACT, country markets are linked directly to global markets with price markups that summarize trade policies and transportation costs, with national net-trade without bilateral dimensions. Commodity markets assume perfect price transmissions with prices determined by global supply and demand. GLOBIOM uses a spatial equilibrium approach of regional markets, where bilateral trade between regions is based on the cost competitiveness of homogenous goods, including transportation costs and trade policies and barriers.[38,39] This means that in GLOBIOM regional prices are more sensitive to changes in regional production and demand, whereas in IMPACT they are more sensitive to global price shocks due to changes in global production and demand.

Table 6.4: Comparing GLOBIOM and IMPACT

	GLOBIOM[36]	**IMPACT**[40]
Economic sector	Agriculture sector including crops, livestock, bioenergy, and forestry	Agriculture sector including crops, agricultural processing, and livestock
Time horizon	2000–2050/100	2005–2050
Role of markets	Regional markets linked through global markets determine supply and demand	Global markets determine supply and demand
Geography	Global representing 30 country/regions	Global representing 159 country/regions
Resolution of production side	Bottom-up approach at detailed grid-cell level (>10,000 worldwide) (4 crop production systems and 8 livestock production systems)	320 food production units (intersection of national and hydrological boundaries) (2 crop production systems and 8 livestock production systems)
Commodities	30 agricultural commodities (18 crops, 5 forest products, 7 livestock products, 9 bioenergy products)	62 agricultural commodities (39 crops, 6 livestock, 17 processed goods)
Environment	GHG accounting, irrigation water use, and endogenous land-use change	Hydrology, water basin management of irrigation water, exogenous and endogenous land-use change
Climate change	Represented by EPIC crop models	Represented by DSSAT crop models and linked hydrology models

The regional implications of climate change for agriculture are highly uncertain, and there are limited metrics to determine the best (most predictive) climate models.[33] Therefore, multiple models should be used to explore this uncertainty. Like the decision to select economic models, selecting climate scenarios must be tempered by time constraints in processing all of the climate data and running them through crop models for use in the economic models. To simplify this selection process, 4 GCMs (General Circulation Models), which were used previously by both economic models and available through the ISI-MIP project,[41–43] were

selected. Multiple RCPs (representative concentration pathways) can be used to explore the uncertainty of increasing CO_2 in the atmosphere and its radiative forcing on the environment within each GCM. However, with the projection period ending in 2050 the difference across the RCPs is less notable than through their extended projection to 2100 (figure 6.2). As the objective of the scenario process is to explore a large possibility space, it was decided to use the most extreme climate scenario RCP 8.5 and a constant 2000 climate (similar to RCP 2.6) to provide an envelope of possible climate change effects within the climate scenarios available from the IPCC's 5th Assessment Report.

In addition to the choice in GCMs and RCPs, the choice of crop model is important. Differences between crop models results can be larger than those coming from the economic models alone, as was found by Nelson and colleagues.[34] With such uncertainty, it was decided to use more than one crop model in this exercise. To explore this uncertainty each economic model used climate inputs from different crop models. GLOBIOM used EPIC (Environmental Policy Integrated Climate), originally developed by USDA.[44] IMPACT used DSSAT (Decision Support System for Agrotechnology Transfer), developed by the University of Florida.[45,46] To further expand the possibility space around climate change uncertainty, it was decided to run climate scenarios in DSSAT with 2000 levels of CO_2 fertilization, while EPIC simulated 2050 climate with additional CO_2 fertilization. Table 6.5 summarizes the global climate scenarios that were eventually combined with the regional scenarios in table 6.3.

It should be noted that in both models the final projected yields include economic feedbacks in addition to the biophysical effects modeled by the crop models. These economic effects simulate producers' response to changes in productivity and commodity markets, and include changes in crop allocation, and application of inputs (e.g. fertilizers) in response to changes in relative crop suitability and prices.[40,47]

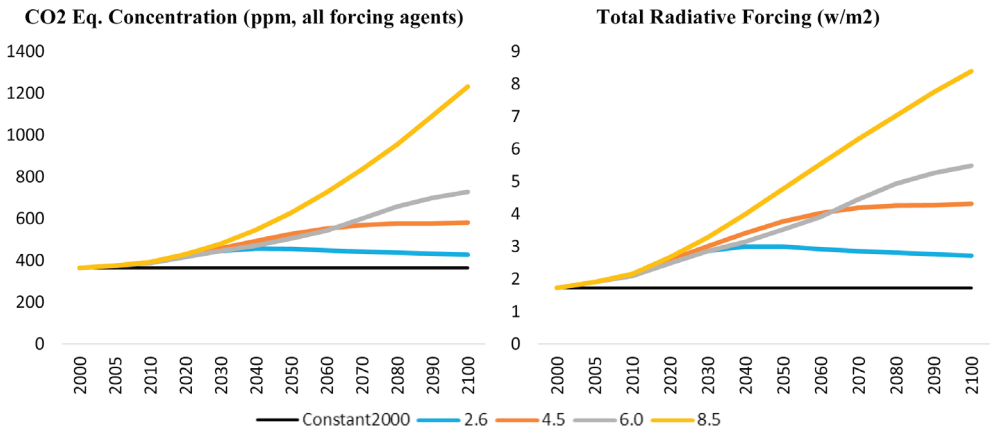

Figure 6.2: Comparing representative concentration pathways.

Notes: Data downloaded from the RCP Database version 2.0.5;[48] RCP 2.6:[49,50]; RCP 4.5:[51–53]; RCP 6.0:[54,55]; RCP 8.5:[56].

Table 6.5: Climate scenarios

RCP	GCMs	Crop model suite[a]	Crops[b]	CO_2 fertilization
8.5	GFDL-ESM2M, HadGEM2-ES, IPSL-CM5, MIROC-ESM	EPIC	Barley, dry beans, cassava, chickpea, maize, cotton, groundnut, millet, potato, rapeseed, rice, soybeans, sorghum, sugarcane, sunflower, sweet potato, and wheat	Additional CO_2 fertilization
		DSSAT	Groundnut, maize, potato, rice, sorghum, soybean, and wheat	CO_2 fertilization at current levels
Constant 2000 climate	Represented by each model's baseline assumptions without climate change			

Notes: all GCM climate data comes from CMIP and ISI-MIP[41–43] and are downscaled for use in the crop models. [a] The EPIC crop models are used by GLOBIOM, and the DSSAT crop models are used by IMPACT. [b] Crops represented in the economic models not covered by their respective crop model suite are mapped from the above crops based on biophysical similarities.

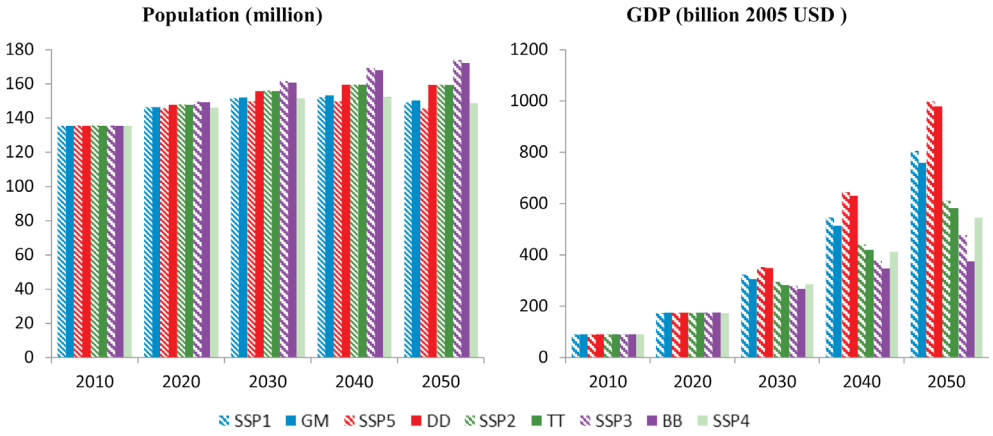

Figure 6.3: Southeast Asia population and GDP compared across the SSPs and regional scenarios.

Notes: The regional scenarios are clustered and colored according to which of the SSPs the regional scenario is most similar to. The regional scenarios are the Land of the Golden Mekong (**GM**), The Doreki Dragon (**DD**), Tigers on a Train (**TT**), and Buffalo, Buffalo (**BB**). *Source:* SSP population[57,58] and GDP[59] downloaded from the SSP database.[60]

6.2.4 Model inputs for each regional scenario

The regional scenarios were quantified following the consistency paradigm,[61] where the SSPs[15,16,18,62] served as boundary conditions.[63] This consistency is critical, as the regional workshops only provided semi-quantification for the region, and it was necessary for the two global economic models to have key drivers for the whole world. The regional scenarios provided different assumptions for gross domestic product (GDP), population, and production costs for farmers. Figure 6.3 gives an example of how the GDP and population trajectories of the regional scenarios compare to the regional values in the SSPs.[57–59]

The SSPs and regional scenarios contain similar narrative elements (table 6.3), which were used to ensure their compatibility with the regional scenarios.[18] For example, SSP1 (sustainability) is a future with increased regional coordination, rapid technological growth that allows for improved efforts on both mitigation and adaptation to climate change. The Golden Mekong (**GM**) scenario is an optimistic scenario where the region develops in a sustainable and coordinated way similar to SSP1. The population and GDP growth assumptions are similar, with population growing to around 150 million and GDP to over 750 billion USD by 2050—though this growth hides inequalities and tensions around migration in **GM** not featured in the SSP1 narrative. SSP2 is a middle of the road scenario, which is most similar to the Tigers on a Train (**TT**) scenario—although there are differences due to **TT**'s narrative, which focuses on a transition away from agriculture, combined with problems of protectionism. SSP3 is a more negative scenario with slower economic growth and fast global population growth, characterized by greater levels of conflict and fragmentation that stunts efforts to act collectively on climate change issues. This "fragmentation" scenario is most similar to the Buffalo, Buffalo (**BB**) scenario, where there is rapid population growth reaching over 170 million with a stagnant regional economy below 400 billion USD by 2050. SSP5 (conventional development) is a scenario of rapid but unsustainable economic growth, which is most similar to the Doreki Dragon (**DD**) scenario. SSP4 is a scenario that is represented by higher levels of inequality and the global scenario is not linked directly to any of the regional scenarios, however, it served as a useful guideline for all four regional scenarios which incorporate issues of inequality into their respective narratives. For this exercise, the quantification of the drivers for SSP2 were selected for the rest of the world. This scenario provides a middle of the road future, which allowed us to focus on the implications of the regional scenarios within the region rather than the effects of alternative global trends on development within the region. Nevertheless, in the future it may be of interest to combine the regional scenario with different global scenarios, and allow decision-makers to consider the implications of a changing world on the regional context (for more on the effects of SSPs on global agricultural production, demand, and trade as well as food security see Wiebe and colleagues[64] and Hasegawa and colleagues[65]).

The interaction between population and GDP (per capita GDP, figure 6.4) are critical for both economic models, serving as a proxy for average income, an important determinant of demand. All things equal, a scenario with high income levels will generally see higher levels of total demand, although per capita demand may begin to level off or even decrease for certain commodities as tastes and preferences change with increased affluence.[66–68]

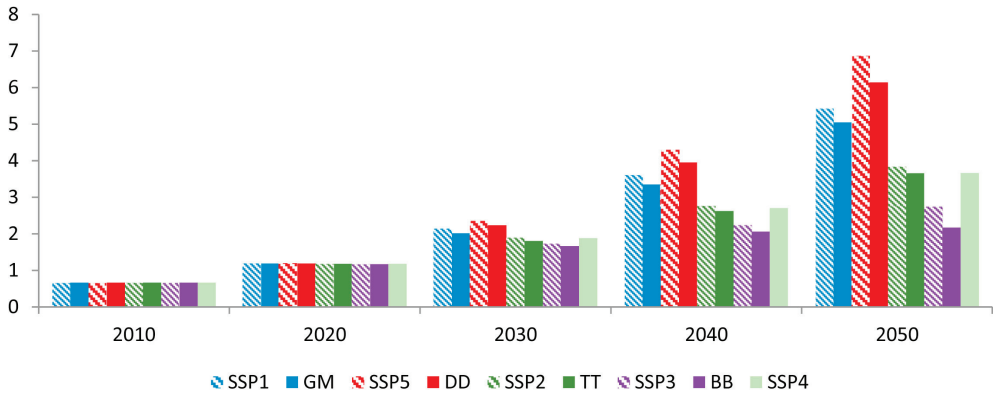

Figure 6.4: GDP per capita (000 real 2005 USD) for Southeast Asia.

Notes: The regional scenarios are clustered and colored according to which of the SSPs the regional scenario is most similar to. The regional scenarios are the Land of the Golden Mekong (**GM**), The Doreki Dragon (**DD**), Tigers on a Train (**TT**), and Buffalo, Buffalo (**BB**). *Source:* computed from population and GDP assumptions.

In general, the GDP per capita story follows the general trends described above, with the **GM** scenario similar to SSP1, **BB** to SSP3, **DD** between SSP5 and SSP1 (due to more optimistic population growth assumptions than SSP5), and **TT** similar to SSP2 and SSP4. The range of per capita GDP across these scenarios is significant. The more pessimistic **BB** scenario has a per capita GDP of just over $2000 by 2050 as compared to over $5000 and $6000 for the **GM** and **DD** scenarios, respectively. These differing economic growth assumptions have significant effects on demand, which will be seen in the following section.

Each of the regional scenarios has specific assumptions on the development of the agricultural sector in the region. These assumptions were developed at an aggregate commodity level, although different trends were specified by production systems (i.e. cash crops, high vs. low input, etc.). These aggregate trends were then fit around the baseline productivity trends of the two economic models, and were represented as percent deviations from each model's baseline. The original quantification focused on GLOBIOM's modeled commodities, with a mapping to IMPACT commodities based on economic and biophysical similarities (i.e. yams were given the same trend as sweet potatoes, and coffee from other high value cash crops). Figure 6.5 summarizes agriculture productivity changes for each scenario, as well as its potential effects on the domestic supply (excluding imports) of calories.

Figure 6.5 shows agricultural productivity is closely tied to assumptions on general economic development in the regional scenarios. The **GM** and **DD** scenarios, which were more optimistic with respect to per capita GDP growth (see figure 6.4), and increasing technological development show the highest levels of productivity increase (kilocalories/ha), with an assumed increase of calorie supply of nearly 40 percent over the projection period, compared to the more negative 20 to 30 percent assumed under the **BB** and **TT** scenarios. Figure 6.5 also suggests that agricultural productivity will be increasing over time across the four re-

gional scenarios. However, when we consider the varying assumptions on population growth we see significant differences with respect to the per capita domestic supply of calories, prior to any optimization inside the two models (including imports). If we examine the exogenous assumptions of population growth and the exogenous productivity developments together we see that in **BB** and **TT**, for example, the scenarios are similar in terms of productivity, but once population is considered they present different food security stories. High population growth combined with low agricultural productivity in **BB**, suggests a future where the region will become more dependent on imported food to maintain consumption levels, a troubling outcome in a future with stagnant income growth.

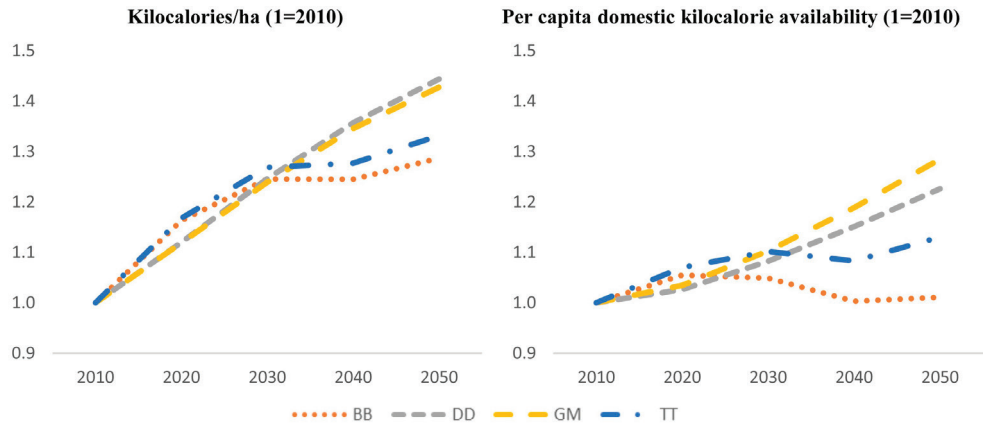

Figure 6.5: Total crop productivity across regional scenarios and implication on domestic food supply.

Notes: All values are indexed to 2010 values. The regional scenarios are the Land of the Golden Mekong (**GM**), The Doreki Dragon (**DD**), Tigers on a Train (**TT**), and Buffalo, Buffalo (**BB**).

Another critical driver of change in these scenarios is land-use change. Pressures to produce greater amounts of food can be met through a combination of both extensive and intensive strategies.[69] Land-use change was explicitly incorporated in the scenario narratives and semi-quantification, as a primary factor of change. To ensure both models represented this factor similarly it was decided to harmonize on GLOBIOM's land-use trends. GLOBIOM was chosen because it considers the major uses of land (e.g. cropland, pasture, forest, etc.), and can simulate the transition between these land-uses. Nevertheless, from previous modeling exercises we recognize that land-use itself is a major point of model uncertainty,[70] and in subsequent workshops the scenarios were extended to include LANDSHIFT to explore alternative futures of land-use change. Figure 6.6 summarizes the cropland-use assumptions used for the regional scenarios, and figure 6.7 presents the change in the share of the regional area in terms of the other major land-use categories.

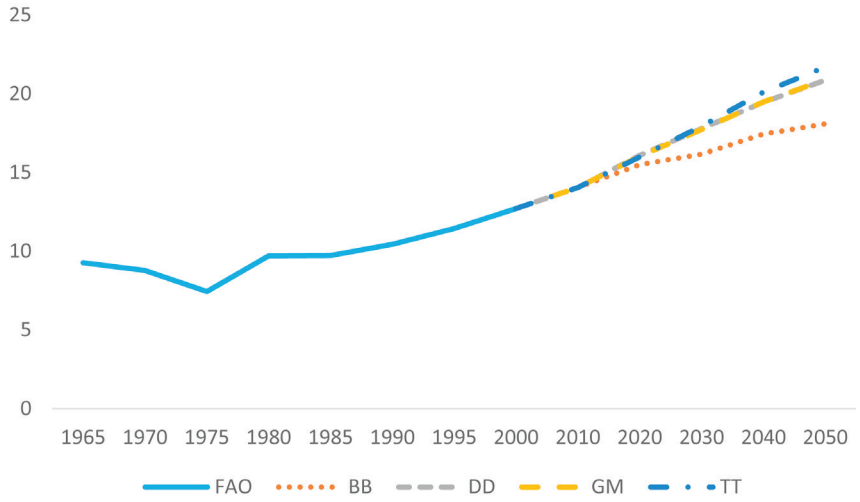

Figure 6.6: GLOBIOM cropland projections for Southeast Asia used by both models (million ha).

Notes: FAO data represents historical trends on land-used for agricultural purposes. The regional scenarios are the Land of the Golden Mekong (**GM**), The Doreki Dragon (**DD**), Tigers on a Train (**TT**), and Buffalo, Buffalo (**BB**). *Source:* FAO for historical trends;[71] future land-use projections from GLOBIOM.[36]

Cropland in the region has been increasing since the 1980s, and faced with increasing global commodity demand is projected to increase in all four of the regional scenarios (figure 6.6). Grassland, critical to livestock production is also projected to increase in all of the scenarios (figure 6.7). For all of the scenarios, the increased agricultural land (cropland and grassland) comes primarily from unmanaged forest and other natural land. While agricultural land-use is increasing in all of the scenarios, the magnitude of this increase varies.

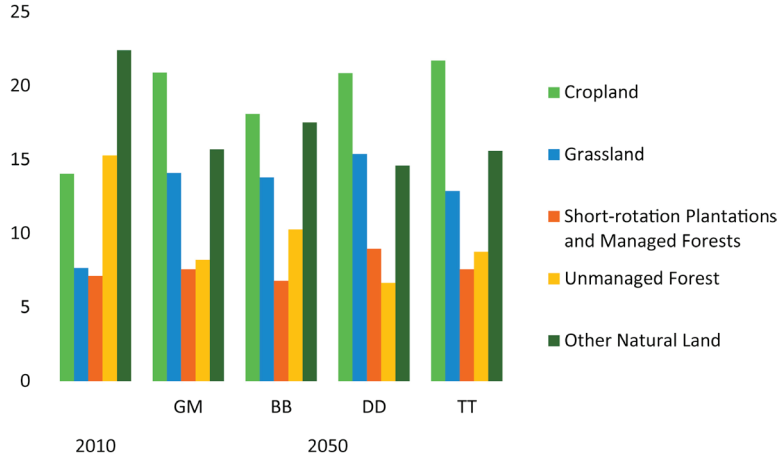

Figure 6.7: GLOBIOM projections of land-use change (million ha) by scenario.

Notes: Figure shows land-use in Southeast Asia in 2010 and 2050 under the 4 regional scenarios: the Land of the Golden Mekong (**GM**), The Doreki Dragon (**DD**), Tigers on a Train (**TT**), and Buffalo, Buffalo (**BB**). *Source:* GLOBIOM.[36]

The **DD** and **GM** scenarios see the largest increase in agricultural land, with an increase of 14.5 and 13.3 million hectares respectively. Both scenarios have high productivity assumptions, which increases the value of cropland, with both scenarios showing similar levels of cropland growth (49 percent by 2050). Greater income growth in the **DD** scenario increases regional demand for livestock products, which drives up the value of grasslands, and explains the additional 1.2 million hectares of grasslands in 2050 as compared to the **GM** scenario.

In both the **TT** and **BB** scenarios, slower income growth shifts consumption away from more expensive livestock products to staple crops. Lower demand for livestock products combined with lower productivity growth reduces the demand for additional grasslands in both of these scenarios. In the **TT** scenario, the region is still competitive in agricultural export markets despite slower productivity growth than in the **DD** and **GM** scenarios. To maintain production to meet domestic and export demands extensification is required, which drives demand for cropland area in 2050 to 21.7 million hectares (0.8 million hectares greater than **DD**). In the case of the **BB** scenario, the even lower productivity assumptions reduces regional agricultural competitiveness, which drives down demand for additional cropland (more than 2 million hectares less cropland in 2050 compared to the other 3 regional scenarios), as it becomes relatively cheaper to produce agricultural commodities in other regions.

