Food Systems and Climate Change: A Comparison of Global Emission Estimates, A Systems Framework for Mitigation Efforts, and Intersections of Mitigation Efforts with Sustainable Development Goals

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Thesis Abstract

Global food systems are estimated to contribute approximately one-third of anthropogenic greenhouse gas (GHG) emissions, and alone, are large enough to make the goals of the Paris Climate Agreement unattainable. The need for the rapid reduction of GHG emissions in our food systems is well established, with calls for food systems transformation focusing on the intersection of climate, food security, public health, sustainability, and social reform as people do not have equal access to nutrition, land, or economic benefit. The multifaceted nature of our food systems crisis requires thoughtful and expansive solutions. This dissertation strives to understand the contribution of the global food system to GHG emissions today and in the future, explore recommendations to reduce food system GHG emissions using a systems thinking framework, and how these interventions may affect broader sustainability goals. In my three chapters, I: (1) synthesize and explore estimates of global food system GHG emissions in the past and future; (2) explore interventions and expert recommendations to mitigate food system emissions through a systems thinking lens, and use systems change frameworks to propose more transformational recommendations; and (3) explore how interventions to mitigate food system emissions might affect the achievement of the United Nations Sustainable Development Goals (SDGs). I find that: (1) existing estimates for global food system GHG emissions are often too aggregated to contribute to understanding what drives climate damages, while there are no global food system GHG emission projections for the future that include post-production emissions; (2) there is a mismatch between expert calls for food systems transformation to mitigate GHG emissions and expert recommendations, but we can expand our expert recommendations to mitigate food systems utilizing systems change frameworks to create better, more transformational recommendations; and (3) that there are likely to be environmental- and economic-benefits of interventions to mitigate food system emissions, but advancement on justice-centered SDGs is likely only if policies center on reducing inequalities, and marginalized and vulnerable populations are included and empowered at the forefront of mitigation policy planning and implementation. Food system mitigation interventions that are inclusive, holistic, and interdisciplinary that are designed to consider all the SDGs initially are likely to bring us closer to the transformational food system changes necessary to meet the goals of the Paris Agreement, achieve sustainable diets, and reduce inequalities in our food systems. Overall, my work suggests that climate mitigation research would benefit from: current food system emissions estimates that are sufficiently disaggregated to illuminate what is ultimately driving climate damages in our global food system; projections of comprehensive GHG emissions that include the entire life cycle of our global food system; a new focus in our recommendations and efforts on interventions that have higher potential to achieve desired food system transformations; and include aspects of sustainability beyond climate change mitigation to ensure our future efforts to reduce GHG emissions do not exacerbate the existing inequalities in our current food system.

Table of Contents

List of Tables

Chapter 1

Chapter 2

Chapter 3

List of Figures

Chapter 1

Chapter 2

Chapter 3

List of Abbreviations

AFO - aquaculture feed only
AFOLU - Agriculture, Forestry, and Other Land Use
BAU - business-as-usual
CH_4 - methane
CFS - Committee on World Food Security
CGIAR - (formerly) the Consultative Group for International Agricultural Research
CIRAD - the French Agricultural Research Center for International Development
CO_2 - carbon dioxide
CO_2eq - carbon dioxide equivalent
DNS - does not specify
EDGAR - Emissions Database for Global Atmospheric Research
EPA - US Environmental Protection Agency
ES - ecosystem services
F-gas(ses) - Fluorinated gas(ses)
FAO - United Nations Food and Agriculture Organization
FAOSTAT - the UN Food and Agriculture Organization’s database on food and agriculture
FILAC - Fund for the Development of the Indigenous Peoples of Latina America and the Caribbean
GDP - gross domestic product
GHG - greenhouse gas
HLPE - High Level Panel of Experts on Food Security and Nutrition
ICT - information and communication technologies
IFAD - International Fund for Agricultural Development
IFPRI - International Food Policy Research Institute
INRA - the French National Institute of Agricultural Research
IPCC - Intergovernmental Panel on Climate Change
IPCC SRCCL - Intergovernmental Panel on Climate Change Special Report on Climate Change and Land
LUC - land use and land use change
N_2O - nitrous oxide
NASA - the United States National Aeronautics and Space Administration
NGO - non-governmental organization
SDG - Sustainable Development Goal
SDGs - Sustainable Development Goals
SOFI - the State of Food Security and Nutrition (formerly known as the State of Food Insecurity)
SPM - Summary for Policy Makers
SSB - sugar sweetened beverage
TAAFNs - Transnational Alternative Agrifood Networks
UN - United Nations
UNDP - United Nations Development Program
UNICEF - United Nations International Children's Emergency Fund
US - United States
VSS - voluntary sustainability standard
WFP - World Food Program
WHO - World Health Organization
WRI - World Resources Institute