6.3 Results

6.3.1 Model outputs

As the regional scenarios were fit around each model's global SSP2 baseline scenario, it is necessary to recognize the global context these baselines provide. This is true because the region is relatively small in terms of its share of global agricultural production and demand, with the exception of coffee, where Viet Nam is the world's second largest producer,[71] and rice, where Southeast Asia accounts for 25 percent of global production.[72] Thus, we will present each model's baseline alongside the model results for the regional scenarios.

In general, GLOBIOM shows larger increases in production over time than IMPACT in its baseline, as well as for all the regional scenarios. Nevertheless, in both models we observe increasing agricultural production across all of the scenarios. There is a clear outlier in the magnitude of this increase, as both models show lower growth in production in the **BB** scenario. This slower growth in agricultural production can be attributed not only to the lower assumptions on productivity growth (figure 6.5), but also on the smaller increase in cropland (figure 6.6). Among the remaining three regional scenarios, we see different pathways in achieving similar levels of total agricultural production in 2050. The **TT** scenario relies more on agricultural extensification, whereas higher productivity leads the way under the **DD** and **GM** scenarios. Figure 6.8 summarizes the consequences of the different productivity and land assumptions for the crop sector as a whole. There can be significant differences by

crop, which we will illustrate by comparing model results for rice, which was treated as a commercial crop by stakeholders, and sweet potatoes, which was treated as a staple crop.

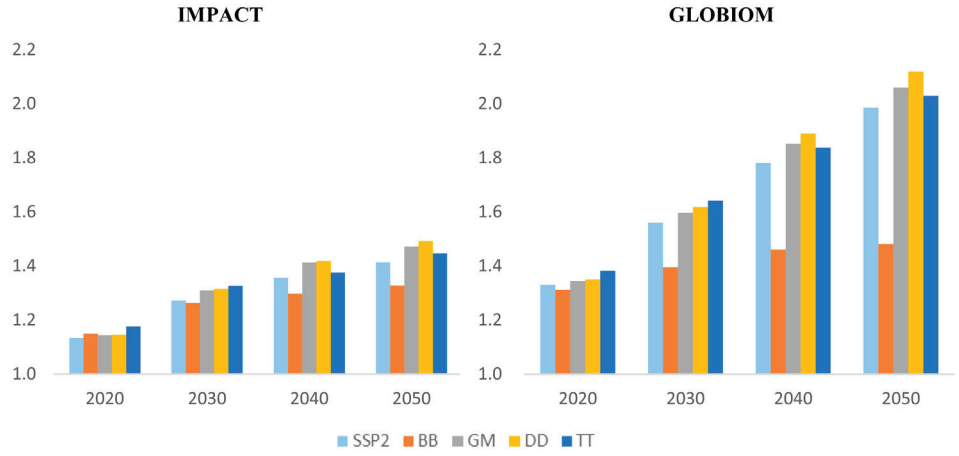

Figure 6.8: Total crop production (metric tons, indexed to 2010) across the scenarios.

Notes: Values are indexed to 2010. SSP2 shows the baseline scenario results for each model along with the 4 regional scenarios: the Land of the Golden Mekong (**GM**), The Doreki Dragon (**DD**), Tigers on a Train (**TT**), and Buffalo, Buffalo (**BB**).

6

6.3.2 Comparing rice and sweet potato yields

The baseline assumption (SSP2) for rice productivity across the two models is rather low with stagnant yield increases in IMPACT of under 10 percent by 2050 compared to over 20 percent in GLOBIOM, which reflects slow rice yield growth since the Green Revolution,[72] and significant additional investments in agricultural research and extension needed to rapidly close the regional rice yield gap.[73,74] The sweet potato baselines differ more across the economic models, with IMPACT showing yield growth of over 50 percent by 2050, more than double the yield growth assumed by GLOBIOM. This model uncertainty reflects significant yield fluctuations in the 1990s and 2000s.

Southeast Asia is a major rice exporter,[72,74] and as such it is more closely tied to global markets, leading to similar rice results in both economic models. Through 2030, rice yields increase across all of the scenarios. However, after 2030 rice yields diverge, with continued growth occurring under the **DD** and **GM** scenarios (increasing between 3–5% and 3–8% over the baseline for IMPACT and GLOBIOM respectively). The **TT** scenario sees a plateauing with final yields at similar levels as the baseline SSP2 scenario (1 percent and 2 percent lower yields compared to SSP2 for IMPACT and GLOBIOM respectively). The **BB** scenario is the most negative scenario with yield declines of 3 and 9 percent from the SSP2 baseline for IMPACT and GLOBIOM respectively. Sweet potatoes serve as a staple and emergency food crop in Southeast Asia,[75] and were therefore given a different treatment in the scenario semi-quantification. In contrast to rice, where the highest yields are in the **DD** scenario,

the highest sweet potato yields are in the **GM** scenario, which sees yields in 2050 about 13 percent higher than in the **DD** scenario. This difference is due to the role of agricultural industrialization in the **DD** scenario, which presents greater difficulties to smallholder farmers, the primary producer of sweet potatoes. Figure 6.9 summarizes the differing yield trends for IMPACT and GLOBIOM for both crops.



Figure 6.9: Comparing rice and sweet potato yields under a constant 2000 climate (indexed to 2010).

Notes: Values are indexed to 2010. SSP2 shows the baseline scenario results for each model along with the 4 regional scenarios: the Land of the Golden Mekong (**GM**), The Doreki Dragon (**DD**), Tigers on a Train (**TT**), and Buffalo, Buffalo (**BB**).

Model uncertainty is also evident in the effects of climate change, which are summarized in figure 6.10. In contrast to the baseline rice assumptions, the two models disagree on the potential effects of climate change on rice. In IMPACT, climate change has a negative effect, with 10 percent yield declines in 2050 compared to the constant 2000 climate scenario (CC2000). In GLOBIOM, climate change has a positive effect with yield increasing by about 10 percent. To put into context, this yield effect is similar in scale to the changes in yields observed in the **DD** scenario compared to the SSP2 scenario (figure 6.9). This suggests the role of CO_2 fertilization is a point of major uncertainty in the impact of climate change on rice yields. For sweet potatoes, both models agree climate change is likely to have a negative effect. However,

the models differ on the magnitude of the losses with yields declining by less than 5 percent in IMPACT compared to an average decline of 15 percent in GLOBIOM. This larger negative shock combined with low yield growth assumptions has GLOBIOM projecting 2050 sweet potato yields below 2010 levels in 3 of the 4 GCMs used. Such a negative shock would have a profound effect on sweet potato production in the region, with potentially large effects on temporal food security. These negative effects could offset some of the gains expected from broad regional development even in the more optimistic scenarios. The agreement across both models on the negative effects of climate change suggests policy-makers may want to consider targeted investments to help mitigate the effects of climate change on sweet potato farmers, either by improving varieties and management practices, or assisting them in moving to alternative crops better suited for future climates.

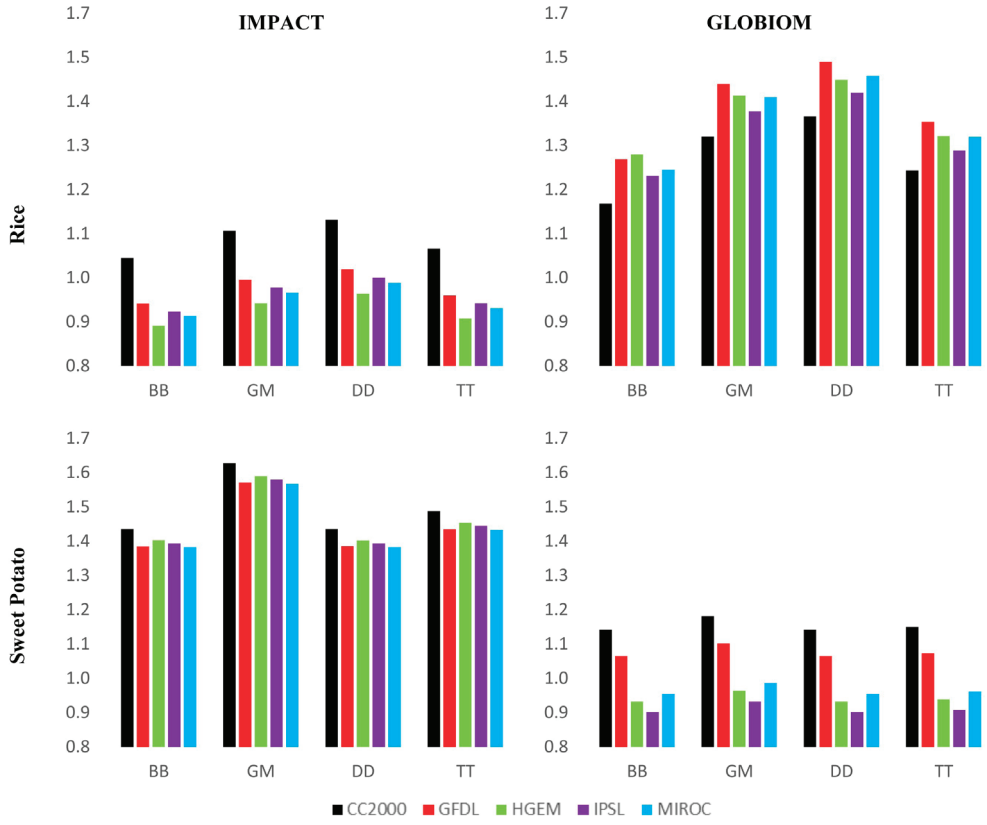

Figure 6.10: Comparing rice yields in 2050 with and without climate change (indexed to 2010).

Notes: Shows yields in 2050 indexed to 2010 across the four regional scenarios and four GCM climate scenarios represented by DSSAT with no additional CO_2 fertilization in IMPACT, and by EPIC with additional CO_2 fertilization in GLOBIOM. The four regional scenarios are the Land of the Golden Mekong (**GM**), The Doreki Dragon (**DD**), Tigers on a Train (**TT**), and Buffalo, Buffalo (**BB**).

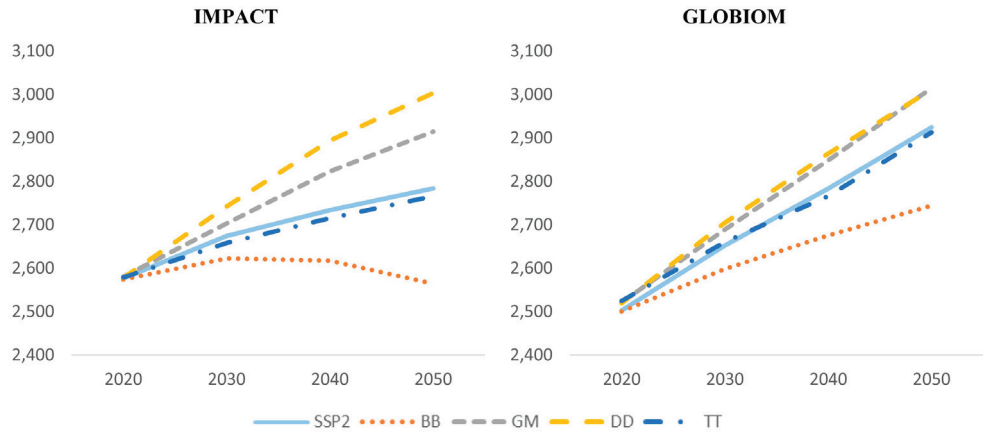

Figure 6.11: Regional kilocalorie availability (kcal per capita per day).

Notes: SSP2 shows the baseline scenario results for each model along with the 4 regional scenarios: the Land of the Golden Mekong (**GM**), The Doreki Dragon (**DD**), Tigers on a Train (**TT**), and Buffalo, Buffalo (**BB**).

6.3.3 Food security implications

Income is the biggest driver of changes in food demand and figure 6.11 illustrates this with the highest increase in kilocalorie availability by 2050 in the **GM** and **DD** scenarios. The **TT** scenario is similar to the baseline SSP2 scenario with respect to its per capita GDP trend, and the food availability in the region under this scenario is similar to the global SSP2 scenario, with steady improvement to around 2800 kcal/person/day in IMPACT and 2900 kcal/person/day in GLOBIOM. The **BB** scenario presents decision-makers with a challenging future with respect to regional food security. IMPACT suggests no gains in calorie availability in 2050 from 2010, with calorie availability under 2600 kcal/person/day. GLOBIOM projects some growth in calorie availability, but it is slower than under its baseline (8 percent less in 2050). It should be noted that while average calorie availability across the other three scenarios is increasing, the region could face issues with respect to economic access to food, as all the scenarios contain narrative elements involving inequality. Currently, both models simulate demand on a single representative consumer per country and cannot simulate the effects of income inequality and economic access to food. Future modeling efforts will be needed to explore this topic.

6.3.4 Using scenarios to inform decision-making in Southeast Asia

The regional scenarios were designed to provide a broad platform to inform diverse policies at various scales (e.g. regional, national, and sub-national). To date, the scenarios have been used in the region in several policy-making processes, showing the adaptability and reusability of these scenarios, a strength of this scenario approach.

The scenarios were first used to inform regional policies in Cambodia. Upon the conclusion of the first workshop in Viet Nam, the Cambodian Ministry of Agriculture, Forestry, and Fisheries (MAFF) expressed interest in embedding the scenarios in the development of their

Climate Change Priorities Action Plan (CCPAP). This was done to set policy priorities to better target the CCPAP's projected 164 million USD budget, and build institutional capacity to use scenarios. Over the course of 6–8 months and in collaboration with one of this paper's authors, the scenarios were used in workshops with donors and implementing partners to help develop the CCPAP. The scenarios stimulated discussions around the challenges presented by climate change and economic development. They highlighted the need for more holistic national policies to achieve climate-smart food systems, an overall objective of the CCPAP. This conclusion led to the inclusion of additional scenario work as a cross-cutting activity in the finalized CCPAP.[76]

As this work moved forward in Cambodia, parallel efforts went ahead in Viet Nam. In collaboration with the United Nation's Food and Agriculture Organization (FAO), a workshop was held in Viet Nam in May 2014, with stakeholders from government agencies, research institutions like the Northern Mountainous Agriculture and Forestry Science Institute, the private sector, and civil society. The objective of the workshop was to use the regional scenarios to help review and revise climate-smart agriculture investments for Northern Vietnam. The stakeholders considered the potential efficacy of the different investment proposals under alternative futures. They explored the potential challenges and complex interactions between the many dimensions of the scenarios. The insights gained from this thought exercise were then integrated into improved versions of the proposals, which have since been taken into further stages of development.

In a third policy engagement process, a regional workshop, organized by CCAFS and UNEP WCMC, extended the scenarios to evaluate and improve national policies in Cambodia, Laos, and Viet Nam. In this workshop, which brought together a new group of national stakeholders, there were parallel objectives to review policies for each country using the regional scenarios. For the Cambodian stakeholders the objective was to review the finalized CCPAP, and devise a plan for its implementation. For the Laotian stakeholders the objective was to evaluate the strengths and weaknesses in their government's economic development plan. For the Vietnamese stakeholders the objective was to review their government's agriculture development policy and develop plans for its implementation. At the forefront of these policy discussions were environmental tradeoffs with respect to agricultural and economic objectives. To better reflect these potential tradeoffs the scenario quantification and analysis was extended to include LANDSHIFT.[77] LANDSHIFT is a spatially explicit land-use model that operates at a higher resolution than GLOBIOM and IMPACT, and was used to spatially project land-use and land-cover changes due to IMPACT's own cropland assumptions (see appendix 6.1 for more details). This also allowed for estimation of changes to biodiversity and ecosystem services,[78] supplementing GLOBIOM's land-use results, and to explore the uncertainty around land-use change assumptions. The scenario discussions in this workshop, similar to other regional experiences engaging with the scenarios, left stakeholders with a greater appreciation and awareness of uncertainty and the need to embed more holistic

approaches to policy-making and planning. In the words of one of the stakeholders, "the scenarios make us look at other aspects and elements" in forming policies that are "more realistic and inclusive".[79]

In this third policy engagement, a survey was done to identify the stakeholder's policy priorities. 67 priorities were identified by the stakeholders, of which 52 could be addressed through the full set of scenario outputs (see appendix 6.1 for the full list of priorities and scenario coverage). The models individually could address between 20 and 40 percent of the policy priorities. There was significant overlap across the models by design, nevertheless, when combined they could address more than 43 percent of the policy priorities. The scenario development process was designed to allow for further extension of the scenarios as needed, and the range of coverage (75 percent of priorities) from the full semi-quantified factor set should allow for straightforward extension of the scenarios to more models. This feature of the development process was put to effect with the extension of the scenarios using LANDSHIFT. The breadth of coverage of the regional scenarios would have been difficult to achieve under a more traditional scenario set that incorporated fewer factors of change and only one model. The stakeholders themselves identified the value of this multidimensional approach, and declared the resulting scenarios superior to previous scenarios created in the region, which were less broad and inclusive. The fact these scenarios have resonated with regional stakeholders, over time, and across many different uses, suggests these scenarios will remain relevant into the future.

6.4 Discussion

The successful application of the regional scenarios to different policy engagement processes argues for the value of a multi-factor, multi-state, multi-model approach to scenario development. The larger policy guidance process must generally allow for a reinvention and reinterpretation of the scenarios, based on the needs and scope of any specific process, ensuring a good fit between the scenarios and the plans they are informing.[7]

Developing and quantifying scenarios in models can take significant time, which can make customizing model representation for every policy question costly. If, however, the scenarios are designed in a broad and multidimensional fashion as they were in Southeast Asia, they can be relevant for a range of policy uses, only needing minor elaboration and reinterpretation.

The approach used in this study presents a powerful methodology that allows for a systematic way of organizing and relating factors and factor-states in developing diverse multidimensional scenarios. It facilitated consensus building in the scenario development process, by incorporating additional elements through the use of sub-factors of change. It also spurred a conversation with decision-makers' around their power to affect change versus responding to it, by incorporating contextual and strategic elements in the scenarios. Consequently, this

approach allowed for more aspects to be analyzed than would be possible under a traditional two-axes approach, which has allowed the scenarios to be applicable to a wide array of policy questions, many of which have arisen after the scenarios have been quantified. The large overlap between the subsequent policy engagements and the original scenario scope has shown them to be adaptable to the needs of a wider public than the original workshop participants in Ha Long.

Models are essential for quantitative interpretation of complex scenarios. However, the use of any particular model can greatly simplify the rich narrative of a scenario. Using models can threaten to confuse the purpose of the scenario development process, from developing rich and plausible futures to parameterizing a model, which would be a sub-optimal use of all of stakeholder expertise.[12] Nevertheless, the quantitative model outputs can complement the knowledge gained from qualitative discursive analyses, illustrating magnitudes of change as well as connecting a broad array of stressors simultaneously and consistently to assess their cumulative effects and expose important interactions and tradeoffs. Tensions between the two forms of representation can highlight and allow the exploration of different worldviews (e.g. participants were encouraged to question land-use-change maps based on their understanding of the multidimensional qualitative narratives). This can help decision-makers to develop a deeper understanding of the uncertainties they face.[9]

Quantifying scenarios with a multi-model ensemble as was done in this exercise has many advantages. It encourages participants to consider a broader range of possibilities, and allows for more scenario richness to be captured, which stakeholders identified as a strength of this approach. Nevertheless, making sure multiple models consistently represent the scenarios is time intensive, and requires extensive collaboration across modeling groups. This collaboration in scenario quantification can be facilitated by having the modelers present at the scenario conception, which embeds knowledge of the background discussions that led to the scenario creation in the modeling efforts. This participation carries the risk of distracting stakeholders from scenario building, but when managed properly provides opportunities to explain the models' strengths and weaknesses, which helps manage future expectations.

The costs of adding additional models can be significant. Harmonizing scenario inputs is not straightforward even among similar models, and additional models must be explained to decision-makers to ensure they understand the uncertainty each model highlights. Nevertheless, using multiple models with different assumptions and areas of focus means a broader range of scenario results can emerge that may be suitable to more policy uses. For instance, the IMPACT model's country-level results were useful for the (sub-)national investment plans in Viet Nam, and were more compatible with LANDSHIFT; GLOBIOM's stronger spatial focus and information on multiple sectors for land-use supported priority setting in Cambodia's CCPAP. As such, we believe the benefits outweigh the costs, and a multi-model

ensemble can broaden the possibility space, while highlighting points of greater uncertainty, facilitating a conversation around the scenarios and their implications.

The evaluation of potential environmental impacts of socioeconomic development globally and regionally are often expressed as simple growth rates (or rates of loss) based on changes across a few factors or drivers, such as agricultural expansion, or population growth. The multi-factor, multi-state and multi-model approach presented here allows for the exploration of complex tradeoffs between agriculture and the environment under a range of socio-economic and climatic change assumptions that would be more constrained under more traditional scenario processes. The exploration of these tradeoffs and potential unintended consequences is critical to improving decision-making related to food security and climate change.

Despite our efforts, many elements of the stakeholder-generated qualitative scenarios were not captured by the models, or have been represented in a simplified way (e.g. story elements around governance and coordination, transparency and corruption, conflict, community-level resilience, etc.). For this reason, the model results were treated not as the final results of the scenario process, but as part of an overall scenario conversation. In communicating model results, the gaps in the model's scenario representation were explained to help build the capacity of decision-makers to comprehend multidimensional uncertainties, the overall objective of this regional scenario process. We believe that approaches similar to the one presented here could contribute to better policy-making by increasing the dimensions of uncertainty included in the scenarios used by policy-makers to systematically test the robustness and efficacy of future policies.

Author contributions

DMD, JV, and AP wrote the paper. DMD, JV, and AP quantified scenarios for the models. DMD, AP, SI, and PH analyzed scenario results. JV and RP coordinated regional engagement. JV, AP, SI, SL, AH, RP, MS, MV, AvS, AnA, BS, AsA, and LL assisted in scenario development and semi-quantification. All authors were involved with research design. A special thanks to SI, AP, JV, SL, AH, MS, AvS, and BS for helping with editing of the paper.

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Data sharing

GLOBIOM and IMPACT 3 are described in some detail in the paper. Full documentation for both models is available online.

- GLOBIOM (Havlik et al., 2014): www.pnas.org/content/suppl/2014/02/19/1308044111.DCSupplemental
- IMPACT 3 (Robinson et al., 2015): https://hdl.handle.net/10568/150391

OLDFAR is available upon request in English and Spanish for Windows (32 and 64 bit), MacOS, and Linux.

A description of the LANDSHIFT model is provided in Appendix 6.1.

Supplementary data related to this article can be found at https://doi.org/10.1016/j.envsoft.2016.05.008.

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7

Modelling for EAT-Lancet to assess potential environmental and socioeconomic consequences of a food systems transformation

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At the far end of town where the Grickle-grass grows
and the wind smells slow-and-sour when it blows
and no birds ever sing excepting old crows…
is the Street of the Lifted Lorax.

And deep in the Grickle-grass, some people say,
if you look deep enough you can still see, today,
where the Lorax once stood just as long as it could
before somebody lifted the Lorax away.

What was the Lorax? And why was it there?
And why was it lifted and taken somewhere
from the far end of town where the Grickle-grass grows?
The old Once-ler still lives here.

Ask him, he knows.

Dr. Seuss, *The Lorax*

I want to tell what the forests were like
I will have to speak in a forgotten language

W.S. Merwin, *Witness*

7.1 Assessing potential environmental and socioeconomic consequences of a food systems transformation

To explore how food systems could become more aligned with health, environmental, and justice objectives, the potential consequences of their restructuring by dietary change, increased productivity, and reduced food loss and waste (FLW) should be assessed. We use two complementary modelling approaches for this purpose.

First, we assembled a multimodel ensemble of ten global economic models used in high-level assessments of climate change, land use, and food security,[1–6] and involved in the Agricultural Model Intercomparison and Improvement Project.[6–8] This ensemble includes a mix of partial equilibrium models (focusing on the agricultural sector only), with more detailed biophysical and sectoral representation, and general equilibrium models (of the whole economy), which can simulate interactions across non-agricultural sectors (e.g., energy). All simulate important system dynamics that would drive changes across a transforming food system, such as the ability of producers to substitute inputs based on their availability and cost.

Second, we used the Global Input–Output module of the Dietary Impact Assessment model (DIA-GIO), an updated version of the static input–output food model developed for the 2019 EAT–Lancet Commission (Appendix 7.1 pp 30–32).[9] We used this model to improve our comparability with the modelling methods used in the 2019 Commission, recognising that economic systems might lack the capacity to adapt to rapid, large-scale changes. For example, delays to a food systems transformation would constrain the scope of food systems to adapt, hindering the possibility of efficiently reallocating resources across alternate uses, such as energy or fibre production. We therefore used DIA-GIO to assess a food system transformation without economic feedbacks, based on current and projected supply, demand, and trade relationships. Using DIA-GIO allowed us to consider the implications of a more constrained food system with more limited adaptation capacity than that suggested by the economic models.

The ways in which food systems can transform are not certain; as such, we used a range of models and modelling approaches to allow us to engage with this uncertainty. Here, we report ensemble median values and, where appropriate, full ensemble ranges (i.e., minimum and maximum values), and compare these results to DIA-GIO. More detailed documentation on the models and modelling approaches applied in our analysis are provided in Appendix 7.1 (pp 20–32).

7.1.1 Defining alternative future food systems

In addition to updating and extending the modelling suite, our analysis has updated the scenario framework used to assess global and regional changes across food systems. We constructed three core scenarios described in this section (Appendix 7.1 pp 6–7).

The business-as-usual (**BAU**) scenario projects how food systems could look by 2050 assuming a continuation of current trends and policies. This scenario assumes population and economic growth based on the Shared Socioeconomic Pathways' middle-of-the-road scenario (SSP2), a scenario framework designed for the IPCC to model the consequences of climate change in the 21st century.[10–13] This scenario projects a global population growth of 23% to 9.6 billion people, and gross domestic product (GDP) growth of 127% to $282 trillion, between 2020 and 2050 (Appendix 7.1 pp 14–16).[14–16] To simulate the consequences of climate change in the **BAU**, we applied a representative concentration pathway (RCP 7.0) that assumes minimal mitigation efforts and temperature increases of around 2°C by 2050. The biophysical consequences of this future climate were represented with the use of published estimated changes in crop yields,[17] livestock yields,[18] and agricultural labour productivity.[19] Following model parameterisation in the 2019 EAT–Lancet Commission,[9] DIA-GIO and **BAU** projections to 2050 were informed by projections from the International Model for Policy Analysis of Agricultural Commodities and Trade,[20] one of the participating global economic models.

Starting in 2020, the EAT–Lancet food systems transformation scenario deviates from the **BAU** scenario in three key dimensions. In the EAT–Lancet scenario, we assume that by 2050: (1) healthy diets will be adopted by all; (2) a 7–10% increase on top of global BAU agricultural productivity occurs, based on projections quantified as part of previous model intercomparisons[6,21] for SSP1,[6,21] a more sustainable shared socioeconomic pathway (Appendix 7.1 p 16); and (3) food loss and waste in the BAU scenario is halved, consistent with Sustainable Development Goal 12.3. A final scenario, EAT–Lancet Mitigation (**ELM**), combines the EAT–Lancet scenario with ambitious mitigation, recognising that a shift to more sustainable food systems would be implausible without a wider societal transition towards greater sustainability.[3,6] Ambitious mitigation was based on previous modelling efforts to assess determinants of land use across SSP projections[6] and evaluate land-use policies and decarbonisation pathways to limit warming to 1.5°C by the end of the century.[3,6] Ambitious mitigation includes a range of policies (e.g., emissions pricing and land-use regulations) that define market conditions that determine the technologies and practices adopted to maintain carbon budgets, such as afforestation, renewable energy, and bioenergy (see Appendix 7.1 pp 8–13 and 28–29 for details on model specifications of ambitious mitigation). This scenario allowed us to assess potential synergies and trade-offs between a food systems transformation and ambitious economy-wide mitigation efforts, particularly through potential competition for land use. Although mitigation efforts would be expected to reduce climate impacts by the end of the 21st century, we use the climate impacts of the BAU (i.e., RCP 7.0) in the EAT–Lancet Mitigation scenario and recognise the uncertainty of these efforts translating to reductions in climate impacts by 2050.

We emphasise that these scenarios only aim to explore endpoints of a food systems transformation, and do not explore possible pathways that could lead to these outcomes by 2050. Assessing the implication of these endpoints is an important first step in understanding the potential benefits and costs of the changes simulated in these scenarios. Future work is needed to explore the pathways of change under varying assumptions of global development.

7.1.2 Comparing alternative food systems projections across modelling approaches

Across the model ensemble, the BAU scenario shows a 37% increase in global agricultural production by 2050 compared with 2020 (Figure 7.1A). Livestock production increases by around 33%, and crops by 37%. All regions see increased overall agricultural production by 2050 compared with 2020 values, with the largest increases in sub-Saharan Africa (around 100%) and the smallest increases in China (11% for the model ensemble and 18% for DIAGIO) and Europe (18% for the model ensemble and 16% for DIA-GIO; Figure 7.1B).

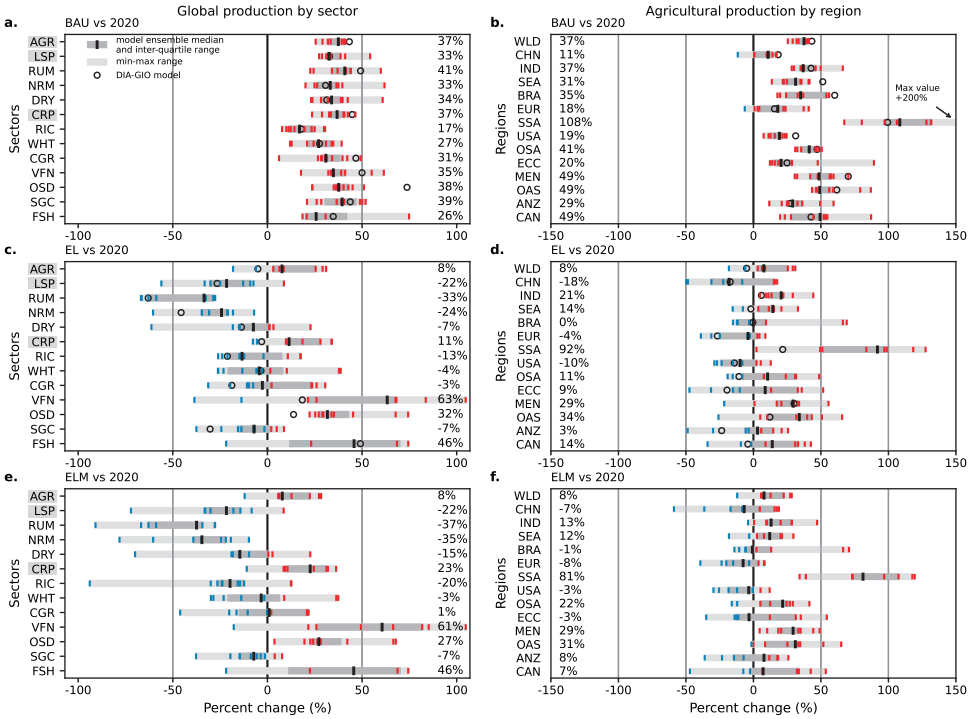

Figure 7.1: Projecting 2050 agricultural production by sector and region.

Notes: (A) Global production by sector for the BAU scenario versus 2020. (B) Agricultural production by region for the BAU scenario versus 2020. (C) Global production by sector for the EAT–Lancet scenario versus 2020. (D) Agricultural production by region for the EAT–Lancet scenario versus 2020. (E) Global production by sector for the ELM scenario versus 2020. (F) Agricultural production by region for the ELM scenario versus 2020. All scenario results are reported as the percentage change between 2050 and 2020. Individual model results in the ensemble are given by vertical lines within the grey shaded range (dark grey areas are IQRs; light grey areas are minimum and maximum ranges). Black vertical lines indicate median values, which are also expressed numerically in each figure. Results are coloured blue for a percentage decrease and red for a percentage increase. The DIA-GIO model results are given by the unfilled black circle and only include BAU and EAT–Lancet scenarios. Sectors are grouped by crop and livestock commodities. Aggregate sectors (i.e., AGR, LSP, and CRP) are highlighted in light grey. Regions are ordered in terms of size of total agricultural production in 2020 based on data from the Food and Agriculture Organization of the UN.[22]

BAU=business as usual. DIA-GIO=Global Input–Output module of the Dietary Impact Assessment model. AGR=all agricultural products (excluding FSH). CGR=coarse grains. CRP=all crops. DRY=dairy. FSH=fisheries and aquaculture. LSP=all livestock products (excluding FSH). NRM=non-ruminant meat products (i.e., poultry, pork, and eggs). OSD=oilseeds. RIC=rice. RUM=ruminant meat. SGC=sugar crops. VFN=vegetables, fruits, and nuts (and legumes). WHT=wheat. ANZ=Australia and New Zealand. BRA=Brazil. CAN=Canada. CHN=China. ECC=Eastern Europe, Caucasus, and central Asia. EUR=Europe. IND=India. MEN=Middle East and north Africa. OAS=other Asia. OSA=other South and central America. SEA=southeast Asia. SSA=sub-Saharan Africa. WLD=world.

Model results suggest that by 2050, the combined effects in an **EAT–Lancet** scenario could result in total agricultural production levels that are close to those reported in 2020, but with important changes in the composition of production (Figure 7.1C). Compared with 2020, livestock production in this scenario declines by 22% (27% for DIA-GIO), which leads to a substantial reduction in the demand for and production of animal feed crops compared with BAU 2050. Although the models agree on the direction of change (i.e., declining crop production compared with the **BAU** scenario), the magnitude of this reduction varies; some models suggest crop production levels in 2050 would be higher than those in 2020, whereas others suggest 2050 levels would be slightly lower.

A sectoral analysis of the **EAT–Lancet** scenario shows that the largest declines are in ruminant production (i.e., cattle, goats, and sheep), with a 55% reduction (75% for DIA-GIO) compared with 2050 levels in the BAU scenario, or a 33% decline (63% for DIA-GIO) compared with 2020 levels across the ensemble (Figure 7.1C; Appendix 7.1 p 37). This reduction is accompanied by a decline in global ruminant animal numbers of 26% (i.e., a result reported by the IMPACT and GLOBIOM models). Non-ruminant production had a smaller decline of 24% (a –46% change in DIA-GIO), with larger declines for pork (a –48% change based on three ensemble models reporting, and a –83% change in DIA-GIO) than poultry production (a –14% change for both DIA-GIO and the mean of two reporting ensemble models; Appendix 7.1 p 37). The economic models generally show smaller declines in agricultural production compared with the DIA-GIO model, as other sectors (e.g., pet food and industrial sectors) increase their demand for animal-based and plant-based products (Appendix 7.1 p 43). Livestock demand for animal feeds declines in the **EAT–Lancet** scenario (–3%) from around 2.5 billion tonnes in 2020, to 2.4 billion tonnes by 2050. This reduction is especially notable compared with the **BAU** scenario, which predicts a 39% increase in feed production (to around 3.5 billion tonnes).

Changes in cereal production between ensemble models are varied, but the median results show modest production declines in rice (–13%), wheat (–4%), and coarse grains (i.e., all other grains; –3%). Across the models, sugar crop production also declines compared with 2020 levels (–7% for ensemble and –30% for DIA-GIO).

The modelling approaches described here differ in their projections of production for vegetables, fruits, nuts and seeds, and legumes, primarily due to different commodity aggregations methods (VFN in Figure 7.1). When we disaggregate these foods, we see much greater agreement between the ensemble and DIA-GIO, with vegetable production increasing by 42% (48% for DIA-GIO), fruit by 61% (36% for DIA-GIO), nuts by 172% (155% for DIA-GIO), and legumes by 187% (56% for DIA-GIO), with roots and tubers declining by 9% (–42% for DIA-GIO). The large variance in projected legume production can be attributed to ensemble models reporting soybeans (which account for the bulk of legume production) as oilseeds rather than as legumes, highlighting differences in how different disciplines (i.e., nutrition

vs agricultural economics) analyse food production and consumption. When we combine oilseeds and legumes across the ensemble, the median production by 2050 is 1.07 billion tonnes for the **EAT–Lancet** scenario across the model ensemble, compared with 1.08 billion for DIA-GIO.

If we consider a scenario with only increased productivity, the median projection for production across the ensemble is similar to the **BAU** scenario (39% for the ensemble vs 37% for **BAU**); however, the range of model projections is somewhat higher in the ensemble than in the **BAU** scenario (31–53% for the ensemble vs 25–41% for the **BAU** scenario; Appendix 7.1 p 39). The use of global economic models highlights that, in isolation (and without dedicated policies), efficiency gains might not translate to lower overall production and could even increase it. Reducing FLW in isolation leads to a smaller increase in production of 30% (17% for DIA-GIO); similarly, dietary change on its own leads to only a 17% increase (18% for DIA-GIO) in agricultural production compared with 2020 levels (Appendix 7.1 p 39). Reducing FLW achieves this smaller increase by shrinking the gap between what is consumed and what is purchased, signalling a need for less production to meet demand. A transition to healthier diets avoids overconsumption and reduces the demand for more resource-intensive, animal-sourced foods and animal feed.

Across livestock sectors, the **ELM** scenario shows larger declines in production compared with the **EAT–Lancet** scenario (Figure 7.1E). Ruminant production in the **ELM** scenario declined by 37% (compared with 33% in the **EAT–Lancet** scenario); non-ruminant production by 35% (compared with 24%); and dairy production by 15% (compared with 7%). These larger reductions are the consequence of increased production costs from the pricing of emissions. However, **ELM** has slightly larger increases in crop production compared with the **EAT–Lancet** scenario, due to increased demand for crops from a growing bioeconomy (e.g., for biofuels, biomass, and bioplastics) to facilitate a transition away from fossil fuels (Figure 7.1E; Appendix 7.1 p 43).

7.1.3 Exploring the biophysical option space of a food systems transformation

We estimated the consequences of an EAT–Lancet food systems transformation on the Earth system. Where possible, we align the control variables with the food system boundaries defined in Section 3 of Rockström et al.[23] (i.e., land, GHG, and blue water). However, where models cannot currently report against these variables (i.e., for nitrogen surplus and phosphorus loss) we have used the control variables of nitrogen use and phosphorus use from the 2019 Commission as proxy indicators[24].

Our modelling results show that in the **BAU** scenario, the environmental impact of agricultural production is projected to increase by 2050 compared with 2020 levels. Agricultural production already exceeds the food systems' share of multiple planetary boundaries, with animal products being responsible for the majority of emissions, and grains for the majority of nitrogen, phosphorous, and water use (figure 7.2A). Agricultural emissions are expected to rise by 33% (20–50% for model range; 51% for DIA-GIO), primarily driven by a 22% (18–25% for model range) increase in ruminant animal numbers. The model ensemble projects agricultural crop yields to increase by 24% (17–46% for model range), which will slow—but not prevent—agricultural land expansion, which increases by 4% (1–7% for model range; 16% for DIA-GIO), or approximately 200 Mha, with cropland expanding by 10% (4–25% for model range). Model results show uncertainty around the potential of water-use efficiency gains and future irrigated area extent, with a median increase of blue water use of 13% by 2050, but with some models suggesting water use could decline (–10% to 43% for ensemble; 1% for DIA-GIO). By 2050, nitrogen application increases by 41% (22–55% for model range; 31% for DIA-GIO) compared with 2020 levels, and phosphorous application by 41% (36–46% for model range; 26% for DIA-GIO). This increase suggests that under a **BAU** future, food systems could exceed the resource-use boundaries by more than 100% for nitrogen use and by 55–75% for land, water, and phosphorous use (figure 7.2B).



Figure 7.2: Environmental impacts of food systems.

Notes: (A) Direct environmental contribution of food groups towards planetary boundaries in 2020. Nitrogen, phosphorus, and water use for animal feed production appear in crop production. Blue water is irrigation water. Rainfed crops do not impact the blue water boundary. Data are from DIA-GIO.[25] (B) Projected environmental impacts of different scenarios in 2050. The first row shows the current state (grey line) of the food system for five environmental variables—land for agriculture, non-CO2 GHG emissions from agriculture, water withdrawals for crops, nitrogen use for crops, and phosphorus use for crops—and their food system boundaries (orange line). The percentage change needed from the current level to reach the boundary is indicated between the two lines. The lines continue from the first row and are translated to percentage change from the current state in the subsequent rows. Each subsequent row represents percentage changes relative to the current state for different scenarios in 2050: the core scenarios (highlighted in grey) are BAU, EAT–Lancet, and ELM; their drivers are increased productivity, reduced FLW, diet shift, and climate mitigation. Vertical lines represent the multimodel median; lighter dots indicate individual model results. Colours indicate whether results are below (green), between (orange), or exceeding (red) the food system boundary. Open black circles indicate results from the DIA-GIO model. Grey vertical lines mark the planetary boundary thresholds.

BAU=business as usual. DIA-GIO=Global Input–Output module of the Dietary Impact Assessment model. EL=EAT-Lancet. ELM=EAT–Lancet Mitigation. FLW=food loss and waste. GHG=greenhouse gas emissions. CGR=coarse grains. DRY=dairy. NRM=non-ruminant meat and byproducts. OCR=other crops. OSD=oilseeds. RIC=rice. RUM=ruminant meat. SGC=sugar crops. VFN=vegetables, fruits, nuts, and legumes. WHT=wheat.

All three components of the **EAT–Lancet** scenario (i.e., dietary change, increased productivity, and reduced FLW) contribute to more efficient and less resource-intensive food systems

by 2050. To achieve the agricultural emissions target of 5 Gt CO_2e per year from CH_4 and N_2O from biological processes, non-CO_2 emissions from agriculture would need to decrease by more than 30% from current estimates of 7.1 Gt CO_2e per year.[26] Under the **EAT–Lancet** scenario, and primarily due to fewer ruminants, agricultural non-CO_2 emissions decline by 20% (the ensemble median) and 32% (DIA-GIO) compared with 2020 levels. However, agreement is low among models as to whether these reductions are sufficient to meet the food system boundary (i.e., changes of –48% to 13% from 2020 levels, depending on the model). By 2050, all regions show emissions reductions in the **EAT–Lancet** scenario compared with the **BAU** scenario, with the largest decreases occurring in sub-Saharan Africa, Brazil, and the rest of Latin America (Appendix 7.1 p 39). When the **EAT–Lancet** scenario is coupled with the emissions pricing and land-use policies of the **ELM** scenario, the model ensemble shows agricultural emissions declining further to 34% (–84% to –18% for model range) of 2020 levels, and below the food system boundary.

Ensemble results suggest that, in the **EAT–Lancet** scenario, total global agricultural land use (i.e., cropland and grazing land) could fall by 7% (–26% to 1% for model range; a decrease of ~340 Mha) compared with 2020 levels, a substantial departure from the projections of the **BAU** scenario described earlier. Most of this decline comes from reductions in grazing land (–11%; –59% to 1% for model range). Latin America accounts for 30% of the decline in grazing land from 2020 levels (with Brazil alone accounting for 16%), and sub-Saharan Africa accounts for 22%. Such a reduction in future agricultural land use could provide room for conservation or restoration of natural ecosystems, particularly in these regions. The ensemble results project an 11% increase in cropland (–3% to 42% for model range) compared with 2020, whereas DIA-GIO suggests that cropland area could decrease by 22% (Appendix 7.1 p 42). Coupling ambitious mitigation with a shift to healthy diets under the **ELM** scenario shows even greater reductions in future agricultural area, with agricultural land declining globally by 14% (–28 to –4% for model range) compared with 2020 levels. This larger reduction is due to both drivers reducing the demand for and production of animal products, especially of ruminants (the main users of grazing land).