Introduction Chapter: What are food systems, and how do they relate to climate change?

What are food systems?

Food systems encompass everything that it takes to deliver the food that everyone across the world eats, and includes each stage of our food supply chain, and the environmental, economic, and cultural systems that govern it. Our food supply chain includes: agricultural production; deforestation and other land use changes to free up land to use for agriculture; the resources it takes to produce food, including the mining and processing of raw materials to create farming equipment, fertilizers, food processing and transportation infrastructure, and food service and consumer food appliances; food storage and refrigeration; agricultural and food insurance organizations; commodity markets; food waste disposal; and the energy needed to power all of these operations.

Many conceptualizations and visualizations have been created to help define our large and complex global food system. Some organize food system components by the stages of the supply chain from pre-production to food disposal (HLPE, 2017; Niles et al., 2018). Others organize them by systems that govern food system outcomes including: biophysical; political; economic; cultural; and health systems (Clancy, 2014; HLPE, 2017; Bhunnoo & Poppy, 2020). One of the most comprehensive frameworks relating to food systems and diets is the High Level Panel of Experts on Food Security and Nutrition (HLPE) (2017) conceptual framework which maps drivers (biophysical and environmental; innovation, technology, and infrastructure; political and economic; socio-cultural; and demographic), food supply chain stages, food environments (availability, accessibility, attractiveness, utilization), and consumer behavior to diets and the health and environmental impacts that accompany them (HLPE, 2017). Our food systems are complex, interconnected, and affect every aspect of our wellbeing, the wellbeing of our communities, and the wellbeing of our planet.

What are challenges in our global food system?

The current global food system affects people unequally through access, nutrition, and economic benefit. Over 820 million people are undernourished; habitually their dietary energy needs are not met and they experience chronic hunger, with hunger increasing globally since 2015 (FAO, IFAD, UNICEF, WFP, & WHO, 2018; FAO, IFAD, UNICEF, WFP and WHO, 2019). Micronutrient deficiencies, also known as hidden hunger, affect over 2 billion people globally regardless of whether they are under- or overweight (Dary & Hurrell, 2006; Muthayya et al., 2013; FAO, IFAD, UNICEF, WFP, & WHO, 2018). Poor diets are the leading cause of morbidity and mortality worldwide, because of inadequate consumption of nutritious foods and excessive consumption of harmful ones (Forouzanfar et al., 2015). Additionally, the people who produce the food that we eat often struggle to feed their own families (Montgomery, 2017). Who benefits from agriculture is not evenly distributed across geographies, gender, or race (Alston & Pardey, 2014; Niles, 2018).

While many factors affect dietary choice and composition, current agricultural production has not been sufficiently incentivized to support healthy diets. We produce more than enough calories to meet global dietary energy needs (FAO, IFAD, UNICEF, WFP and WHO, 2009), but studies suggest that production may not meet other nutritional needs and radical change is needed to improve current diets (Bahadur et al., 2018; Berners-Lee et al., 2018; Afshin et al., 2019; Willet et al., 2019). While studies differ in their approaches, most find that we overdeliver grains, fats, and sugars, but underdeliver vegetables and fruits, resulting in a production of nutrients insufficient to adequately nourish the global population (Bahadur et al., 2018; Berners-Lee et al., 2018). The cost of micronutrient-rich foods often make them unavailable to many consumers (Headey and Alderman, 2019; Hirvonen et al., 2019). The call for radical and immediate food systems transformation for personal, public, and planetary health spans multiple disciplines, actors, and geographies (Foley et al., 2011; HLPE 2017; SOFI 2018; Willet et al., 2019; Clark et al., 2020; HLPE, 2020; SOFI, 2021 Slater et al., 2022).