Current estimates indicate that global blue water use remains below the food system boundary. However, regional water scarcity remains a major concern, and additional efforts might be needed to increase water-use efficiency and improve water management, particularly in areas already experiencing water stress (e.g., the Indo-Gangetic Plain and the Mediterranean). The **EAT–Lancet** scenario reduces water use compared with the 2050 projections from the **BAU** scenario, but there is low agreement across the ensemble as to whether this reduction is sufficient to fall below 2020 levels (4%, –25% to 39% for model range; –8% for DIA-GIO). Ensemble results suggest similar blue water use by 2050 in the **ELM** scenario compared with the **EAT–Lancet** scenario (3%, –40% to 45% for model range), but with a wide range of outcomes. Under the EAT–Lancet scenario by 2050, nitrogen and phosphorous use decline compared with the **BAU** scenario; however, the planetary boundary remains

transgressed as both nitrogen use (15%, –17% to 32% for model range) and phosphorous use (15%, 5% to 25% for model range) increase compared with 2020 levels. DIA-GIO results suggest that under the **EAT–Lancet** scenario, nitrogen and phosphorus inputs could decline substantially compared with current inputs (35% reduction in nitrogen and a 53% reduction in phosphorus). The difference between DIA-GIO and the economic models illustrates the potential for larger reductions in resource use if targeted measures are available to avoid rebound effects and reallocation of resources to other non-food uses.

Important complementarities exist across the three drivers of the **EAT–Lancet** scenario that, when combined, achieved better environmental outcomes than any individual driver in isolation.[27] Dietary change alone could substantially contribute to improvements in land and emissions boundaries; however, outcomes for water, nitrogen, and phosphorus use by 2050 varied due to rising demand for the many commodities that depend on these inputs. DIA-GIO showed greater environmental gains from increased productivity and reduced FLW compared with economic models, for which rebound effects in demand reduce the environmental gains from these drivers. For example, increased productivity in ruminant production lowers the cost of ruminant products, which in turn leads to lower consumer prices and stimulates increased consumer demand. This increase in demand leads to a larger ruminant herd, leading to similar emissions under the increased productivity scenario compared with the **BAU** results (figure 7.2B). A shift to healthy diets would avoid this outcome as it would reduce demand for ruminant products; however, it would also increase demand for perishable fruits and vegetables and could increase the volume of FLW, highlighting the increased importance of interventions to reduce FLW in an EAT–Lancet future.

The range of environmental results (i.e., cropland extent, and blue water, nitrogen, and phosphorus use) highlights substantial uncertainty in how agrifood systems could respond to a food systems transformation. A transition to a healthy diet would include reductions in demand for some agricultural commodities (e.g., animal-sourced foods and sugar), accompanied by a drop in intermediate demand from these sectors for inputs (e.g., animal feed). However, this transition would also increase the demand for other agricultural commodities, such as fruits, vegetables, legumes, and nuts.

Various factors can affect whether a transition to a healthy diet would lead to a net reduction in resource use by agriculture. The first factor is whether resources dedicated to producing crops that are no longer demanded (e.g., cropland, water, and fertilisers) can easily be converted and used to produce agricultural commodities that are growing in demand. For example, not all cropland dedicated to feed crops would be suitable (either climatically or economically) to produce fruits, vegetables, legumes, and nuts. The second factor is whether the crops increasing in demand are less resource-intensive than those that are declining in demand. Although animal-sourced foods are generally resource-intensive, so too are many of the crops increasing in demand (especially with respect to water and fertiliser use).

Finally, many crops that are important for animal feeds (e.g., cereals and oilseeds) are also inputs in various industrial uses (e.g., cosmetics, bioplastics, and biofuels). Less demand for animal feeds would make these agricultural commodities cheaper, which could spur additional demand from outside the food system, reducing environmental gains. Models with larger reductions in resource use (e.g., DIA-GIO) assume small rebounds in demand and fewer alternative uses for freed-up resources, whereas many of the economic models suggest that resources could have a wide range of other potential uses, which could lead to smaller environmental gains without additional policies (e.g., land-use regulations or taxing environmental externalities) that encourage less aggregate resource use. Potential increased competition for resource use is more evident in the **ELM** scenario, which shows increased demand for agricultural products from the bioeconomy as part of the transition away from fossil fuels, and greater agricultural intensification on existing cropland due to restrictions on land expansion.

Together, these factors suggest that the changes modelled could contribute greatly to reducing environmental pressure. However, uncertainty remains with regard to whether these reductions fully place food systems within the safe operating spaces of planetary boundaries. Much of this uncertainty depends on how broad the scope is for alternative uses of natural resources and agricultural commodities, emphasising the need to couple supply-side and demand-side changes to avoid undesired consequences and rebound effects. The modelling results present an important foundation for a food systems transformation, and could be used as a guide for additional policies and innovations[28,29] that promote improved efficiency and resource use within the food system (e.g., through precision agriculture, fertiliser management, or improved production allocation). Further reductions in FLW, applications of sustainable intensification approaches, or circularity[30–32] might be required to return to a safe operating space.

7.1.4 Socioeconomic and justice implications of a food system transformation

Assessing agricultural labour and livelihood implications

Changes in labour demand can have implications for production costs and income, and ultimately production and total demand.[33] Across all scenarios (i.e., the **BAU**, **EAT–Lancet**, and **ELM**), assumed economic development and increasing urbanisation leads to an agricultural sector that contributes a smaller share of total economic output and employment by 2050.[34,35] Transitioning to a healthy diet (as in the **EAT–Lancet** scenario) with the projected effects on food production (figure 7.1) would have important consequences for the sectors that are increasing or decreasing their labour demands. Globally, we see modest additional reductions in agricultural demand for labour in the **EAT–Lancet** or **ELM** scenarios compared with the **BAU** scenario (figure 7.3A; Appendix 7.1 pp 46–49). These results are consistent with recent DIA-GIO analyses using current sectoral and regional labour requirements, which found that shifting to a healthy diet could lead to a less labour-intensive global food system.[36] These

results all suggest that transitioning to a healthy diet would not only be less resource intensive (as highlighted in the previous section), but also modestly less labour intensive to produce. The global reduction in labour intensity is driven by various factors, including a reduction in the production of animal feeds and more labour-intensive animal sectors (eg, industrial pork, poultry, and dairy production), which would offset the increased labour demand from expanding crop production sectors (eg, for vegetables, fruits, and nuts).

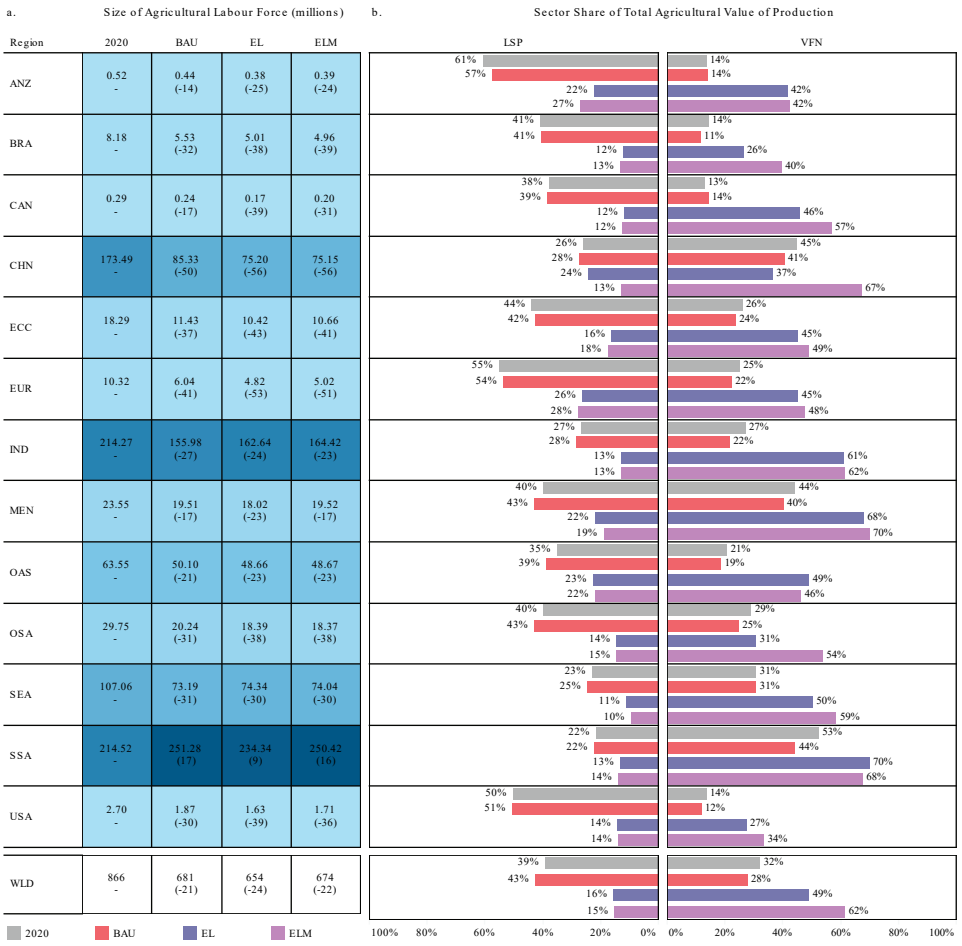

Figure 7.3: Summary of regional disaggregation of agricultural labour and value of production

Notes: (A) Agricultural labour force (millions) for the world and 13 regions by 2050 under BAU, EAT–Lancet, and ELM scenarios. Shading intensity reflects the regional share of global agricultural employment. Employment numbers are derived from benchmarking the percentage change (ie, 2050 vs 2020) of the median model to agricultural employment in 2020.[22] Percentage changes from 2020 by scenario are shown in parentheses. Full model results are available (appendix 7.1). (B) The share of value for LSP and VFN within total agricultural value of production for 2020 (grey), BAU (red), EAT–Lancet (blue), and ELM (purple) scenarios. Agricultural value of production is given in current prices. BAU=business as usual. ELM=EAT–Lancet Mitigation. LSP=livestock production. VFN=vegetables, fruits, legumes, and nuts. ANZ=Australia and New Zealand.

BRA=Brazil. CAN=Canada. CHN=China. ECC=Eastern Europe, Caucasus, and central Asia. EUR=Europe. IND=India. MEN=Middle East and north Africa. OAS=other Asia. OSA=other South and central America. SEA=southeast Asia. SSA=sub-Saharan Africa. WLD=world.

Livestock sectors would face particular economic challenges from a shift to a healthy diet, with the livestock share of agricultural production declining from approximately 40% in 2020 (in dollar terms), to around 15% by 2050 in the **EAT–Lancet** and **ELM** scenarios (figure 7.3B). This reduction is due to the combined effect of a 41% decline in global production and a 31% decline in producer prices for livestock products[37], which contributes to a 36% reduction in livestock labour demand by 2050 compared with the **BAU** scenario. The increased demand for some plant-based foods—especially vegetables, fruits, and nuts—would drive increased demand for labour in these expanding sectors, which offsets most of the decline in livestock labour demand worldwide. These ensemble results are broadly consistent with DIA-GIO results, which suggest the shifts in sectoral demand for labour would result in a modest reduction in overall agricultural labour demand (<5%) globally.

The agricultural sector contributes a larger share of GDP and employment in low-income regions (<40%) compared with high-income regions (<5%).[38] Despite a decline in the contribution of agriculture to the economy compared with current levels, by 2050 agriculture would remain a large source of GDP and employment in many regions (e.g., in India and sub-Saharan Africa). The sectoral demands for labour also vary substantially across regions and food systems. As such, the challenges of restructuring agricultural and food sectors vary regionally. Restructuring food systems could be more challenging in regions with large agricultural labour forces (e.g., in India, sub-Saharan Africa, and China), or large livestock sectors (e.g., Latin America). Regions with large vegetable, fruit, nut, and legume sectors (e.g., China) could benefit from changes in demand without the need for substantial reallocation of resources across agricultural sectors. The sizes of agricultural labour forces by region, and the relative importance of livestock and vegetable, fruits, nuts, and legume sectors are shown to highlight regions where restructuring the demand for labour could be more challenging (figure 7.3).

Changes in labour demand would have consequences beyond aggregate employment levels, including on wages, but also on what jobs are needed, and how well they are remunerated. Model ensemble results suggest that agricultural wages could keep pace with the overall economy, with average agricultural wages increasing by 81% for **BAU**, 74% for **EAT–Lancet**, and 73% for **ELM** by 2050. However, substantial restructuring across agricultural sectors (i.e., reductions in animal production and expansion of fruit and vegetable production) would have important justice implications. The model assumes a smooth transition to 2050 across all three scenarios; however, for such a transition to occur in the **EAT–Lancet** scenario, clear and consistent market signals would be needed to discourage new entrants (e.g., producers newly entering a specific sector) into contracting sectors (i.e., ruminants), while encouraging entry into expanding sectors (i.e., vegetables, fruits, nuts, and legumes), along with the nec-

essary investments in human and physical capital to facilitate labour transitions both within and outside of food systems.

Assessing production costs and food expenditure implications

Using various modelling approaches, we observe a smaller and less resource-intensive food system with the **EAT–Lancet** scenario compared with the **BAU** scenario. A food system aligned with the **EAT–Lancet** scenario would require fewer natural resources (i.e., land and water), and less labour and chemical (i.e., nitrogen and phosphorus) inputs. Across the ensemble, these changes could amount to a moderate reduction (8%) in average agricultural producer prices for the **EAT–Lancet** scenario by 2050 compared with the **BAU** scenario (figure 7.4A). Assuming current input requirements and prices, DIA-GIO projected a similar reduction in costs (10%). These modelling results suggest that, compared with the **BAU** scenario, transforming food systems by 2050 could produce healthy diets for all while also reducing input costs, natural resource use, and environmental pressures. However, whether this potential is realised will ultimately depend on the transition pathway (i.e., the mix of policies, technologies, and cultural changes) followed to foster a food systems transformation that is compatible with the EAT–Lancet recommendations.

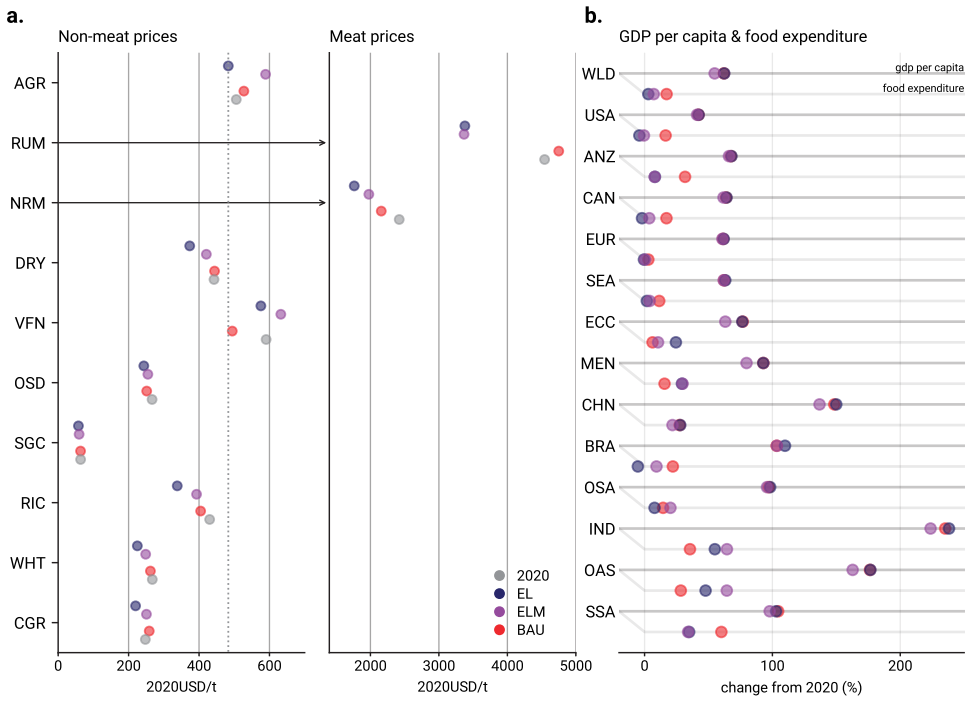

Figure 7.4: Changes in agricultural producer prices and food expenditure implications

Notes: (A) Global average prices by sector for 2020 (grey), the BAU scenario in 2050 (red), the EAT–Lancet scenario in 2050 (blue), and the ELM scenario in 2050 (purple). Global prices are expressed in 2020 US dollars per tonne (note the different scale for non-meat and meat prices). 2020 prices were obtained from the Food

and Agriculture Organization of the UN.[22] Percentage change in prices (from 2020 to 2050) given by model results were applied to 2020 prices. (B) GDP per capita and food expenditure by region for BAU, EAT–Lancet, and ELM scenarios, expressed as a percentage change from 2020. Median GDP per capita for three reporting models (i.e., AIM, ENVISAGE, and MAGNET) is located at the region's first row, followed by food expenditure results in the second row, which are expressed as percentage change from BAU 2020.

BAU=business as usual. ELM=EAT–Lancet Mitigation. GDP=Gross Domestic Product. AGR=all agricultural products. CGR=coarse grains. DRY=dairy. NRM=non-ruminant products (i.e., poultry, pork, and eggs). OSD=oilseeds. RIC=rice. RUM=ruminant meat. SGC=sugar crops. VFN=vegetables, fruits, nuts, and legumes. WHT=wheat. ANZ=Australia and New Zealand. BRA=Brazil. CAN=Canada. CHN=China. ECC=Eastern Europe, Caucasus, and central Asia. EUR=Europe. IND=India. MEN=Middle East and north Africa. OAS=other Asia. OSA=other South and central America. SEA=southeast Asia. SSA=sub-Saharan Africa. WLD=world.

Across food systems, lower production costs could increase the average affordability of food if this reduction is passed on to consumers. However, lower producer prices can contribute to lower agricultural wages and income, with negative consequences on food affordability, particularly in rural areas. Ensemble results suggest that average agricultural prices would not change substantially from 2020 prices for both the **BAU** and the **EAT–Lancet** scenarios. However, in the **ELM** scenario, producer price increases by 2050 would contribute to a 10% increase in consumer prices compared with 2020. Food expenditure (reported by AIM, ENVISAGE, and MAGNET), which is a factor of consumer prices and food demand, is projected to grow in all three scenarios, but at a slower rate than per capita income, with the share of global income spent on food falling from 7% to 5% (for the **BAU** scenario), 4% (for the **EAT–Lancet** scenario), and 4% (for the **ELM** scenario) by 2050 (figure 7.4B). Globally, changes in food expenditure between the **BAU** and **EAT–Lancet** scenarios are driven by two offsetting shifts in a transition to a healthy diet. First, a decline in the demand for—and the prices of—animal-sourced foods, which are moderately more expensive than crop commodities. For example, by 2050 in the **EAT–Lancet** scenario, demand and producer prices for ruminant meat decline substantially compared with 2020 levels, even as ruminant prices remain substantially higher than prices of all other commodities (figure 7.4A). Second, demand for and prices of vegetables, fruits, nuts, and legumes increase substantially, which, at the global level, mostly offset decreased spending on animal products.

Although these two shifts mostly offset each other by 2050, some regions currently consuming low levels of animal-sourced foods (e.g., India), or regions requiring large increases in demand for vegetables, fruits, nuts, and legumes (e.g., eastern Europe, the Caucasus, and central Asia) to achieve a healthy diet, could see increased food expenditure in 2050 compared with the **BAU** scenario. By contrast, regions that are currently overconsuming animal-sourced foods (e.g., the USA) could see declining food expenditures. This result is consistent with a recent analysis with DIA-GIO, which found that healthy diets could already be more affordable than unhealthy diets for individual consumers in HICs and UMICs, even as they remain more expensive in LICs and LMICs.[39]

Even as the share of income spent on food is declining for all regions and scenarios compared with 2020, the affordability of diverse healthy diets remains a concern. Low-income regions that import a substantial share of their vegetables, fruits, nuts, and legumes (e.g., many countries in south Asia, central Asia, and the Pacific) could be especially vulnerable to international price shocks on domestic food affordability and availability. Furthermore, although food affordability is projected to improve in sub-Saharan Africa by 2050, the region continues to spend a larger share of income (21%) on food in the **EAT–Lancet** scenario than any other region. These regional results suggest that low-income regions (listed at the bottom of figure 7.4B) could remain vulnerable to food poverty, and that targeted interventions to account for higher prices of vegetables, fruits, nuts, and legumes, and social protections to ensure consumers can afford a healthy diet, might be needed.

These results highlight that a food systems transformation, if achieved, could contribute towards social and environmental goals. However, the mechanisms for this transformation (e.g., taxes, repurposing of subsidies, and true cost accounting approaches) will be essential for informing and incentivising behaviour change towards more sustainable production practices and healthier consumption patterns. The cost of these actions will ultimately determine whether a food systems transformation increases or decreases the cost of individual foods and the overall diet.

Mitigation efforts (Appendix 7.1 p 40) could increase the cost of agricultural production by restricting land supply and pricing emissions. Across the ensemble, mitigation efforts in isolation would increase consumer prices by 17% (0–40% for model range) compared with 2050 prices in the **BAU** scenario. This price projection is broadly consistent with past studies, suggesting that mitigation efforts could increase food prices.[5] This increased risk is due to multiple factors that raise the price of producing and consuming food. First, mitigation and land-use policies increase the cost of key agricultural inputs (e.g., land and fertilisers), which raises the cost of production. Second, emissions pricing raises the cost of agricultural products, particularly of emission-intensive commodities (e.g., ruminant meat). Vulnerability to food pricing changes varies, with low-income regions (e.g., sub-Saharan Africa) already at heightened risk of food insecurity being the most vulnerable to price increases. Exactly how components of the **EAT–Lancet** scenario contribute to changes in producer and consumer prices, and their potential policy implications, are explored in Panel 7.1and Figure 7.5.

Panel 7.1: Understanding the Drivers of Price Changes to Inform Policy Priorities

To assess which scenario drivers (i.e., dietary change, increased productivity, reduced food loss and waste [FLW], and ambitious mitigation) were most responsible for changes in agricultural prices, we conducted a decomposition analysis using four models from the ensemble (i.e., AIM, CAPRI, ENVISAGE, and MAGNET) that reported regional consumer and producer (e.g., farm gate) prices (see Appendix 7.1 pp 41–43 for full ensemble results of producer prices).