How do food systems relate to climate change?

Food systems contribute to climate change. Greenhouse gas (GHG) emissions in food systems come from a variety of activities at each stage of the supply chain. Pre-production emissions come from the production of fertilizers, pesticides, and seeds, as well as deforestation and land-use change. Emissions from agricultural production come from nitrogen fertilizer application, livestock enteric fermentation, manure management, rice cultivation, agricultural burning, and on-farm energy use. Beyond agricultural production, food system emissions are also caused by post-production activities such as processing, packaging, refrigeration, transport, and retail. Consumption emissions come from food preparation and cooking in homes, cafeterias, restaurants, and other food establishments. Emissions from food waste management come from industrial and consumer food waste, and repurposing food (Vermeulen et al., 2012; Niles et al., 2018; IPCC SRCCL; Crippa et al., 2021).

Food systems are also vulnerable to climate change. Climate change increases the risk of changes in suitability of lands for specific crops (Zabel et al., 2014), the spread and expansion of pests and diseases (Dinesh et al., 2015; Bebber et al., 2013), extreme weather events (Wheeler & Von Braun, 2013; Lesk et al., 2016), and shifts in yield impacts of many staple crops (Deryng et al., 2014; Challinor et al., 2014). Climate change will also have implications for other components of food security including food access, utilization, and stability (Wheeler & Von Braun, 2013). Agriculture is one of the economic sectors most affected by climate change (Wheeler & Von Braun, 2013), and comprises a much larger share of the gross domestic product (GDP) of low-income countries than it does in high-income countries (Alston & Pardey, 2014; Gouel & Laborde, working paper). This means more people in low-income countries will experience additional income and food insecurities as the effects of climate change continue to negatively impact production.

How much do food systems contribute to climate change?

No estimates of food system GHG emissions to date include all of the components mentioned in the opening paragraph, but these food system estimates are becoming much more comprehensive over time (Vergé et al., 2007, Tubiello et al., 2021, Xu et al., 2021). Some of the oldest GHG estimates of food systems contained only emissions from agricultural production (Vergé et al., 2007). Over time, other related aspects were included in these estimates. Agriculture, Forestry, and Other Land Use (AFOLU) has been the sector that is used by the Intergovernmental Panel on Climate Change (IPCC), and many others in the space use a similar framework to include GHG emissions from land use change in addition to GHG emissions from agricultural production (Tubiello et al., 2015; IPCC 1.5 Special Report, IPCC SRCCL). There is a growing recognition of the importance of a food systems perspective (Rosenzweig et al., 2020), and the IPCC Special Report on Climate Change on Land (IPCC SRCCL) was the first IPCC publication to include an estimate that extends beyond the AFOLU sector to include a more holistic food system GHG estimate.

The IPCC SRCCL estimates that the global food system is responsible for 21-37% of anthropogenic GHG emissions (IPCC, 2019). However, more recent food system GHG emissions estimates are at the higher end of this range, with all three global GHG estimates for food systems published in 2021 exceeding 30% of anthropogenic emissions (Crippa et al., 2021; Tubiello et al., 2021; Xu et al., 2021). Work by Clark et al. (2020) shows that without intervention, food systems will consume the entire 1.5°C GHG emissions budget and make the 2°C goal of the Paris Climate agreement almost impossible to achieve. If we want to meet the goals of the Paris Climate Agreement, we need action on every food systems front as soon as possible (Clark et al., 2020).