Ambitious mitigation could increase the cost of production in all regions by restricting agricultural land expansion and pricing emissions. However, increased producer prices translate to higher consumer prices, posing a risk to food security. Dietary change has a more varied effect on prices: in Brazil and the USA (regions with a high consumption of animal-sourced foods), adoption of healthy diets could reduce average consumer prices by 7% (in Brazil) and 4% (in the USA; figure 7.5G and 7.5H, yellow bar). However, in India, where red meat consumption is low, increased demand for vegetables, fruits, nuts, and legumes could contribute to a 10% increase in average consumer prices (figure 7.5E, yellow bar).

Increased productivity and reduced FLW contribute to more efficient food systems, reducing the cost of production and leading to lower consumer prices in all regions. The potential to mitigate price increases is particularly important in low-income regions with greater food security challenges. For example, in India and sub-Saharan Africa, reduced FLW and increased productivity partly offset price increases due to ambitious mitigation and dietary change (red and blue bars of figure 7.5). FLW reductions contribute more to reductions in consumer prices than producer prices, with the biggest gains being in regions with high levels of consumer waste (e.g., in the USA; figure 7.5B and 7.5H). These results suggest the importance of supply-side interventions that increase the efficiency of food systems, particularly in low-income settings where price rises pose immediate food security risks.

Previous modelling[40–43] has suggested supply-side measures (i.e., investments in resource-use efficiency, agricultural research and development, and improved extension services) would be insufficient to alleviate food insecurity. As such, policies and interventions that improve infrastructure and functioning of markets, as well as demand-side interventions such as price subsidies and poverty alleviation measures, would be needed to manage higher diet costs in low-income regions.

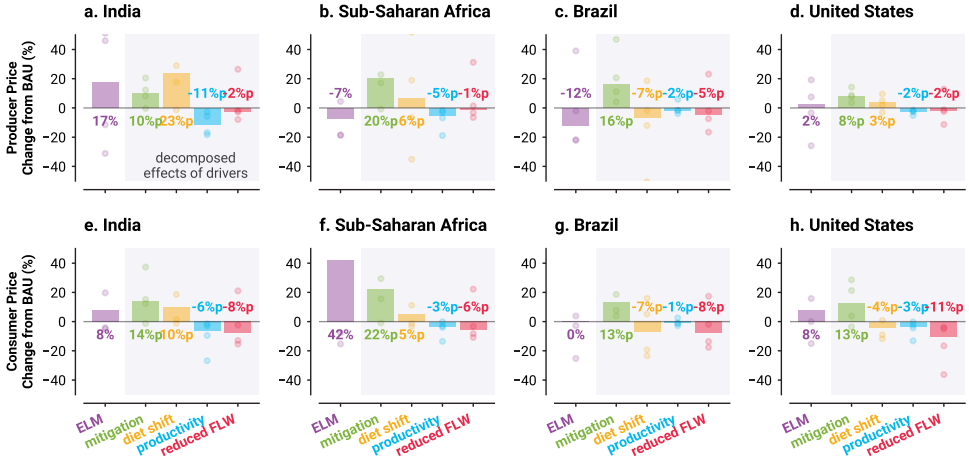

Figure 7.5: The key drivers of price changes in the ELM scenario.

Notes: Regional impact of the ELM scenario (purple) on producer (A–D) and consumer (E–H) prices as percentage changes (%) from the BAU scenario, decomposed into four key drivers shown as percentage points: mitigation (green), diet shift (yellow), increased productivity (blue), and reduced FLW (red). Note that decomposition values are not additive due to the interactions between the four scenario drivers (see Appendix 7.1 p 19 for an explanation of decomposition).

BAU=business as usual. ELM=EAT–Lancet Mitigation. FLW=food loss and waste. %p=percentage points.

Low-income and middle-income regions (e.g., China, Brazil, and sub-Saharan Africa) are responsible for the largest reductions in emissions and agricultural land use in the **EAT–Lancet** and **ELM scenarios**, and are regions at greater risk of increased food prices as a result of dietary change. Historically, these are also the regions that have recently observed large changes in land use and have had the least access to novel technologies and affordable, reliable energy. These regional inequalities highlight the importance of increasing productivity to reduce agricultural yield gaps, and of reducing FLW, both of which could have important roles in alleviating price pressures caused by a shift to healthy diets or ambitious mitigation (or both). Potential complementarities exist between a transition to a healthy diet and ambitious mitigation: both alleviate land-use pressure and reduce consumption of GHG-intensive foods. Further demand-side interventions could also help in managing food affordability concerns. Previous modelling suggests that targeted food subsidies, bundled with mitigation policies[44,45] or full cost efforts (which try to cost negative and environmental externalities),[46] could help to manage these price increases.

Author contributions

This Commission is co-chaired by JR, SHT, and WCW, together with the leadership team (i.e., FDeC, LJG, MH, CCH, and ECW). The co-chairs and the leadership team developed the idea, conceptualisation, and structure of the Commission, including integration across sections.

The Commissioners and postdoctoral research fellows conducted thematic assessments of each section of the Commission, and of the work as a whole (i.e., RAg, SB, ACB, BC, CCo, NC, JF, NGF, MFG, XG, EK, CK, AL, RL, TMM, DM-D'C, CAM, AN, JN, TDO, W-HP, NR, JAR, JPWR, MSp, MSu, StW, DPvV, SV, and PW). Additional authors were included to make detailed contributions on areas of specific disciplinary expertise (i.e., LA, RAm, AB, IB, FB, DB, AHWB, JB, CCh, MC, JC, WdV, NE-C, IP-D, DG, CDG, SKJ, PSJ, MK, HL-C, FM, EM, AM, FO-C, AP, LS-U, ES, FHMT, KT, HHEVZ, W-JvZ, and XZ).

All Commissioners and postdoctoral research fellows conducted reviews and writing for specific sections (i.e., those on healthy diets, food system planetary boundaries, sustainable and ecological intensification, just food systems, modelling, food system solutions, and food systems transformation). Each Commissioner and postdoctoral research fellow contributed to at least one section, but often to more than one.

The model intercomparison included in this study was led by DM-D'C and MH, with support from MSp, MHG, TDO, and MSu. The intercomparison included ten dynamic global food system models (i.e., AIM, CAPRI, ENVISAGE, FARM, GCAM, GLOBIOM, IMPACT, IMAGE, MAGNET, and MAgPIE) and the static DIA-GIO model.

Declaration of interests

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During the preparation of this work, the corresponding author (FDeC) used ChatGPT to produce an initial draft of the Executive Summary by uploading a PDF of the Commission to the tool. After using this service, FDeC and all Commissioners reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Discussion and conclusions

Arriving at each new city, the traveler finds again a past of his that he did not know he had: the foreignness of what you no longer are or no longer possess lies in wait for you in foreign, unpossessed places.

Marco [Polo] enters a city; he sees someone in a square living a life or an instant that could be his; he could now be in that man's place, if he had stopped in time, long ago; or if, long ago, at a crossroads, instead of taking one road he had taken the opposite one, and after long wandering he had come to be in the place of that man in that square. By now, from that real or hypothetical past of his, he is excluded; he cannot stop; he must go on to another city, where another of his pasts awaits him, or something perhaps that had been a possible future of his and is now someone else's present. Futures not achieved are only branches of the past: dead branches.

"Journeys to relive your past?" was the Khan's question at this point, a question which could also have been formulated: "Journeys to recover your future?"

Italo Calvino, *Invisible Cities*

8.1 Introduction

Quantitative foresight modelling and anticipatory governance are valuable tools for engaging systematically with the complexity and uncertainty that characterize food system change. This chapter synthesizes the methodological and substantive insights that emerge from the six case studies presented in Chapters 2-7, which together span a decade of foresight research across a diverse range of food system challenges, ranging from acute supply shocks to novel food technologies, long-run dietary transformation and regional climate-food system interactions. Figure 1.2 from Chapter 1, included again below, provides a graphical overview of the research undertaken (Figure 8.1).

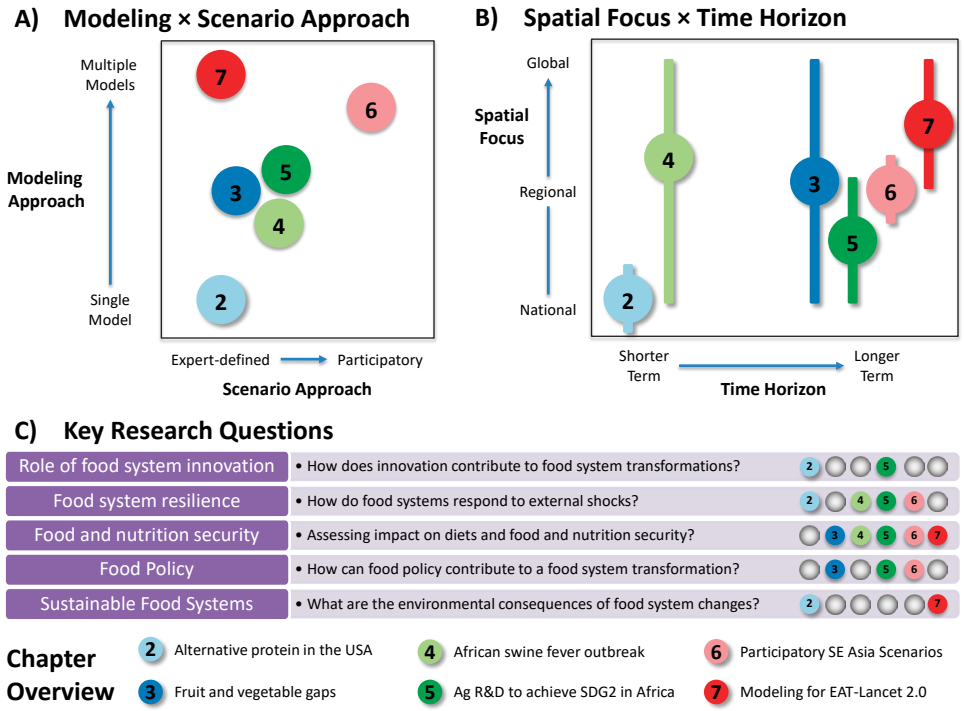

Figure 8.1: Graphical summary of the research undertaken

Notes: Reproduced from Figure 1.2 in Chapter 1.

The six case studies were not designed as a unified research program from the outset. Nevertheless, they demonstrate an overarching interrogation and reflection over a set of interconnected questions, synthesized across this thesis:

- What analytical tools are most appropriate for different food system questions?
- How to design scenarios to be both rigorous and policy-relevant?
- How can we apply foresight models holistically to best inform broader system change?
- What does it take to move research findings from academic outputs into policy deliberation?

These are not just methodological questions and are at the heart of trying to understand how to practice anticipatory governance more rigorously, reflexively, and responsibly.

This chapter is composed of four main sections:

1. Section 8.2 discusses key insights emerging from the synthesis of the thesis. This section is organized around six interconnected themes including the complementarity of qualitative and quantitative approaches, the need for intentional scenario design, the need to match models to research problems, the role of timescales on scenario design, the need

for holistic approaches that embrace complexity, and the unavoidability of unanticipated consequences.
2. Section 8.3 reflects on the science-policy engagement undertaken across the thesis and what it suggests about how and when foresight research can inform policy.
3. Section 8.4 presents a critical assessment of the tools and approaches used in this thesis including data, scenario, and model limitations. It ends with eight priority areas for future research.
4. Section 8.5 summarizes these findings in a final synthesis.

Two key principles can be consistently observed across this thesis.

First, **models are better as tools for structured inquiry than prediction of the future**. Their value lies less in producing definitive answers than in expanding the horizon of what decision-makers consider possible. They facilitate the interrogation of assumptions and trade-offs embedded in policy choices, helping to make these assumptions more explicit and contestable. They can also help to assess stakeholder capacity to act, and their scope of control to better situate and prioritize actions. Consistent with this, the most policy-relevant findings across this thesis tend to arise less from any single model result than from a more contextualized comparison of outcomes across scenarios and models, the juxtaposition of metrics across different domains (e.g., environment, health, and justice), and the identification of system dynamics that are robust across different modelling and scenario approaches. This reframes what methodological rigour means in anticipatory governance. Rather than focusing on the precision of a single model output, it means emphasizing the transparency, pluralism, and critical reflexivity of the anticipatory governance project.

Second, **responsible anticipatory governance demands uncompromising intellectual honesty**. This means engaging with uncertainty rigorously and transparently, resisting the temptation to oversimplify the complexity of food system transformation, and acknowledging limitations clearly and openly. It also requires recognition that the application of anticipatory governance tools is not a normatively neutral act. Anticipatory governance requires making many assumptions about the future, and these choices will prioritize certain questions over others, as well as prioritize whose futures get explored. Practising anticipatory governance responsibly therefore requires continuous reflexivity about not just what models can and cannot represent, but whose questions they are designed to answer.

8.2 Key methodological and substantive insights

8.2.1 Effective anticipatory governance requires both qualitative and quantitative elements

Food system foresight generates its greatest value not from quantitative precision, but from the productive interplay between rigorous modelling and the interpretive frameworks that

give model outputs meaning[1–3]. A central insight across the thesis chapters is that the distinction between qualitative and quantitative research is less sharp than it may initially appear in the technical context of scenario construction. Qualitative reasoning is fundamental in all stages of scenario design and model quantification, just as quantitative data and reasoning inform and validate qualitative reasoning.

Qualitative narratives provide logical scaffolding for the development of complex scenarios with multiple drivers. Whether drawing on established global frameworks like the Shared Socioeconomic Pathways[4,5] used in Chapters 3, 5, and 7, or on regionally developed stakeholder narratives as in Chapter 6[6,7], the quantitative modelling is always grounded in a prior qualitative account of how and why the world might change in a particular way. This narrative foundation ensures compatibility and consistency across drivers and allows the interpretation of scenario results and how they were generated. This is critical to inform decision-makers who need to understand not only what the models suggest, but what these results suggest about change in the real world.

Some amount of qualitative judgements is embedded in all model parametrization. For example, the perpetual inventory method used in Chapter 5 to translate agricultural R&D investments into productivity changes required deliberate choices about the relationship between knowledge accumulation and obsolescence, knowledge spillovers, and the efficiency of conversion to productivity growth. These choices required many judgement calls that needed to be transparently justified even if they were grounded in theory and literature rather than direct observation[8–11]. Similarly, the ethical assessment framework applied in Chapter 2 required decisions about which moral lenses to apply and how to translate these to interpreting and assessing the outcomes of the adoption of plant-based alternatives to beef in the USA[12]. These are qualitative judgements that have been formalized into numbers, but they remain judgements. Like the hard choices facing policymakers described later in section 8.2.5, there are no objectively correct answers to these decisions, only more or less well-reasoned and transparent ones. This is precisely why transparency and explicit justification of modelling choices are not optional, they are fundamental and necessary for responsible anticipatory governance[1,2].

The scenario development process is as much an art as a science, with the relationship between qualitative and quantitative elements iterative and integrated throughout. This iterative process is fundamentally a social process of co-production, with scenario construction enriched by sustained interaction between modellers, domain experts, and where present stakeholders and decision-makers, each bringing different perspectives and assumptions about what futures are plausible or desirable.

Quantitative models play a key role in refining scenarios, surfacing logical inconsistencies between qualitative narrative assumptions and quantitative model behaviour. A scenario that

generates implausible results may signal more than a model error but a narrative assumption that needs rethinking. At the same time, scenarios are typically grounded in a substantial base of quantitative historical data. Trends across a range of key drivers of change (e.g., population growth, income, productivity, land use, nutrition transition, etc.) provide the empirical foundation of our understanding of the past and present, and a starting point for imagining the future, helping to bound the modelling exercise within the range of what is historically plausible[13]. The challenge, however, is that hindsight is usually clearer than foresight, and that while we can be fairly sure the future will be different, it is much harder to anticipate in what ways it will differ. Over-anchoring to historical trends risks reproducing the very assumptions that transformative futures will need to challenge, which is why the most valuable foresight research deliberately explores how and where the future might diverge from the past, rather than simply extrapolating from it[3,14] .

Sometimes the feedback from model to scenario is even more dramatic. A model that fails to solve can itself be a valuable diagnostic signal, revealing logical gaps in scenario specification or model structure that would otherwise go unnoticed. The first attempt to run a full healthy diet adoption scenario in IMPACT in support of the first EAT-Lancet report[15,16] crashed the model because the dramatic reduction in animal production led to a collapse in demand for oilseed meals, which in the IMPACT model are used exclusively by the livestock sector[17]. With no alternative use specified, prices went negative and the model failed to solve. Rather than a technical failure, this proved an interesting problem and highlighted a failure of imagination. The initial diet transition scenario had not adequately specified what would happen to animal feed by-products under a transformed food system. The model's failure to solve forced a more careful consideration of how dietary transformation reshapes not just primary food markets but the whole food system. Resolving this crash required adding new model equations to allow the market to clear even when demand for a commodity collapses, in real world terms, allow stuff that is not valuable to get thrown away. These changes made the model both more realistic and more capable of representing more extreme scenarios of food system transformation. This kind of productive failure is not always celebrated in published literature, but it is a genuinely critical part of the development of almost all complex scenarios using quantitative foresight models.

Beyond scenario construction, qualitative lenses play an equally vital role in interpreting what model results mean. Changes in output variables are not normatively self-explanatory. Multiple pathways can achieve the same outcome, but the normative implications can be quite different. For example, reducing the number of people suffering from food insecurity through poverty alleviation is quite different than due to loss of life from war. Increasing agricultural productivity is not an unalloyed good. If it is achieved through increasing chemical inputs or automation can have different rebound effects and consequences for labour and the environment[1,18]. Across all six chapters significant insights emerged not just from the model results but from more careful normative analysis of the potential implications of

those results. This normative analysis requires researchers to bring explicit ethical, social, and political frameworks to bear on model outputs, and to be transparent about the values and assumptions that shape what they choose to highlight and what they choose to set aside[1,19].

8.2.2 The importance of intentional scenario design, reflections on top-down vs. participatory approaches

Scenarios are not neutral analytical vessels, and the choices made in designing them (i.e., what futures are explored, which variables are treated as drivers, what baselines are used, and who is involved in their development) shape what the analysis can and cannot reveal, whose perspectives are represented, and how easily results can be communicated to different audiences[19–21]. These choices are therefore not merely technical decisions but normative ones, and making them intentionally and transparently is fundamental to practising responsible anticipatory governance[1]. Across the six case studies in this thesis, scenario design choices were made deliberately, balancing scientific rigour with the need to represent food system complexity, while managing real world constraints around project resources and timelines. In Chapter 4, for example, in response to an ongoing outbreak there was a pressing need to provide foresight inputs quickly. This precluded the development of complex scenarios, with speed prioritized to answer important questions at the timescale relevant to policymakers, so stylized scenarios grounded in historical evidence from past outbreaks were developed. Chapter 6, on the other hand, was part of a broader multi-year research agenda (i.e., CCAFS regional scenarios project), which was designed around deliberative co-design of regional scenarios with stakeholders from Vietnam, Cambodia, and Laos. These two cases demonstrate some of the diversity of choices, and how they are embedded and informed by the research question, and intended use.

Scenario design approaches can be usefully characterized along a continuum from predominantly top-down to predominantly participatory, as summarized in Figure 1.5 of Chapter 1. Top-down approaches, which draw primarily on existing literature, historical data, and expert judgement, offer important strengths. They are relatively resource-efficient, reproducible, and transparent in their assumptions, and they facilitate comparability across studies by grounding scenarios in shared frameworks. The Shared Socioeconomic Pathways[4,5,22,23] used in Chapters 3, 5, and 7 are a good example. By drawing on a common, peer-reviewed set of population and economic growth assumptions, these chapters were able to situate their findings within the broader scenario literature, something that has facilitated later comparison in subsequent research, for example meta-analysis of globally modelled food demand by Hadjikakou et al.[24] and hunger cost abatement modelling by Chichaibelu et al[25]. However, this increased comparability can come at a cost. Their ease of use (i.e., off the shelf scenario inputs) can reduce reflexivity with respect to future assumptions, as the use and re-use of these components narrows what kinds of futures, or framings of food system challenges are explored[13,19,20]. The global nature of many of these frameworks can also be generic, lacking local context, which also contributes to a narrower exploration of possible futures[20,26].

Participatory approaches address some of these limitations by broadening who participates in defining what futures are worth exploring. Chapter 6 illustrated the most participatory approach to scenario design in the thesis, engaging stakeholders from government, civil society, academia, and the private sector across Vietnam, Cambodia, and Laos in a co-design process that produced four regionally contextualized scenarios. These workshops not only generated a set of regional scenarios, but in the process of their creation surfaced perspectives and priorities that would not have emerged from a purely expert-driven process. Participatory scenarios can also broaden the possibility space, inviting consideration of futures that challenge dominant assumptions rather than simply extrapolating from them[3,20,21]. Participatory processes also invite important discussions about spheres of influence and control. A well-facilitated scenario process can help decision-makers distinguish between drivers they can directly control and change, versus those that require coordination with others to shift, and those that are largely outside their sphere of control and can only be prepared for and responded to[7,21,27]. These boundaries are not fixed. And these participatory processes can help to highlight these dynamics, recognizing that what is beyond a single actor's control today may become tractable through sustained collaboration and coalition building over time. Making these distinctions explicit through participatory scenario processes helps decision-makers to focus their agency more strategically, identifying where intervention is most likely to be effective and where building resilience and adaptive capacity is the more realistic goal[1]. This connects directly to the hard choices argument in section 8.2.5 and the implications of unintended consequences discussed in section 8.2.6. The learning and co-production dimensions of participatory scenario design are discussed further in section 8.3.

In practice, the top-down/participatory distinction is a useful heuristic rather than a rigid binary. No scenario is entirely one or the other. Even predominantly top-down scenarios require qualitative judgements about which historical trends are most relevant and how to represent them, as discussed in section 8.2.1. And even the most participatory processes require some top-down inputs to ensure plausibility. Chapter 6 illustrates this hybrid reality well. While the scenario narratives were co-developed with regional stakeholders from Viet Nam, Cambodia, and Laos, not all elements of the scenarios were within their expertise or purview. Population projections from the SSPs[4,5,22,23] were used to inform and bound the demographic dimensions of the scenarios, as there was no expectation that stakeholders would be experts in demography. Similarly, exogenous climate scenarios were incorporated as inputs rather than co-developed, recognizing that global climate projections require a level of technical expertise outside the scope of most stakeholders, and that global climate change was outside their sphere of direct influence. These choices reflect the layered and iterative nature of scenario design, where decisions about what to co-develop and what to specify externally require careful and transparent judgement at every step. In this sense, scenario design is as much an art as a science, demanding not just methodological competence but wisdom (hopefully) about when to involve stakeholders, when to draw on established frameworks, and how to preserve the integrity of both in the final product.