What drives greenhouse gas emissions in our global food systems?

The foods we produce and consume do not contribute to climate change equally. Animal-sourced foods often release more GHG emissions than plant-based foods throughout their life cycle per unit of food produced, oftentimes having emissions more than an order of magnitude larger than plant-based foods. For example, even the highest impact plant-based proteins (i.e., tofu and groundnuts) have lower average emissions than the lowest impact animal-sourced proteins (i.e., eggs, poultry, and fish). Much of the reason for this significant difference is due to livestock enteric fermentation in ruminant production and the inefficiencies in which livestock convert animal feed into food. Meat and dairy products often require much more land to produce than their plant-based alternatives, resulting in high carbon opportunity costs associated with their production, and climate double dividends reaped from shifts away from their production (Hayek et al., 2020; Sun et al., 2022). Given the need to radically draw down food system emissions, dietary shifts towards plant-rich diets are necessary (Vermeulen et al., 2012; Campbell et al., 2018; Clark et al., 2018; Niles et al., 2018; IPCC SRCCL; Rosenzweig et al., 2020; Bajzelj et al., 2014; Foley et al., 2011; Willet et al., 2019). (Poore & Nemecek, 2018)

One well-established dietary relationship is that as incomes increase, so does the consumption of animal-based foods (Bennett et al., 1941; Tilman et al., 2011). This trend, in conjunction with a higher demand for food-calories, leads to high-income countries consuming diets with much higher emissions than the average diets in low-income countries (Tilman et al., 2011; Tubiello et al., 2021).

Much deforestation is driven by just a few commodities. Pendrill et al. (2019) finds that 40% of global deforestation is driven by cattle production, and another 40% is driven by the production of forestry products, palm oil, cereal grains, and soybeans. The World Resources Institute Global Forest Review finds that 57% of all tree cover loss from agriculture is due to just 7 commodities (i.e., cattle, palm oil, soy, cacao, plantation rubber, coffee, and plantation wood fiber) (Global Forest Review, 2021). While it is estimated that about 70% of deforestation is driven by domestic production and only about 30% is driven by international trade, commodity production has been associated with land grabs, where people are driven off the lands they have long occupied and are dispossessed by corporations or wealthy individuals (Borras Jr. et al., 2011; Ross et al., 2019; Pendrill et al., 2019). Within food systems and in greater climate change research, the impact of affluence on emissions is becoming increasingly clear: greater affluence means greater climate change damages (Tilman et al., 2011; Chancel & Piketty, 2015; Wiedmann et al., 2020; Tubiello et al., 2021; Chancel et al., 2022).

What can we do to transform our current food system to one that is sustainable and equitable?

Luckily, there are solutions and approaches that have been trialed (and even more that have been modeled or proposed) for every stage of the food supply chain, for every dimension of our food environments, and in every system that governs our food system outcomes that work to create a sustainable and equitable food system. The research space examining global food systems is expansive and interdisciplinary. Describing global progress on reducing hunger and improving nutrition is the focus of *The State of Food Insecurity* (SOFI), an annual collaborative report published by FAO, IFAD, UNICEF, WFP and WHO. The state of climate change and the risks it poses to natural, social, political, and economic systems, as well as possible responses to mitigate and adapt to climate change across economic sectors are the focus of scientific reports produced by the Intergovernmental Panel on Climate Change (IPCC). Reviews relating to every aspect and dimension of food systems are available on topics including: adopting personal and planetary health diets (Hyseni et al., 2017; Bianchi et al., 2018; Clark et al., 2018; Willet et al., 2019; Rust et al., 2020; Harguess et al., 2020; Atwood et al., 2020; Modlinska et al., 2020); agriculture and Nationally Determined Contributions (NDCs) (Ross et al., 2019; Crumpler et al., 2019); livestock GHG emissions mitigation (Grossi et al., 2018); and reducing food waste (Lipinski et al., 2013; Walia and Sanders, 2017; Schanes et al., 2018; Goossens et al., 2019; Ishangulyyev et al., 2019; Kim et al., 2019; Spang et al., 2019; van Gefffen et al., 2019; Alvarez de los Mozos et al., 2020; Mariam et al., 2020; Reisch et al., 2021). In addition to an extensive coverage of different food systems topics, interventions have been proposed at every scale, with recommendations ranging from changing microfood environments (Bianchi et al., 2018), to community-driven interventions (Ramsing et al., 2021), to international trade policy reform (Friel et al., 2020).