The same hybrid logic applies in the other direction. Even the most expert-driven scenario processes in this thesis incorporated iterative bottom-up validation that shares important parallels with participatory approaches. The IMPACT model baseline scenarios used in Chapters 3-6 were revised and validated through a structured process of expert elicitation, drawing on commodity specialists from across the CGIAR to review assumptions about food demand elasticities, productivity trends, and price dynamics[17,28]. Similarly, the multi-model ensemble process in Chapter 7 involved extensive cross-model comparison and discussion among modelling teams and the broader EAT-Lancet commission, surfacing differences in assumptions, values, and model specifications that required collaborative resolution before the ensemble results could be interpreted meaningfully[29] . Both processes share the deliberative and iterative character of participatory scenario design. The real question is therefore not whether to combine top-down and participatory elements, but how to do so intentionally and transparently, in ways that are matched to the research question, the policy context, and available resources[2,21]. A practical implication of this hybrid approach is that translating stakeholder narratives into quantitative model inputs requires careful handling to preserve their integrity and ensure that the spirit of the scenarios is reflected in what the model actually simulates[7,30]. The boundary between expert-driven and participatory scenario design is ultimately more porous than it might appear. The primary difference is not the nature of the deliberation, but who is defined as an expert.

8.2.3 Not all problems are nails, need to select models that can satisfy research and policy needs

The choice of models is a vital one[2,3,30], as different models can facilitate the exploration of different system behaviours to varying extents. Poor matching of models to research questions can obscure key system dynamics, and fail to produce relevant outputs, limiting the applicability of results to inform policy[2]. The diversity of research questions and contexts (i.e., national vs global, or long- vs short-run shocks) addressed across this thesis required a range of analytical tools (e.g., partial equilibrium, general equilibrium, PIM, and crop models), and flexibility to combine and adapt them to answer these questions. This was not limited to only using different models (e.g., USAGE-Food in Chapter 2, and IMPACT in Chapter 3) but also adapting and combining them in new configurations (e.g., IMPACT+GLOBE in Chapters 4 and 5, IMPACT and GLOBIOM run in parallel in Chapter 6, and a multi-model ensemble of 10 economic models in Chapter 7) to better simulate key food system behaviours. In each case, the model selection was intentional, to ensure the selected model(s) had the appropriate level of detail to answer the research question.

For example, Chapter 4, explored the potential consequences of a severe outbreak of African swine fever in China on food and nutrition security within and beyond China[31]. To do this required an approach that could capture changes in food demand and nutrient supply resulting from shocks to agricultural production and subsequent impacts on income and food prices, key drivers of food demand[32]. It also needed to capture interconnected links between

competing food and animal feed uses of crop production, to better understand how a shock in the Chinese pork sector could propagate across global food chains. Given the need for detailed representation of agriculture, and changes in livelihoods (i.e., income) there was a need to blend two modelling approaches. In this case, IMPACT (a partial equilibrium model) and GLOBE (a general equilibrium model) were coupled to leverage each model's strengths. IMPACT captured the links between feed and food demands for crop production, including detailed changes in food prices. These results were then passed to GLOBE to assess changes in income and employment, which were fed back to IMPACT to estimate changes in food demand, and food and nutrition security.

This approach demonstrated a bi-directional coupling between the models, with IMPACT results serving as inputs to GLOBE, and GLOBE results feeding back to IMPACT (Figure 8.2).

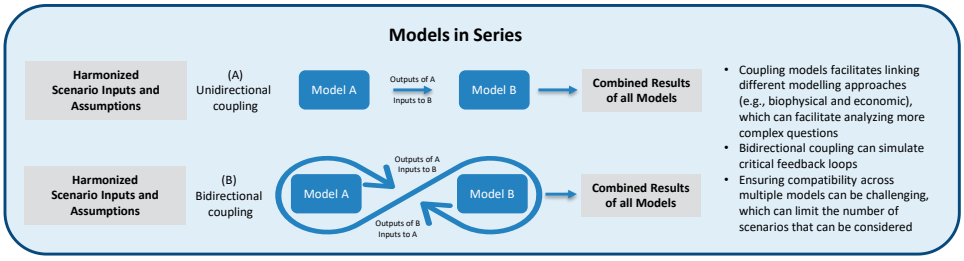

Figure 8.2: Stylized representation of models run in series.

While bi-directional coupling between IMPACT and GLOBE was necessary to capture the feedback loops driving food security outcomes in Chapter 4, not all research questions require this level of iterative coupling. Sometimes the value of linking models lies less in capturing feedback loops and more in expanding what kind of scenarios can be explicitly represented. For example, Chapter 5 applied a unidirectional coupling[9], where a perpetual inventory method (PIM) model of knowledge accumulation[11] was used to parameterize R&D investment scenarios. This was done to facilitate communication with policymakers who can determine R&D investment levels but are not able to directly determine future agricultural productivity. Applying a PIM model, therefore allowed for scenario inputs that were within the control of relevant policymakers (i.e., funding agricultural research), and translating it into changes in agricultural productivity. The consequences of these changes in agricultural productivity could then be simulated in IMPACT-GLOBE to assess the potential benefits towards reducing hunger in Africa. Thus, the coupling of an additional model improved the representation of investment scenarios, as well as allowed for better communication of these scenarios. This model improvement has since facilitated the use of IMPACT-GLOBE to explore the consequences of R&D investments for a growing range of questions, such as the consequences on the environment and the cost of climate adaptation in the agriculture sector[34].

Running models in series, whether bi-directionally as in Chapter 4 or unidirectionally as in Chapter 5, improves the representation of specific system dynamics and scenario inputs. However, each model or model configuration produces an individual realization of how food systems might behave. Each model embeds assumptions about how food systems function, and those assumptions shape what outcomes are possible. If instead of running models in series, they are run in parallel (i.e., model ensembles) then it is possible to explore model uncertainty, and how differing representations of system behaviour can influence projected outcomes. Where models agree on the direction and magnitude of change, confidence in findings is strengthened and where they diverge, the spread of model results is informative, pointing to where system dynamics are poorly understood or contested. Running multiple models in parallel can help to create greater confidence in the results particularly when the models agree, and when they don't agree they can highlight where more research is needed[2,3,6]. Multi-models can help make more visible model uncertainty, although it should be noted that it can also complicate communication of results due to the added modelling complexity, and may encourage over confidence in the "correctness" of the projections when the models agree, ignoring the possibility that all the models may be missing important feedback loops.

Chapters 6 and 7 demonstrated the application of multi-model ensembles run in parallel to more broadly engage with model uncertainty[6,29]. In Chapter 6, IMPACT and GLOBIOM[35], both global PE models but with structural differences in the representation of agricultural land-use, global trade, and productivity growth, were selected because those structural differences facilitated a greater exploration of plausible representations of the regional South-east Asian scenarios, including different treatments of land-use change, and the role of CO_2 fertilization in determining climate impacts.

Chapter 7 applied a 10-model ensemble to inform the second EAT-Lancet Commission on healthy, sustainable, and just food systems[29]. The range of model results helped to highlight where there was greater agreement across the models, and a better understanding of potential consequences of an EAT-Lancet style food system transformation. Wider ranges of model results, on the other hand, help to point to outcomes with a wider possibility space, and where more attention is needed to better understand mechanisms of change and their potential consequences. For example, the results of the dietary change scenarios suggested that the wide-scale adoption of a healthy diet could reduce agricultural emissions and land-use, with all models agreeing on the direction of change, granted with a wider range on the magnitude of the reduction. However, with respect to other results such as food prices, or other environmental outcomes (e.g., water and fertilizer use), there was less agreement, with some models projecting increases and others decreases compared to the business-as-usual scenario. This suggested that the scenario which focused solely on consumers adopting a healthy diet, needs to consider more explicitly how producers would change in an EAT-Lancet world, beyond just responding to changes in producer prices. The ensemble also highlighted that there was greater agreement in aggregate globally, with much more uncertainty on how food

system transformations might occur at the regional level, pointing to a need for greater work of bridging between the macro and meso levels.

8.2.4 Horizons of change: temporal dimensions shape scenario design and model specification

How we consider the role of time shapes not only which modelling approaches are appropriate. It informs what kinds of scenarios are meaningful, the baseline assumptions that are needed, and what policy windows the analysis can inform[2,3,13]. Across this thesis, two contrasting temporal windows were applied, each highlighting different challenges and opportunities presented by food system change.

Comparative statics compare equilibrium states before and after discrete exogenous shocks (see Chapter 1), and is better suited to assess short-term system resilience, and are often used to run scenarios to stress-test systems. Because comparative statics do not require a baseline trajectory of system evolution, scenarios can be constructed around a single, well-defined shock, without needing to specify other drivers of change like population and income growth. For example, the outbreak of African swine fever in China (Chapter 4), or the widespread adoption of plant-based beef substitutes in the USA (Chapter 2). However, the simplifications that facilitate targeted short-term analysis also means that comparative statics does not capture how systems learn, adapt, or transform in response to shocks over time[3,32].

Recursive dynamics (applied in Chapters 3, 5, 6, and 7), on the other hand, simulate in a stepwise manner through the scenario projection (often annually or in 5- or 10-year jumps), with each period's equilibrium serving as the starting point for the next (see Chapter 1). This approach is necessary when considering processes that unfold over many years (e.g., climate change) and where the system would be expected to adapt and change along-side the shocks to the system. Recursive dynamics also introduces the need for a carefully constructed baseline reference scenario, projecting food system behaviour under current trends and policies (See Chapter 1). In Chapters 3 and 7, the Shared Socioeconomic Pathway (SSP) framework provided foundational building blocks for this baseline structure, grounding long-run population and economic growth in widely used and peer-reviewed quantitative projections[4,5,22,23]. Chapter 5 similarly drew on SSP assumptions for population and income growth, while extending the baseline to R&D investment trajectories, knowledge accumulation rates, and agricultural productivity growth. In Chapter 6, multiple climate shock scenarios derived from crop models were layered onto the long-run no climate change baseline to engage explicitly with the uncertainty of biophysical drivers over a multi-decadal horizon.

Together, comparative statics and recursive dynamics offer complementary windows into food system change. The former illuminates the immediate scale and distribution of impacts from specific one-time shocks. Whereas the latter traces how systems may evolve under sustained pressures and cumulative interventions. Both, however, are still simplifications, and

cannot fully capture transition dynamics, non-linearities, behavioural feedbacks, and potential tipping points that characterize food system change in practice[3,18]. This is a structural limitation of equilibrium models specifically, but of all models more broadly. Addressing these limitations will require methodological advances in modelling and scenario design that can better integrate across temporal scales (discussed further in Section 8.4).

8.2.5 Food system transformation requires whole-of-society changes

Food systems generate substantial value, but they also impose costs across environmental, economic, health, political, and cultural domains. Food system interventions that drive changes across one domain will ripple across other domains[1]. For example, in Chapter 7, policies targeting agricultural emissions to achieve climate objectives increased the price of food and increased food insecurity if not coupled with other policies or interventions[29,36]. The systemic interdependence of food systems has three critical implications for efforts to achieve sustainable transformations:

1. single-metric analysis is insufficient to assess food system interventions,
2. multiple objectives necessitate multiple interventions across food systems, and
3. trade-offs among multiple objectives make hard choices unavoidable.

Multidimensional Assessment

Across the thesis chapters, even when considering individual shocks or interventions (e.g. Alternative protein adoption in Chapter 2), there was a deliberate effort to assess the consequence across social, economic, nutritional and environmental outcomes, including food security, agricultural emissions, employment and wages, blue water use, and dietary quality. The following illustrate how this played out across the chapters, with Chapters 2 and 7 providing the most explicit multi-dimensional analyses:

- Chapter 2 developed and extended the USAGE-Food model beyond standard economic metrics linking to LCA studies for estimating environmental footprints of production, and the application of a structured ethical framework. This framework was applied to assess outcomes across four moral lenses: (1) valuing the natural world, (2) human rights, (3) distributional justice, and (4) animal welfare. This revealed that the adoption of plant-based alternatives to beef in the USA could generate an array of trade-offs. Agricultural emissions declined across all scenarios, but substantial reductions in labour demand in the cattle and meat processing sectors raised concerns about economic dislocation in rural communities. Furthermore, the modelling suggested that freed up feed resources from the beef sector could encourage an expansion of pork and poultry production, with animal welfare implications.
- Chapter 3 highlighted the need for interventions across the fruit and vegetable supply chain, as increased production of fruits and vegetables could contribute to greater food loss and waste and increase environmental pressures if not accompanied by complementary interventions.

- Chapter 4 expanded the analysis of food and nutrition security beyond calorie supply to include dietary quality and nutritional adequacy of micronutrient supply. This was done by incorporating detailed nutritional composition tables to extend dietary analysis.
- Chapter 7 considered the environmental and socioeconomic implications of an EAT-Lancet style food system transformation, highlighting trade-offs between producing sufficient healthy food and reducing fertilizer use. Chapter 7 also showed the risk that a shift to healthy diets could make food less affordable in low- and middle-income regions, without additional targeted interventions.

True transformation of complex systems requires solution bundles

The challenges facing food systems are complex, and fit the definition of wicked problems, i.e., they are characterized by deep interconnections, multiple and often conflicting objectives, and fuzzy, poorly defined solutions[37–39]. In contrast to tame problems, which can be solved with targeted technical interventions, wicked problems resist simple solutions, as addressing problems along one dimension can reveal or create novel challenges along other dimensions. Chapter 3 illustrated this, showing that achieving healthy consumption levels of fruits and vegetables cannot be accomplished by targeting consumers alone. Current food systems in many countries are locked into a low-consumption equilibrium sustained simultaneously by production constraints, supply chain inefficiencies, affordability challenges, and consumer preferences including cultural norms and taste. Moving to a higher consumption equilibrium would require multiple coordinated interventions, including:

- Technological improvements in production, processing, storage, and distribution,
- Economic incentives to facilitate and encourage consumers and producers to change behaviour,
- Information and awareness programs which work by changing meta-desires (i.e., informing and encouraging consumers and producers to want to want new things).

A food system transformation is a nested doll of wicked problems, and requires simultaneously achieving multiple goals (e.g., reducing agricultural emissions, improving nutrition, protecting livelihoods, etc.). Each layer of this nested doll presents its own policy dilemmas, with interventions designed to address one problem potentially generating new challenges that threaten to undermine progress toward other objectives. The Tinbergen Rule established that achieving N policy objectives requires at least N independent policy instruments[40], implying that for a sustainable food system transformation a bundle of complementary and coordinated interventions is not optional but a necessity. A growing body of literature has formalized this logic through the concept of solution bundles[41] and nexus approaches[42], which argue for the deliberate development of portfolios of interventions, innovations, and policies that are aligned across multiple objectives. The practical implications are stark, positive food system change cannot be achieved with silver bullets. For example:

- Addressing food insecurity requires simultaneously improving productivity, reducing poverty, increasing market access, and improving dietary knowledge.

- Reducing agricultural emissions cannot be achieved through efficiency gains alone if demand continues to grow.
- Improving dietary quality is as much a supply chain challenge as one of affordability and consumer choice.

Together this points to the same conclusion. Sustainable and just food system transformations require not just more interventions, but better coordinated ones. The following illustrate how the thesis engaged with the challenge of bundling interventions, with Chapter 7 providing the most explicit application of solution bundling:

- Chapter 2 showed that the adoption of plant-based beef alternatives could contribute to reductions in agricultural emissions, but was not an environmental panacea, with more ambiguous consequences on water use, and potential animal welfare concerns. It also highlighted potential challenges of socioeconomic dislocation, which would necessitate additional interventions for more just transitions.
- Chapter 3 demonstrated that achieving healthy fruit and vegetable consumption would require coordinated effort across the entire food chain, with complementary demand- and supply-side interventions.
- Chapter 5 illustrated the potential of increased investment in agricultural R&D to reduce food insecurity in Africa, while showing that without complementary interventions in market access and poverty reduction, increased R&D investments alone would not fully eradicate hunger by 2030.
- Chapter 7 explored an EAT-Lancet style food system transformation, composed of four bundled drivers: (1) increased productivity, (2) reduced food loss and waste, (3) a shift to a healthy diet, and (4) ambitious mitigation efforts[29]. Drivers were assessed individually and in combination[43], which showed that increasing agricultural productivity reduced the cost of food, but in isolation had a small impact on environmental objectives, due to rebound effects on demand. It was only when productivity gains were coupled with dietary shifts and reduced food loss and waste that efficiency gains translated to improved environmental outcomes.

Complexity and Hard Choices: the oxymoron of win-win solutions

The desire to frame food system transformation around win-win solutions is understandable. Politically, emphasizing complementarities and shared benefits is essential for building broad coalitions needed to sustain collective action[1,44]. It is also important to note that synergies and complementarities do exist, as highlighted in the recent IPBES Nexus assessment[42] and 2nd EAT-Lancet commission[29]. However, win-win framings can be a form of wishful thinking that obscures rather than resolves the hard choices that transformation inevitably requires. Change does not benefit everyone, everywhere, all at once. Costs are real and unavoidable. Ignoring this reality only defers the political and moral reckoning.

The philosopher Ruth Chang has argued that hard choices are hard precisely because different alternatives are not consistently better across all dimensions of interest[45], and that critical outcomes may not be strictly comparable[46]. In food systems, this is compounded by the n-lemma, where multiple objectives and finite policy instruments ensure trade-offs are unavoidable. N-lemmas are common in complex policy decisions. For example the impossible trinity in monetary policy where only two of three objectives can be achieved simultaneously (a fixed exchange rate, independent monetary policy, and capital mobility)[47]. In food policy, the energy-water-food nexus presents a direct analogue, where water allocation can only be optimized to one of many uses (irrigation, environmental flows, energy, etc.)[42]. Such trade-offs are a defining condition of food system transformation. Choices about which interventions to prioritize, how costs are distributed, and at what pace change occurs will produce different outcomes for different people, determining who benefits and who bears the costs of change. These are not fundamentally technical questions with objectively correct answers. They are value judgements that require transparent deliberation and public discourse[48] amongst decision-makers, stakeholders, and the communities from which they come.

Foresight models are powerful learning machines that can make hard choices more visible. However, these tools should not be used to outsource judgement. They cannot tell us what kinds of futures we should want. While anticipatory governance cannot resolve challenging value judgements for decision-makers, it can equip them with tools to surface critical trade-offs, make assumptions more explicit and transparent, and create conditions for more honest and informed deliberation[1,3,13]. As such, the goal is not to identify the objectively correct path forward, but to illuminate the choices that lie along different paths, and to do so in ways that are transparent, and inclusive. The following illustrate how the thesis engaged with hard choices, with Chapters 2 and 6 providing the most explicit engagement:

- Chapter 2 explicitly applied four moral lenses (valuing the natural world, human rights, distributional justice, and animal welfare) to the same modelling results, demonstrating that what counts as a good outcome depends fundamentally on the values brought to the assessment[49]. The finding that employment in beef processing could decline by more than 40 percent under high adoption scenarios was not simply a distributional footnote. It raised critical questions about who bears the costs of technological change, an important question as we begin our transition into the world of AI.
- Chapter 6's participatory regional scenarios demonstrated that no single future was uniformly best across all stakeholders and objectives. Critically, the most consequential insights of the participatory process emerged not from the model outputs themselves but from the discussions they provoked, with modelling results serving as boundary objects that surfaced assumptions, exposed disagreements, and created conditions for more honest deliberation about the choices ahead[7,50].
- Chapter 7 as a part of the second EAT-Lancet Commission[29], embedded an ethos of justice through the explicit application of three intersecting justice lenses: distributive, procedural, and recognitional, proposing nine Social Foundations as minimum condi-

tions for a just food system transformation. While modelling in this chapter could not address all nine foundations directly, it highlighted potential consequences relevant to several, including threats to the right to food through reduced affordability in low- and middle-income regions, and risks to the right to decent work through agricultural labour displacement.

8.2.6 Unanticipated consequences are the rule not the exception

The six case studies in this thesis repeatedly revealed unanticipated consequences, not as analytical failures, but as substantive insights that only become visible when foresight models are applied holistically enough to capture key system interactions. This has an important implication for anticipatory governance. The goal of foresight analysis should not be to predict the future, but to expand the horizon of what policymakers recognize as possible, and to encourage increased futures literacy as they prepare to adapt to and shape an ever-changing future.

Substitution effects can undermine intended benefits

Chapter 2 found that while plant-based beef substitutes reduced cattle numbers and carbon emissions, the reallocation of saved resources (land, water, capital) across the broader economy produced ambiguous results across other environmental outcomes. Similar results were observed in Chapter 7, where increased productivity in isolation could lead to lower prices and increased demand eroding potential environmental gains from improved resource use efficiency. These results highlight the importance of understanding substitution and rebound effects, which can be overlooked by those championing technological innovation, despite a long history of rebound effects undermining environmental and natural resource gains (e.g., Jevons Paradox)[1].

Global trade networks can contribute to wide-ranging and unexpected impacts

A consistent finding across the thesis is that global trade acts as both a buffer and a transmission mechanism. Trade links regional food systems in ways that are often surprising and politically consequential. Shocks and transformations that appear within one region or sector regularly propagate across global supply chains, sharing the burden to consumers and producers elsewhere. In Chapter 4, for example, trade stabilized domestic food supply in China following an outbreak of African Swine Fever, but in doing so had positive and negative consequences to producers and consumers in other regions. Decline in the Chinese pork sector led to lower maize prices globally, good for consumers of maize, but a challenge for maize producers. Chapter 7 demonstrated that trade contributed to more efficient global resource use as production shifted to meet healthy diet targets, but in doing so risked exposing vulnerable agricultural workers to economic dislocations[18,51]. These findings complicate simple narratives of self-sufficiency and globalization, highlighting that resilience at one level can come at the expense of vulnerability at another.