Paralleling movement in the agricultural and food system GHG estimation space, expert recommendations in food systems have also become more holistic. There have been shifts away from siloed and sectoral approaches (agriculture- or energy-specific) to more cross-cutting ones, finding that multidisciplinary and multilevel interventions have the greatest success in changing our food systems (Hyseni et al., 2017; Perez-Cueto et al., 2019; Sunderland and Vasquez, 2020; Moberg et al., 2021; Ramsing et al., 2021). We have also seen a shift in focus from mitigation actions that individuals can take at every stage of the food supply chain, towards a new emphasis on the importance of systems change and transforming the governance structures that shape our food environments like enabling political environments (Ross et al., 2019), structure and enforcement of multilateral agreements (Friel et al., 2020), and the importance of locally-adapted collective actions for change (Loboguerrero et al., 2019). There is a growing recognition of the role that power, or a lack of power, has in food system outcomes like diets, health, income, land access, and emissions, and the need to reshape food systems to improve justice outcomes (Niles et al., 2018; SOFI, 2019, 2020, 2021; HLPE, 2020). Another emerging idea is the need to build interdisciplinary coalitions to bridge gaps in research and policy so that we can minimize trade-offs, and find synergies with other goals of food system transformations when we work to mitigate food system emissions (Campbell et al., 2018; Loboguerrero et al., 2019; Lipper et al., 2020; Sunderland & Vasquez, 2020).

Where does my research fit in?

This dissertation builds on the wealth of research highlighting the contribution of our food systems to climate change. I expand on previous work in this space, highlighting the need for a systems perspective in our food systems estimates and in our interventions to mitigate them. The three core ideas explored are as follows:

- With my first chapter, advance our understanding of food system GHG emissions by comparing differences in past estimates and future projections for global food system GHG emissions.
- With my second chapter, explore current expert recommendations to mitigate GHG emissions, examine how these recommendations align with transformative change through an order of change lens, and show how systems change frameworks can be utilized to expand expert recommendations.
- With my third chapter, explore how interventions to mitigate food system emissions can facilitate or impede the achievement of the United Nations Sustainable Development Goals to show the need for climate interventions that center around the empowerment of marginalized people to achieve SDGs beyond climate action.

The first chapter focuses on identifying and understanding the problem, and the second and third chapters focus on how to fix it. The second reminds us to step back and think bigger (and more creatively), and the third reminds us that we must be thoughtful, and explicitly include other aspects of sustainability if we hope to accomplish them too. The conclusion chapter summarizes the work, motivation, key findings, policy implications and applications, and areas of future research for each of the three preceding chapters.

Chapter 1: Understanding global food system emissions: analyzing key differences in past estimates and future projections

1.1 Summary

Interest in the role that food systems play in climate change has increased dramatically. Numerous papers quantifying the food system's contributions to climate change in the past, present, and the future have emerged that are built on a variety of approaches. Here, I analyze and compare the results and methodologies of papers that estimate past global greenhouse gas (GHG) emissions, and project global food system GHG emissions into the future. There are a greater number of past estimates (here n= 9) for comprehensive food systems GHG emissions than there are future projections (n=0). While the search with the original inclusion criteria yield no future food system emissions that include post-production GHG emissions, nor any that include F-gas emissions from refrigeration, when the inclusion criteria are loosened, six different future projections for food system GHG emissions can be compared. Much of the variation in past estimates and future projections come from differences in allocations of deforestation to agricultural expansion; the inclusion of human disturbances such as savannah burning and peatland drainage; the inclusion of agricultural production of non-food goods; and the inclusion of post-production emissions such as food waste, cooking, and wastewater. Conventional ways of displaying food system GHG emission data are too aggregated to show what proportion of GHG emissions plant- and animal-based foods are responsible for. Where these data disaggregation exist, animal agriculture is shown to have an outsized impact, responsible for almost 60% of total food system emissions. I find that GHG emissions estimates for the food system in past and future periods are likely to be underestimated, as they often exclude one or more greenhouse gasses, emission stages, and activities within the food system. Identifying food system solutions with great potential to mitigate GHG emissions requires an accurate understanding of emission sector contributions, both past and in the future. This work shows the importance of advancing food system GHG estimation so that we can make data-driven mitigation interventions.

1.2 Introduction

There is an increasing appreciation of the food system's contribution to climate change in both scientific literature and in the popular press. Popular press articles discuss topics like: the impacts of one's diet (Stylianou et al., 2019); feeding the world without destroying it (Leahy, 2019); and the urgent need to reduce food system emissions if we want to meet the goals of the Paris Climate Agreement (Fountain, 2020). Popular science and data communication platform, Our World In Data, has several articles covering food and climate, with much of their coverage centered around how much our global food systems contribute to climate change, and what drives the environmental impacts in our systems of food production (Ritchie & Roser, 2020; Ritchie, 2020; Ritchie, 2021).

These popular press and science communication articles are often based on scientific research published in academic journals that is written by many different research groups. Vermeulen et al. (2012) took a literature review approach, compiling estimates for specific components of food systems from the literature to create one of the first comprehensive food system greenhouse gas emissions estimates. Poore and Nemecek (2018) take a bottom-up life cycle approach, while others take a top-down emissions inventory-based approach (Bajzelj et al., 2013, Crippa et al., 2021, Tubiello et al., 2021). The Emissions Database for Global Atmospheric Research (EDGAR) is a global database of greenhouse gas emissions and air pollution. EDGAR-FOOD is a subset of this database specifically for food systems, and Crippa et al. (2021) is their flagship publication describing the dataset and the main insights it can provide. The UN Food and Agriculture Organization's database on food and agriculture, FAOSTAT, also includes GHG emissions from our food systems. Tubiello et al. (2021) uses this FAOSTAT data in their analysis. These estimates vary, but to date, there is no comprehensive review of how they differ. **This chapter explores how greenhouse gas estimates of our global food systems compare.**

This chapter compares: the included greenhouse gasses; the scope of the included GHG emissions-generating activities; and the time period of estimated emissions. There are past estimates for food system emissions that are published as the data becomes available, as well as future projections that use past and current data trends to forecast food system emissions in the future (Bajzelj et al., 2013; Bajzelj et al., 2014; Searchinger et al., 2019; Clark et al., 2020; Crippa et al., 2021). This chapter seeks to synthesize and compare past and future global food system GHG emission estimates, as well as to understand consistencies and variation in methodologies across these estimates using a life cycle perspective.

To understand food system emissions better, we need to know where food system emissions come from. GHG emissions come from activities at every stage in the supply chain. Land use and land use change (LUC) emissions come from multiple activities including: ecosystem conversion to crop- and pasture-lands, drained organic soils, and peat fires. Pre-production emissions come from activities such as: extracting fertilizer and pesticide inputs, fertilizer and pesticide manufacturing, and fertilizer and pesticide transportation. Emissions from agricultural production come from activities such as: fertilizer and manure application, on-farm energy use, tillage, crop residues, crop residue burning, rice production, manure management, and enteric fermentation. Post-production emissions come from activities such as: food transport, processing, packaging, refrigeration, retail, cooking, and food waste disposal through solid waste management, incineration, industrial processes, and domestic wastewater treatment. (Vermeulen et al., 2012; Crippa et al., 2021; Tubiello et al., 2021, Xu et al., 2021)