Interconnected supply chains drive complex up- and down- stream impacts

The trade findings discussed above reveal how food system shocks and transformations propagate across geographic regions. A parallel dynamic operates within food systems themselves. Interventions that appear targeted and contained at one point in the value chain regularly generate consequences that percolate upstream through supply chains and downstream through markets, employment, and household welfare. Where trade connects food systems horizontally across regions, value chain linkages connect them vertically across production, processing, distribution, and consumption. As economic development and the nutrition transition continue globally[52–54], food systems are characterized by increasingly complex and longer supply chains, with more interconnected upstream relationships and a wider array of potential uses for agricultural commodities[41,55]. Chapter 4 illustrated upstream propagation with large-scale reduction of pork production caused by African Swine Fever in China freed cereals previously destined for animal feed for direct human consumption, contributing to improved food security in Eastern Africa, even as depressed household incomes in China altered Chinese food demand. Chapters 3 and 7 highlighted a different upstream dynamic, showing that achieving healthy consumption levels of fruits and vegetables could increase the use of chemical inputs, complicating efforts to simultaneously improve diets and reduce agricultural environmental pressures. Chapter 2 demonstrated the downstream dimension, showing that the adoption of plant-based beef alternatives could displace agricultural labour, underscoring that the benefits of food system innovation are rarely distributed evenly across the supply chain[1]. Together these findings point to a common lesson. The full consequences of food system interventions cannot be understood without tracing their effects across the entire system.

Responsible innovation critical for a just food system transformation

Innovation, broadly defined to include technological, institutional, and social innovations, has been a critical driver of past food system change[1,56–58]. The thesis engaged this reality across the full range of innovation types, from R&D investment and novel food technologies to governance innovations and demand-side dietary shifts[18]. Yet the unintended consequences documented across the preceding sub-sections point to a structural challenge that innovation processes have historically been too narrowly conceived, underestimating systemic complexity and side-lining those most exposed to the costs of change. Addressing this requires more intentional and responsible innovation, innovation that is anticipatory, reflexive, inclusive, and responsive[59]. When applied systematically, such approaches can support mission-oriented innovation systems that align portfolios of technologies, practices, and governance structures with shared social and environmental goals[41,60,61].

The anticipatory governance approaches demonstrated across this thesis directly contribute to building this culture of responsible innovation. The repeated surfacing of unintended consequences (rebound effects, upstream supply chain cascades, labour displacement, distributional trade-offs) is evidence of what foresight modelling can reveal when applied

holistically enough to capture system interactions. Each finding is not an analytical failure but a contribution toward the more reflexive and anticipatory approach to food system innovation that Mason-D'Croz et al. argues is needed[1]. Building this culture will require not just better models, but more deliberate integration of anticipatory governance into innovation decision-making to ensure that the questions foresight research asks are as important as the answers it provides[3,18].

8.3 Bridging the gap between research and policy

Impact-oriented research for development (R4D) must move beyond the generation of knowledge toward translating it into development outcomes. Theories of Change (ToC) and impact pathways are representations of change processes that embed impact-oriented research within the context of how change happens[62–64]. Figure 1.1 in Chapter 1 illustrated a stylized impact pathway connecting inputs, research activities, outputs, and wider impact. Evidence-based decision-making can only be achieved when there is an alignment of multiple factors including[7,65–67]:

- Relevant research and a political window of opportunity,
- Credibility and legitimacy of researchers,
- Accessibility of outputs,
- The presence of boundary actors who can translate findings across the science-policy interface.

Absent these enabling conditions, even exemplary foresight work risks remaining confined to academic circles[18,65]. As such, academic publishing is a necessary but rarely sufficient condition for research to influence decisions.

Moving along the science-policy engagement continuum (Figure 8.3) requires progressively deeper investment, from knowledge production, through boundary and translation work, to co-creation opportunities where researchers and policymakers jointly define research questions and co-develop responses. This deeper engagement is time-consuming and highly iterative, demanding sustained effort to build and maintain trust. However, without this effort the opportunities to inform policy will be limited, as this engagement not only benefits researchers in terms of access to decision-makers, but it also increases awareness of the needs and challenges confronting them. The most impactful foresight research is often explicitly demand-driven, where co-development and co-creation processes are oriented around questions expressed by stakeholders, rather than questions generated primarily by researchers.

If only the science-policy interface were like Tolstoy's happy families.[V] However, science-policy engagement is unique and specific to each context. As such, it is not reasonable to expect each individual research output to follow the exact same pathway to impact. While there

V Anna Karenina Principle: All happy families are alike; each unhappy family is unhappy in its own way.

is some touch of serendipity to most successful efforts at science-policy engagement, R4D practitioners can improve their chances by proactively engaging with science translation. They must prioritize the development of rigorous, transparent, and open research, but also the communication of findings to decision-makers, civil society, and the general public. This represents policy informing work (i.e., publications, and translation) and it represents a floor in terms of policy engagement.



Research Role	Knowledge Producer	Knowledge Broker	Co-producer
Extent of Boundary Engaging Work	Limited and passive engagement	Active and framed around specific decision-making processes	Active and iterative with more blended roles between researcher and policymaker
Depth of Relationships	Shallow and uni-directional	Requires greater levels of trust, and more bilateral engagement	Partnership requiring high level of trust for sustained collaboration
Key Activities	Publish journal articles, reports, and initial translation to broader audience (e.g., blogs, briefs, visualizations)	Greater focus on outreach and communication, with more targeted translation of policy implications of research to inform specific questions	Embedding research in the policymaking processes with joint agenda setting in terms of research questions and policy design

Figure 8.3: Science-policy engagement continuum.

Notes: The most impactful foresight research tends toward the right of this continuum, with research questions that are explicitly demand-driven and co-defined with intended users.

Policy Informing

A consistent effort was made to ensure the research in each chapter of this thesis was open and transparent. This extended beyond the final publications themselves to include technical reports, model documentation, conference presentations, and policy briefs with the objective of making models, model results, and their implications more accessible. For example, detailed model documentation for IMPACT[17], GLOBE[68], USAGE-Food[69] as well as documentation for model coupling of DSSAT-IMPACT[70,71], and IMPACT-GLOBE[72] provided detailed description of model specification and baseline assumptions. This was with the goal for transparency and reproducibility of the modelling conducted across the thesis. Additional translation efforts included the development of policy briefs extending and contextualizing the findings of Chapter 5 with other IFPRI research on hunger eradication in Africa[73], and an interactive online data visualization to facilitate access to and use of Chapter 3 results[74]. Efforts to reach non-specialist audiences have included engaging with journalists and podcasters to translate findings to a wider public. These activities collectively represent the

policy informing foundation upon which the deeper engagements described in the following sub-sections were built.

Policy Supporting

Over the course of this thesis, there were also opportunities to engage more deeply with decision-makers to help translate research into action. Several of these engagements were explicitly demand-driven, with institutional partners defining the questions that research was asked to address. The Farm Journal Foundation commissioned a report drawing on findings from Chapter 3 to inform U.S. congressional debate on the role of nutrition and agricultural policy in supporting global food security[75], a direct example of research being oriented around a specific policy question expressed by an institutional partner. Similarly, the modelling work underlying Chapter 5 originated as a commissioned FAO report, with the research question defined in direct response to FAO's institutional priorities. Results from this work subsequently contributed to broader discussions around CGIAR investment portfolio with USAID[76], extending the reach of the findings across multiple institutional contexts. The visibility of Chapter 2's findings on alternative proteins also facilitated inclusion in a UNEP summary report on the present and future of alternative proteins[77]. This demonstrates how peer-reviewed research can be an important input into intergovernmental knowledge synthesis. Chapter 7's embeddedness in the second EAT-Lancet Commission has generated substantial translation efforts, including regional launch events aimed at building awareness among policymakers and civil society, as well as with interested groups of stakeholders actively working to translate the Commission's science into concrete policy and actions. While these latter efforts remain at an early stage, they present the possibility for future deeper engagement.

Policy Co-Creation

Policy co-creation is perhaps the gold standard of evidence-based decision making. However, it is also the hardest to achieve, given the substantial efforts in translation, engagement, and sustained partnerships that are needed. Despite these demanding requirements, the work in this thesis has contributed to several meaningful policy co-creation processes.

- The clearest example of co-creation comes from Chapter 6, where participatory stakeholder processes were embedded at the core of developing the South East Asian regional scenarios[6,7]. Scenario design was aligned to the specific interests and questions of regional stakeholders, and the resulting scenarios and modelling were used to help shape agricultural policy in Southeast Asia, including contributing to Cambodia's Action Plan for Agriculture[78] and investment proposals for Climate-Smart Agriculture in Vietnam[79]. Importantly, this work was one component of the broader CCAFS regional scenarios project, which developed participatory socioeconomic and climate scenarios across seven regions: East Africa, West Africa, South Asia, Southeast Asia, the Andes, Central America, and the Pacific. This project engaged with nearly 250 organizations over the project's lifetime[79–81]. Across these regions, the scenarios were explicitly designed to evaluate and

develop policies and investment plans. Documented policy outcomes include Uganda's Mechanization Framework and National Agriculture Policy and Tanzania's National Environmental Policy[81], scenario-guided agricultural policy processes in Ghana[80], and Honduras's National Strategy for Climate Change Adaptation in Agriculture[80]. The Economic Community of West African States established a close collaboration with CCAFS built around the West Africa regional scenarios process, with the approach gaining considerable institutional support for shaping regional and national policy priorities[82]. This sustained multi-regional effort illustrates what becomes possible when foresight research is designed from the outset with co-creation in mind, looks to embed long-term relationships with institutional partners, and is supported by the resources needed to sustain such engagement over time.

- Research on food system innovation, including Chapters 2 and 5, contributed to a different but equally significant co-creation process. FAO identified a need for a rigorous evidence base to underpin a new flagship report on agri-food system innovations (FAO Agri-Food Technology and Innovation Outlook[83]), creating an explicitly demand-driven co-creation opportunity. Prior published work on food system innovation[41,56–58] illustrated how sustained investment in a coherent body of published research can create the credibility and visibility needed to contribute to high-level institutional knowledge co-creation processes. However, the story of this engagement likely would be considered marginally successful. Changes in institutional priorities and key personnel led to a deprioritization of this area of work. This underscores the fragility of science-policy engagement and a recurring challenge to co-creation. It takes two to tango, and without policy partners the critical link between research and policy uptake can unravel. Learning how to build more resilient and institutionalized relationships, rather than relying on individual champions, remains an important frontier for impact-oriented anticipatory governance research.

These reflections are not intended to overstate the policy influence of this body of work. Rather, these reflections are intended to illustrate the deliberate effort to move research along the research for development impact pathway, and to reflect honestly on what that journey reveals about the science-policy interface. Collectively, these experiences suggest that the impact pathway depicted in Figure 1.1 is best understood not as a linear production model, but as an iterative, contested, and politically embedded process in which the credibility, salience, and legitimacy of research outputs are continuously negotiated with intended users[65]. Improving this process requires[1,13,84]:

- researchers to develop more adaptive, iterative, and co-produced foresight research,
- building long-term relationships with institutional partners,
- systematically learn from both successful uptake and failed translation,
- proactively develop greater science and futures literacy amongst policymakers, through targeted capacity-building efforts and participatory scenario exercises[85,86]

Substantial work remains to better understand under what conditions foresight research can change policy, and what design features enhance policy relevance without sacrificing academic credibility[13]. And anticipatory governance is not a silver bullet[1]. Nevertheless, a more honest and reflexive engagement with anticipatory governance's own theory of change and a proactive engagement in the science-policy interface is a precondition for informing and hopefully co-producing more just and sustainable future food systems.

8.4 Critical Assessment and Next Steps

The six case studies in this thesis demonstrated how foresight modelling can help to identify key trade-offs and potential unintended consequences. And how the surfacing of these is critical for informing better anticipatory food policy. However, an honest assessment of this body of work cannot be done without also engaging openly with its limitations, a practice that is itself central to rigorous anticipatory governance[1].

All models are, by necessity, simplifications of reality, and the value of foresight modelling lies not in producing definitive answers but in systematically and transparently engaging with uncertainty[3,13]. As such, acknowledging limitations should not be seen as a concession of failure, but a prerequisite for responsible use of model outputs in policy contexts. To this end this section will assess the principal limitations of this thesis across three domains (data, scenario design, and modelling) before moving to suggesting next steps for foresight modelling and anticipatory food system governance.

8.4.1 Data Limitations

Data availability is a recurring constraint that shapes what can be modelled as well as how confidently we should interpret model results. Chapter 3 explicitly noted that due to data limitations in the international databases (i.e. FAOSTAT) used to parametrize IMPACT, fruits and vegetables had to be represented in four broad commodities, limiting the ability to capture substitution effects within the fruit and vegetable sectors. Food loss and waste is a topic of increasing interest and an SDG target (12.3). Nevertheless, FLW estimates remain notoriously uncertain. The most widely cited estimate suggests approximately one third of all food produced globally is lost or wasted across the supply chain[87,88]. However more recent analyses suggest this figure could be as much as 40 percent when on-farm losses are fully accounted for[89,90], with other past studies suggesting it could be as high as half[91]. These divergent estimates reflect not just different methodologies but serious knowledge gaps. This real ignorance of the current state of FLW is a serious challenge in terms of how to consistently simulate it in food system models[92]. In Chapter 3, this uncertainty was partially addressed by using a range of food loss and waste scenarios (0-33 percent) to get some sense of sensitivity of results to varying FLW assumptions. In Chapter 7, this uncertainty was partially addressed by using a multi-model ensemble where each model had a somewhat different representation of food loss and waste dynamics. Efforts to estimate the nutrient adequacy of diets are similarly constrained due to the scarcity of real-time consumption and utilization data and

the paucity of regional studies[93]. Efforts to better characterize baseline nutrient supply[94,95] are therefore essential, and have provided the empirical grounding for modelling efforts to assess nutrient supply in Chapter 4. Data limitations are also a serious barrier to the modelling of heterogeneous actors and under-represented populations, a structural challenge that limits the detail to which distributional consequences can be represented[3].

Multi-model ensembles can partially mitigate data limitations by exploring how different data sources and model structures affect projected outcomes (e.g., Chapters 6 and 7). However, additional models cannot eliminate the consequences of limited data entirely, and the use of multiple models can threaten to introduce more noise and complexity which can challenge communication of results with decision-makers. Well-designed scenarios similarly can help navigate data uncertainty. Scenarios can be designed to bracket key unknowns within plausible ranges, and test how sensitive the system is to changes in assumptions, as was done with FLW in Chapter 3. However, again these approaches are adaptive responses to data limitations, and do not substitute for continued investment in improving the underlying data systems that food system models depend on.

8.4.2 Scenario Design Limitations

Scenarios are useful tools for exploring alternative futures and engaging systematically with system complexity and future uncertainty. Nevertheless, applying scenarios does not ensure that the futures considered fully encapsulate the possibility space, or are salient to all potential stakeholders. Two related limitations are particularly relevant to the scenario design choices made across this thesis: (1) the tendency to cluster around conventionally plausible futures, and (2) the tendency toward linear representations of change.

The predominantly top-down approach to scenario design used across this thesis (see section 8.2.2) prioritizes scientific rigour, reproducibility, and transparency, but can inadvertently sideline broader normative discussions of what futures are or should be desirable[3]. A critique that has been levelled at many global scenario outputs, which have often clustered their research around more "plausible" futures, based on conventional understandings of the past and present (Figure 8.4), at the expense of exploring wilder, more transformative alternatives[96,97]. And while participatory scenarios can open up futures discussion if well designed, they too face real limitations[19]. Participatory processes can be biased toward the perspectives of more organized and better-resourced stakeholders, potentially side-lining the voices of more vulnerable stakeholders. Additionally, it is not feasible to engage stakeholders in the quantification of all model parameters, meaning that despite even the best efforts, there is still some element of expert judgement needed[30], for example the inclusion of crop model inputs for Chapter 6. As such it is essential to find ways to blend the strengths of both approaches in a transparent and careful manner. A hybrid approach to scenario design that combines the analytical rigour of data-driven methods with the contextual richness and political legitimacy of participatory processes[7,21].

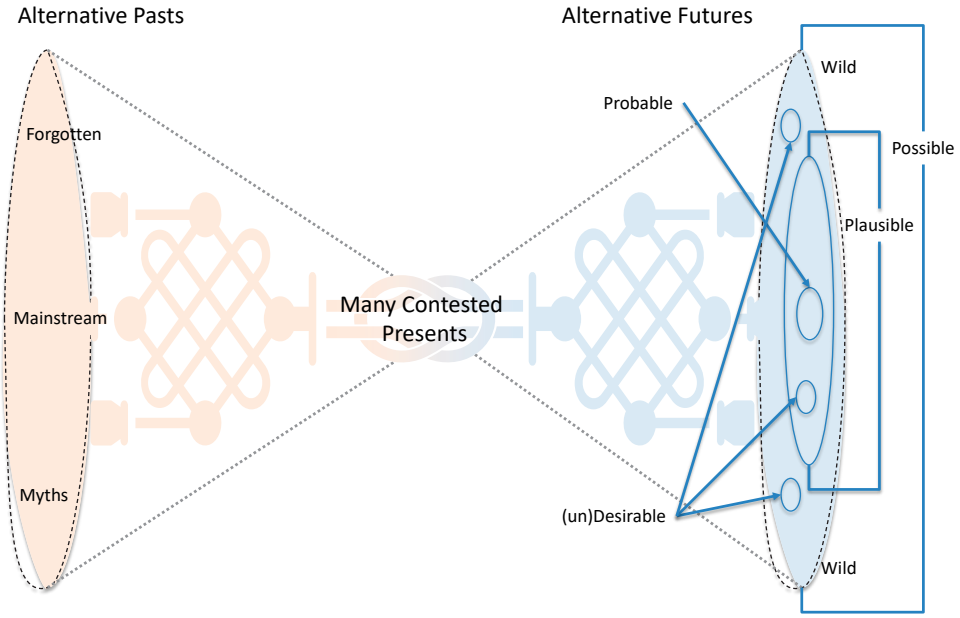

Figure 8.4: Past and Future Cones

Notes: Adapted from Theunissen 2026[96].

Linear thinking is a more fundamental limitation of the scenarios applied across this thesis, and broadly a challenge to how we design narratives of change. Most scenarios focus on end-state outcomes, asking what the food system might look like under different assumptions, rather than on the pathways of change that connect the present to those futures. As Mason-D'Croz and Herrero[18] noted, plausible food system transformation will be a lot messier than the current stylized scenarios of food system transformation suggest. There will be much less regional coordination and convergence, and a broad range of non-linear outcomes. Real transformation pathways are messy, non-linear, and path-dependent, shaped by political windows, behavioural feedback loops, and the (un)managed obsolescence (i.e., the deliberate phasing out of entrenched technologies, norms, and vested interests) of existing practices and institutions. Expecting models based and validated on past behaviour to endogenously simulate system transformative change is not reasonable. Nevertheless, substantial effort can be made to engage with a wider range of modelling approaches (e.g., agent-based, and system dynamic models) that are better suited to capturing a wider range of behaviours than are simulated in equilibrium models[3]. Even so the need for messier wilder scenarios of change is also clear[3,26], and the development of richer and more realistic transition narratives that engage with the socio-political conditions, institutional changes, and behavioural shifts remains one of the most important frontiers for food system foresight research[18].

8.4.3 Model Limitations

The economic models applied across this thesis are powerful tools, but like all models they rest on simplifying assumptions that shape what they can and cannot represent. All the economic models used in this thesis, whether general or partial equilibrium, are based on neoclassical economic theory and assume rational actors that are profit or utility maximizing. They are primarily macro (i.e., national, and global) in scale, with limited representation of heterogeneity at the household or firm level. This is a reasonable simplification for capturing aggregate behaviours and broad trends, but it limits the ability to assess distributional consequences, or detailed behaviours along the value chain. Furthermore, these models are less suited to simulating the socio-political drivers of food system change, including shifts in cultural norms, and political economy dynamics, which if they are included in analysis are captured as exogenous shocks. As a result, many of the scenarios represented in this thesis are necessarily of the "what if" variety, exploring the consequences of an assumed change rather than the conditions under which that change might occur. This highlights the importance of combining quantitative foresight modelling with qualitative scenarios that can engage more directly with the socio-political dimensions of transformation[3,18,26], whether it is done through participatory approaches or through the development of scenarios based on historical precedents.

Beyond the challenges of trying to simulate these behaviours, or the difficulty if not impossibility of endogenously modelling structural change in a model designed to simulate the behaviour of existing systems, equilibrium-based models present another important limitation, they assume the system can be in equilibrium. This is a major simplification of reality. Equilibrium models assume that a) there is a stable steady state, and b) once shocked from this steady state there is an effort to return as closely as possible to this steady state. This assumption is most consequential in the comparative statics analyses of Chapters 2 and 4, where the analytical logic explicitly compares two equilibrium states before and after a discrete shock. Viewed through the lens of resilience theory, which distinguishes between absorptive, adaptive, and transformative capacities[98], equilibrium models can reasonably simulate the absorptive capacity of the food system (i.e., the ability of a system to buffer and recover from a shock without structural change). Chapter 4's analysis of African swine fever in China is a good example of this. However, equilibrium models are moderately well-suited to capturing adaptive capacity (i.e., how systems learn and adjust their behaviour over time in response to changing conditions) and poorly suited to capturing transformative capacity (i.e., the structural shifts in institutions, behaviours, and cultural norms that characterize deeper system change). This is not a unique flaw of the models used in this thesis but a structural feature of equilibrium modelling more broadly[3], and recognizing these boundaries is not a reason to dismiss equilibrium models but to guide their more responsible use.

A final structural challenge concerns the relationship between model complexity and the science-policy interface. The models used in this thesis are sophisticated enough to capture

important system dynamics, but this very sophistication creates two competing risks. First, complexity can overwhelm policymakers, requiring substantial translation work to build the legitimacy and trust needed for results to be used rather than dismissed[3,67]. Second, and perhaps more insidiously, complexity can also foster overconfidence, as the apparent precision of model outputs can give decision-makers a false sense of certainty[2]. Managing this dilemma requires a careful communication strategy, one that is honest about model limitations and uncertainty without discrediting the genuine value of what models can reveal, and that presents results as inputs to open deliberation of future possibilities[13,99]. The experience across the thesis chapters, and in the science-policy engagement described in section 8.3, suggests that this balance is achievable but demands sustained investment in the relationships, mutual understanding, and communications capacity that effective model-informed governance requires.

8.4.4 Future needs

Addressing the limitations identified above will require sustained investment across several interconnected areas. The following highlights the most pressing priorities for advancing anticipatory governance in food systems foresight research.

- **More people-centric foresight** Food system foresight remains concentrated among a narrow set of research groups, predominantly based in the Global North[19,20]. While there have been efforts to be more inclusive, this concentration remains a barrier to engaging with more pluralistic futures, limiting whose interests are represented in foresight research. Addressing this will require investing in building local modelling capacity and futures literacy through sustained engagement that sees training as two-way partnership rather than a unidirectional knowledge transfer. It will also require directly engaging with inequalities and power imbalances throughout the modelling process, not just in scenario development (Section 8.2.2), but also in model design itself, in the decisions about which behaviours are simulated. More people-centric foresight must treat these questions seriously, recognizing that who gets to build, run, and interpret models is highly consequential[1,3].
- **More multi-scale research is needed** A challenge noted across all chapters in this thesis, and consistently identified in the broader foresight modelling literature, is the need for greater ability to simulate food systems across scales[3,13]. The models used in this thesis operated primarily at the national and global level, but many of the most important consequences of food system change, including on livelihoods, nutrition, and local ecosystems, play out at sub-national and household scales. Greater effort is needed to link across micro, meso, and macro scales to capture important feedbacks, and to bridge the gap between the bottom-up granularity of local analyses and the broad coverage of global models[100].
- **Better representation of value chains and the missing middle** The models used in this thesis evolved primarily from a supply-side food production orientation, with primary production represented in greater detail than processing, distribution, and retail. Gen-

eral equilibrium models capture more of the value chain but often represent these stages superficially due to data limitations and computational constraints. Partial equilibrium models can go into much greater detail within a sector but often have to compromise by not capturing as much detail up and downstream of production. Improving value chain representation will require both endogenizing supply chain dynamics within existing models by expanding sectoral coverage, and linking to more detailed sector-specific models that can represent the whole value chain from processing, distribution and retail[3].

- **Better represent cultural and behavioural shifts** Most of the models used in this thesis represent behavioural changes as exogenous drivers, with preference shifts imposed on the model rather than emerging from it. While it may not be possible to fully endogenize complex behavioural dynamics within equilibrium models, richer representations in qualitative narratives and more creative applications of the models are possible. For example, recent work modelling degrowth in Australia tried to change the utility function in a CGE model to model the change in norms around consumption[101]. Additionally, there is a lot to be learned by coupling equilibrium models with other behavioural models. Agent-based and system dynamic models can better capture heterogeneous behavioural responses and non-equilibrium feedback loops. Developing frameworks that couple these approaches with the equilibrium models applied in this thesis remains an important methodological frontier, and one that could substantially expand the kinds of futures we could model[3,26].
- **Move from "what if" to "how"** Many scenarios have focused on end points. However, there needs to be a greater focus on the representation of transition pathways that can better capture the non-linear realities of system change. As highlighted throughout section 8.4, current models and scenarios are better suited to asking what the food system might look like under different assumptions than to exploring under what conditions and through what processes transformation might occur. Addressing this will require more realistic representations of technological change and managed obsolescence, greater attention to the interactions between interventions and adaptive responses to change along a transition pathway[3,13,18].
- **Greater engagement with wilder futures** There is a need to explore a wide range of transformative futures. A sustainable food system transformation is by definition a radical break with current food systems. Exploring scenarios primarily bounded by plausible business-as-usual assumptions can be informative for many questions. However, it limits what can be said about larger scale systemic change, such as worlds with developed circular economies[102], or where conventional consumerism is replaced by agrowth or degrowth philosophies[101], or where the value of nature is more fundamentally centred in societal choices[103]. Future scenarios should engage more imaginatively with this wider possibility space and ask fundamentally bigger questions. That is, anticipatory governance should try to help ask not just what futures are feasible or plausible, but what futures are worth aiming for[19,26].

- **Strengthening the science-policy interface** Realizing the potential of anticipatory governance requires continued investment in communication and translation of foresight research. A particular challenge is the lack of speed in the development and improvement of models and scenarios. This runs into the time-dependent needs of policy makers, who have to make decisions immediately. Finding novel approaches to speed up development processes is important. Much foresight research is underused, with substantial amounts of effort in developing models and scenarios left untouched after a few papers. Making results more available would be helpful to increasing the use of these outputs, but new tools and approaches that can help to synthesize and generalize modelling results would be invaluable to use existing results and apply them more readily to new questions. AI tools offer promising opportunities both for improving communication of complex model outputs and for accelerating data processing and model development, though more research is needed on how to deploy these tools in ways that enhance rather than undermine the overall quality and integrity of anticipatory governance[3,13]. Building futures literacy among decision-makers and institutions is also critical. Futures literacy varies substantially across and within institutions, and without a baseline capacity to engage critically with scenarios, model outputs, and uncertainty, even the most carefully communicated foresight research risks being misunderstood, oversimplified, or ignored. Targeted capacity-building efforts, from training workshops on specific modelling tools to broader participatory futures exercises, can help build this capacity over time[13,19].
- **Use models as "learning machines"** Model results are too often presented as projections of what could happen, rather than as inputs to a deeper process of learning about how food systems work. Embedding models and scenarios within more participatory co-creation processes can transform them into dynamic learning tools, revealing missing questions, feedback loops, and uninterrogated assumptions. These looped learning processes are also one of the most effective ways to build futures literacy, developing decision-makers' intuition about system dynamics embedded in models, uncertainty, and the limits of prediction through direct engagement with models and scenarios rather than through passive instruction[1].

Addressing these priorities collectively would not eliminate the fundamental uncertainties that characterize food system foresight, but it would improve the ability of anticipatory governance to engage with the full complexity of food system transformation.

8.5 Toward More Rigorous and Responsible Anticipatory Governance

This thesis looked to demonstrate how anticipatory governance research when applied rigorously and reflexively can generate critical insights on current and future food systems[1,3]. The six case studies showed that quantitative foresight modelling can be a powerful tool for expanding the horizon of what decision-makers recognize as possible[13,99]. However, this can only happen when it is deliberately designed to explore food system complexity and engages with future uncertainty. Responsible anticipatory governance requires acknowledging mod-

els are simplifications and that the projections made with them are built on many assumptions and subject to many limitations. However, these should not be seen as failures but as inherent features of modelling. When models are coupled with scenarios their use should be to broaden what alternative futures are envisioned and to help organize dialogue around how systems change, and what kinds of change are desired. This is the core contribution of rigorous anticipatory governance. It is not the elimination of uncertainty, but its systematic, transparent, and honest engagement[1].

The case studies in this thesis point to several cross-cutting implications for food system governance. First, policies aimed at transforming food systems must be designed as portfolios of coordinated interventions. Single targeted interventions can achieve important improvements, but due to the complexity of food systems as well as the complexity of the goal of achieving sustainable and just food systems, they cannot achieve on their own a fully sustainable and just transformation[40,41]. There are no silver bullets. Second, distributional impacts deserve as much attention as aggregate outcomes. Understanding who benefits and who bears the cost of a food system transformation is critical. Transition policies that generate concentrated costs, however beneficial in aggregate, will face both political resistance and legitimate justice challenges[12,29,48]. Third, in a world of increasing complexity and of fundamental future uncertainty, there is a need for greater adaptive capacity across the anticipatory governance spectrum. Research needs to become faster and more responsive. The public sector and civil society need to increase their futures literacy and competence. And all would benefit from a greater appreciation of the law of unintended consequences[1].

This thesis deliberately engaged with multiple disciplinary perspectives, reflecting a conviction that food system foresight research should not be done from a single analytical vantage point. The case studies drew on economics, nutrition science, ecology, agricultural science, and ethics, applying them not in sequence but in synthesis.

- Chapter 2 extended economic modelling through an explicit ethical assessment framework, asking not only what would happen but whether it would be good and for whom.
- Chapters 3 and 4 embedded nutritional science into economic models, recognizing that food security is fundamentally about nourishment rather than just a question about calories (i.e., a man cannot live on bread alone).
- Chapter 5 connected to innovation economics and theories of knowledge accumulation and creative destruction, situating agricultural R&D investment within a broader theory of how technological change drives food system transformation.
- Chapter 6 drew on participatory and social science methods to ensure that regional perspectives shaped and defined the scenario design and use.
- Chapter 7 linked to planetary boundaries science, public health, and justice theory as a part of a wider analysis of potential implications of achieving more sustainable, healthy, and just food systems.

Overall, these chapters suggest that the most important advances in food systems foresight will come from deeper integration across disciplines. This will require reaching across disciplinary walls beyond the natural and social sciences and to engage more deeply with the humanities, philosophy, history, and the arts. These disciplines have much to offer not only in enriching the potential futures that are to be simulated, but also to communicate these futures in more immersive and convincing ways[1,3,26]. Realizing this potential will require not just methodological advances but a broader cultural shift that moves quantitative foresight from an exercise of finding answers to one of structured inquiry. The thesis is offered as modest contributions toward that shift.

Ultimately, food system transformation is not a technical problem awaiting a technical solution. It is a deeply political, ethical, and social challenge. It will require making hard choices, managing trade-offs, and being attentive to unintended consequences. It will require the building and sustaining of coalitions of actors and stakeholders to not only envision novel desirable futures, but to act towards achieving them. Quantitative foresight modelling cannot do this on its own, but when applied rigorously and reflexively, it can contribute to these efforts[1]. As such, this work is less of a blueprint for the future than a contribution to the ongoing conversation about how to navigate it.

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Appendices and Data Availability

Thesis Digital Repository

A compiled digital repository of all supplementary materials and relevant model documentation was created in Zenodo to facilitate a holistic reading of this thesis: Navigating Uncertain Futures: Applied Foresight Modelling and Anticipatory Governance for Food System Transformation. This repository can be accessed at: https://doi.org/10.5281/zenodo.21709113

This repository contains appendices and supplementary data for the published chapters (2-7) in this thesis, and have been renamed to ease access. The following will describe available files by chapter.

Chapter 2

Based on Mason-D'Croz et al. (2022), The Lancet Planetary Health. DOI: 10.1016/S2542-5196(22)00169-3

1. Appendix 2.1 is the published supplementary materials from Mason-D'Croz et al. 2022[1].
2. Appendix 2.2 is a summary of USAGE-Food results uploaded and published in a Mendeley Data Repository[2] in support of this article available at: http://doi.org/10.17632/dmhhfw2yzt.1.
3. Appendix 2.3 is a technical report summarizing USAGE-Food model construction and scenario construction.
4. Additional model details can be accessed at https://www.copsmodels.com/usage.htm, with full model simulations available in the form of zipped archives in a Mendeley Data Repository available at: http://doi.org/10.17632/dmhhfw2yzt.1. The USAGE-Food model was run using GEMPACK 12.1, which requires a licence. A model-specific and scenario-specific GEMPACK licence to reproduce the model results can be made available. Inquiries to access this limited licence as well as for more detailed training in the use of the USAGE model can be addressed to Peter Dixon (Peter.Dixon@vu.edu.au) and Maureen Rimmer (Maureen.Bleazby@vu.edu.au).

Chapter 3

Based on Mason-D'Croz et al. (2019), The Lancet Planetary Health DOI: 10.1016/S2542-5196(19)30095-6.

1. Appendix 3.1 is the published supplementary materials from Mason-D'Croz et al. 2019[3]
2. Appendix 3.2 is the published supplementary data uploaded and published in a Mendeley Data Repository[4] in support of this article available at: http://doi.org/10.17632/d7m5h5z-vw7.1
3. Appendix 3.3 is the full IMPACT version 3 model documentation[5]

Chapter 4

Based on Mason-D'Croz et al. (2020), Nature Food. DOI: 10.1038/s43016-020-0057-2.

1. Appendix 4.1 is the published supplementary materials from Mason-D'Croz et al 2020[6]
2. Appendix 4.2 contains a data file with all the published figures in Mason-D'Croz et al 2020.
3. Appendix 4.3 is the published supplementary data uploaded and published in a Mendeley Data Repository[7] in support of this article available at: https://doi.org/10.17632/zgrngg-5hp5
4. Appendix 4.4 is Willenbockel et al 2018[8] an IFPRI discussion paper with full documentation of the coupling between the IMPACT and GLOBE models
5. IMPACT model documentation is available in Appendix 3.3

Chapter 5

Based on Mason-D'Croz et al. (2019), World Development DOI: 10.1016/j.worlddev.2018.12.006.

1. Appendix 5.1 is the published supplementary materials from Mason-D'Croz et al 2019[9]

Chapter 6

Based on Mason-D'Croz et al. (2016), Environmental Modelling and Software DOI: 10.1016/j.envsoft.2016.05.008.

1. Appendix 6.1 is the published supplementary materials for Mason-D'Croz et al 2016[10] and summarized the LandShift Model[11]
2. Appendix 6.2 is the published supplementary materials for Havlik et al. 2014[12] which documents the GLOBIOM model
3. IMPACT model documentation is available in Appendix 3.3.

Chapter 7

Based on Rockström et al. (2025), The Lancet DOI: 10.1016/S0140-6736(25)01201-2.

1. Appendix 7.1 is the published modeling appendix (Appendix 5) in Rockström et al 2025[13]

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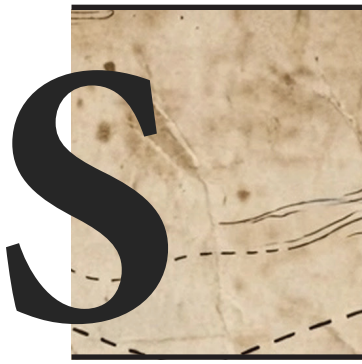

Summary

Aims and research questions

Food systems are increasingly expected to deliver multiple, and often competing, societal objectives: ensuring food and nutrition security, supporting livelihoods, improving environmental sustainability, and promoting social equity in the face of profound uncertainty. Yet policymaking must occur in a context characterized by complex system interactions, long-term structural change, and unpredictable shocks. This thesis addresses this challenge by examining how anticipatory governance, specifically, through the integration of qualitative scenarios and quantitative foresight modelling, can contribute to evidence-based decision-making for food system transformation. The thesis is composed around six case studies spanning national, regional, and global scales, and demonstrates how foresight methods can help decision-makers explore uncertainty, evaluate trade-offs, and identify more robust pathways toward sustainable, healthy, and just food systems.

The research is guided by five overarching questions:

1. What is the role of food system innovation in facilitating food system transformations?
2. How resilient are food systems to external shocks (e.g., climate change, pest and diseases, and technological change)?
3. How do changes across food systems contribute to changes in diets and nutrition and food security?
4. How does food policy contribute (or not) to achieving desired outcomes?
5. What are the environmental consequences of food system changes?

Applied methods

Methodologically, the thesis applies an anticipatory governance framework that deliberately combines qualitative scenario development with quantitative modelling. Multiple approaches to scenario design are employed, ranging from expert-defined scenarios based on established global frameworks to participatory stakeholder-driven scenarios developed through regional workshops. These scenarios are quantified using a diverse suite of modelling approaches selected to match the research question. These include a range of dynamic and static models that bridged across biophysical and economic domains, including:

- Dynamic partial and computable general equilibrium models,
- Climate and crop models
- Knowledge accumulation and R&D models
- Food security and nutrition modules

These models were also coupled in a variety of ways to best leverage their respective strengths to respond to research questions, including coupled modelling suites as well as parallel model runs in multi-model ensembles. Together, these approaches enable the exploration of both short-term shocks and long-term structural transformations, while allowing analyses to span national, regional, and global scales. Throughout the thesis, qualitative narratives and stakeholder knowledge are treated as essential complements to quantitative modelling.

Key insights

Several overarching insights emerge from synthesizing the six case studies. First, the research demonstrates that the greatest value of foresight modelling lies not in predicting the future but in facilitating structured inquiry into complex systems. That is, they are best applied to help ask questions about current and future food systems than to give precise answers to specific questions. Second, effective anticipatory governance depends on the close integration of qualitative and quantitative approaches. Scenario narratives provide the logical framework through which quantitative assumptions are developed and interpreted, while modelling helps identify inconsistencies, reveal hidden assumptions, and expose unintended consequences. Third, the thesis shows that model selection must be driven by the research question rather than methodological preference. Different food system challenges require different modelling approaches, and coupling complementary models or using model ensembles can substantially improve representation of important system dynamics and better characterize uncertainty.

The thesis also demonstrates that scenario design is a critical component of responsible anticipatory governance. Choices about which futures are explored, whose perspectives are represented, and how uncertainty is framed fundamentally shape the knowledge produced. Participatory approaches can broaden the range of plausible futures and incorporate perspectives that are often absent from expert-driven analyses. However, these approaches can be time consuming, expensive, and difficult to replicate. More top-down and expert derived approaches, often built on existing scenario frameworks, and can improve transparency and replicability of scenarios, facilitating comparison across the scientific literature, but can narrow the range of futures that are considered. The thesis highlights that this dichotomy of approaches is actually a continuum, with pragmatic decisions that must often be made based on project and time constraints, recognizing that anticipatory governance rarely if ever is completely bottom-up or top-down, but is a hybrid of these approaches, and that recognizing this fact is critical for policy-relevant foresight. Across all case studies, attention to transparency, reflexivity, and explicit acknowledgment of normative assumptions emerges as essential for responsible use of anticipatory governance.

Collectively, the findings reinforce the importance of adopting holistic systems perspectives when evaluating food system interventions. Policies and innovations frequently generate effects that extend beyond their immediate objectives, producing interactions across nutrition, livelihoods, markets, and environmental outcomes. Consequently, evaluating interventions through multiple dimensions simultaneously is essential for identifying robust policy options and avoiding or mitigating undesirable outcomes, even as the thesis critiques win-win framings and emphasizes the need for decisionmakers to own policy choices recognizing that good policy is not defined strictly by avoiding unintended consequences, which is not possible, but in having the capacity to identify trade-offs and to work towards reducing harm to more vulnerable populations.

Conclusion

This thesis advances both the methodological practice and practical application of anticipatory governance for food systems. By demonstrating how qualitative scenarios and quantitative foresight modelling can be systematically integrated across diverse policy questions and scales, it provides a framework for supporting more transparent, reflexive, and evidence-informed food policy. While acknowledging the inherent limitations of models and the impossibility of eliminating uncertainty, the thesis argues that rigorous foresight can expand the range of futures considered, improve understanding of trade-offs, and strengthen society's capacity to shape food systems that are more sustainable, healthy, resilient, and just.





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Caminante, son tus huellas el camino
y nada más;
Caminante, no hay camino, se hace camino
al andar.
Al andar se hace el camino, y al volver
la vista atrás
se ve la senda que nunca se ha
de volver a pisar.
Caminante, no hay camino sino estelas
en la mar.

Traveler, your footprints are the path
and nothing more.
Traveler, there is no path, you make
the path as you walk.
As you walk, you make your path,
and when you look back
you see the path you will never
travel again.
Traveler, there is no path, only ripples
in the sea.

Antonio Machado, *Proverbios y Cantares*, trans. Mary G Berg and Dennis Maloney

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To my brother, your relentless work ethic is a reminder that I can always dig a little deeper. Despite distance and different paths, I know that you are always there for me, even when that means just engaging in the most inane text conversations, which surely have saved me from the edge of madness on more than one occasion. And yes, Purdue's quarterback is…

And to Ximena, what can I say that could fully express everything that I owe you? It is now over twenty years since we met, and you still surprise me. You both inspire and motivate everything I do. I apologize for the long nights I have had to dedicate to finishing this work, and for days when I may have let my own frustrations make me short with you. I do not know what my life or career would have looked like without you, but I have no doubt it would have been much poorer. You have been there in the hardest moments and made the most joyful moments even more meaningful. Sharing all these moments has been a blessing, and I thank you for agreeing to follow this path with me.





About the author



Daniel Mason-D'Croz is a Senior Research Associate with Cornell Food Systems & Global Change. He is a development economist by background and has been working in anticipatory governance of the food system for more than ten years. His research revolves around assessing the impacts of climate change, the health and environmental consequences of current and future diets, and efforts to identify vulnerabilities in food systems. He applies mixed qualitative and quantitative approaches to better understand the complexity of global and regional food systems.

Daniel's path into this work began in the Peace Corps, where he served in Bolivia from 2004 to 2008, first in community business and information and communication technology (ICT) education, and later as an ICT specialist developing a three-year vocational computer program at a local high school and training fellow volunteers in ICT best practices for community development. This on-the-ground experience shaped his later focus on development economics. He returned to the United States to pursue a Master's degree in International Development and Economics at the Johns Hopkins University School of Advanced International Studies (SAIS), graduating in 2010.

That same year, he joined the International Food Policy Research Institute (IFPRI) in Washington, DC, beginning as a Senior Research Assistant and rising over the following eight years to Scientist and IMPACT Modeler, eventually leading the team responsible for IFPRI's IMPACT model, one of the oldest and most widely cited global agricultural economic models. In 2018, he moved to Australia to join the Commonwealth Scientific and Industrial Research Organisation (CSIRO), where as Senior Research Scientist he oversaw the first phase of updating GTEM, a global integrated assessment model. In 2021, he joined Cornell University, where he has served as lead author of the modelling section of the second EAT-Lancet Commission report and co-coordinator of that Commission's modelling team.

Across these positions, he has co-authored more than 90 peer-reviewed articles and has actively contributed to global assessments including IPBES, several IPCC reports (on 1.5°C/2°C and on Climate Change and Land), AgMIP (the Agricultural Model Intercomparison and Improvement Project), and the EAT-Lancet Commission. He has also contributed to informing policymaking through priority-setting exercises for the CGIAR, the Australian Department of Foreign Affairs and Trade (DFAT), and CSIRO, as well as through regional policymaking engagement in Latin America, sub-Saharan Africa, and South and Southeast Asia. Recent work has included exploring the potential disruptions of extreme events such as the outbreak of African swine fever in China, the potential consequences of large-scale adoption of novel plant-based alternatives to beef, and developing novel approaches to responsible and mission-oriented food system innovation to promote more sustainable food systems.