Beyond categorizing food system emissions into stages and activities, food system emissions can also be broken down by the specific GHGs they produce. There are four main types of GHG emissions in food systems: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gasses (F-gasses). Carbon dioxide emissions typically come from fossil energy combustion, LUC, and biomass burning. Methane emissions come from LUC, rice cultivation, manure management, enteric fermentation, and food waste disposal. Nitrous oxide emissions come from LUC, manure management, fertilizer use, and food-related wastewater treatment. Fluorinated gas emissions come from the use of refrigerants in refrigeration in industrial, retail, and domestic operations. (Vermeulen et al., 2012; Crippa et al., 2021; Tubiello et al., 2021, Xu et al., 2021)

1.3 Methods

Relevant papers were identified until March 2022 through a systematic literature review. I utilized the Google Scholar search engine and database utilizing different combinations of the following terms: “food”, “food system”, “climate”, “greenhouse gas emissions”, “GHG”, “estimate”, and “projection”. Additional papers were added to the search through citation searches of relevant papers, and through expert and peer elicitation. This identification, screening, eligibility, and inclusion process is outlined for estimates of past emissions in Figure 1.1 and future projections in Figure 1.2. Some papers estimate both past and future food system GHG emissions, and many papers with future projections were identified in the initial search for past estimates. Duplicates of the papers, reports, books, and citations already identified and screened were excluded. Through this process, approximately 550 unique papers were identified.

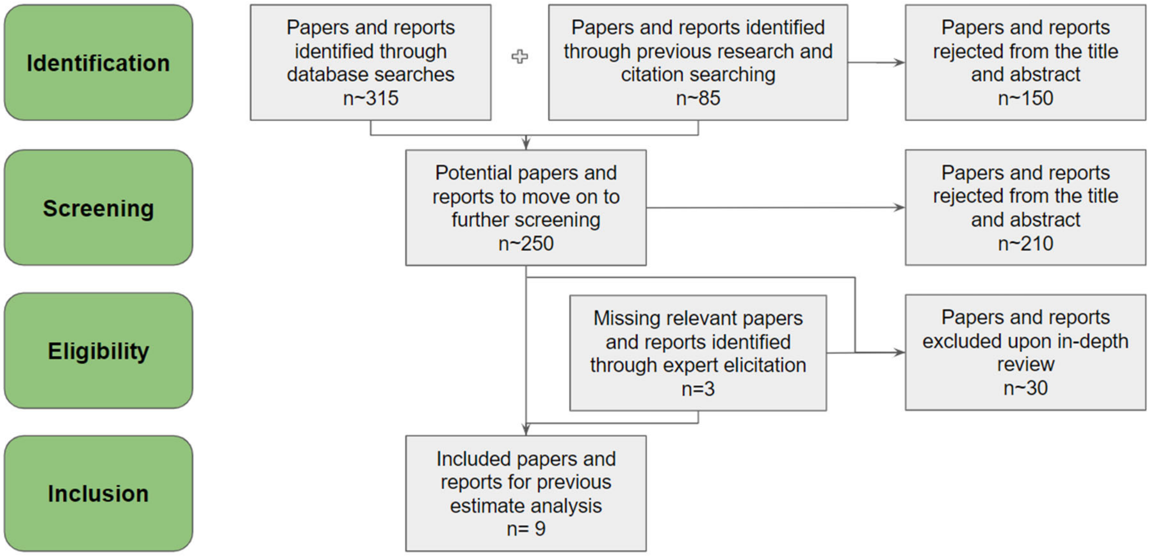

Figure 1.1: Process flow chart for identifying, screening for eligibility, and including papers in this analysis of past estimates of food system GHG emissions.

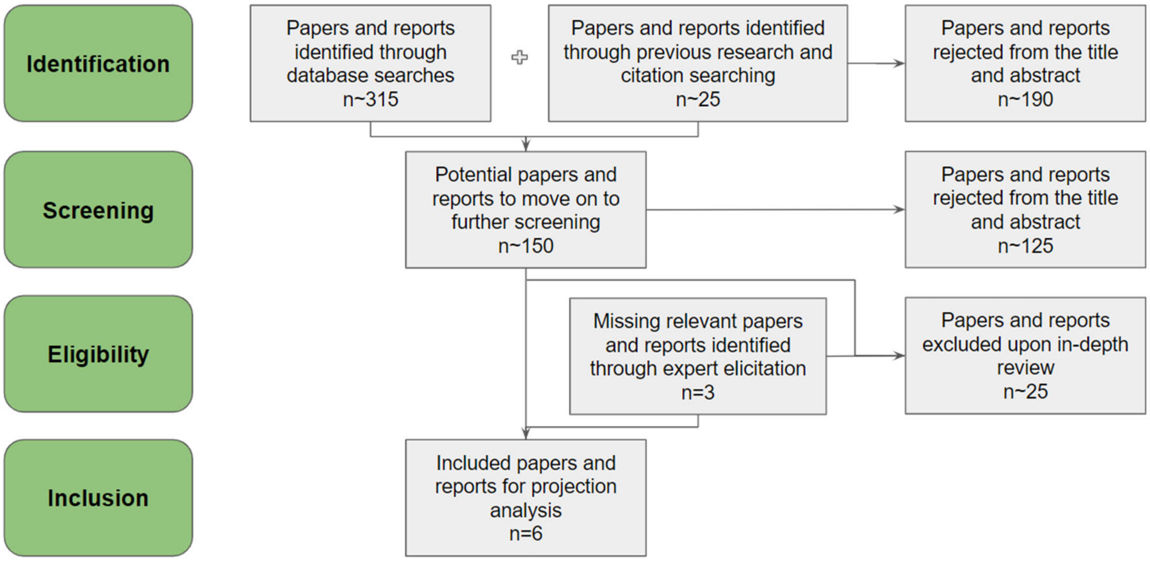

Figure 1.2: Process flow chart for identifying, screening for eligibility, and including papers in this analysis of future projections of food system GHG emissions.

After papers were screened for eligibility, they were selected for inclusion based on six key questions:

1. Is the paper's emissions estimate global in scope?
2. Does the paper include emissions from agricultural production?
3. Does the paper include emissions from LUC?
4. Does the paper include CO_2, N_2O, and CH_4 emissions?
5. Does the paper include pre-production emissions?
6. Does the paper include post-production emissions?

Many heavily-cited and circulated papers and reports did not meet the inclusion criteria for food system GHG emissions estimates. For example, Willet et al. (2019) and Springmann et al. (2018) do not include CO_2 emissions in their estimates, while Searchinger et al. (2019) and Clark et al. (2020) do not include any emissions post-farmgate.

These questions resulted in **9** papers included in past estimate analysis and **0** papers included for food system projection analysis. As the selection criteria did not yield any papers that would otherwise be included in future projections, the criteria were loosened, and any papers that included CO_2, N_2O, and CH_4 were included for projection analysis; this resulted in the inclusion of **6** papers in future projection analysis. The papers included in this analysis are shown in Table 1.1 below.

Table 1.1: Papers included in the comparison of past estimates and future projections of global food system GHG emissions.

Paper	Past Estimate	Future Projection
Bajzelj et al. 2013	X	
Bajzelj et al. 2014		X
Bennetzen et al. 2016		X
Clark et al. 2020	X	X
Creutzig and Niamir et al. 2021		X
Crippa et al. 2021	X	
IPCC SRCCL 2019	X	
Poore & Nemecek 2018	X	
Rosenzweig et al. 2020	X	
Searchinger et al. 2019		X
Springmann et al. 2016		X
Tubiello et al. 2021	X	
Vermeulen et al. 2012	X	
Xu et al. 2021	X	

1.4 Results

Here, I describe my findings for both past estimates and future projections.

1.4.1 Past Estimates

For a greater view of the food system GHG estimation landscape, Figure 1.3 compares non-analogous past estimates for food system GHG emissions. These estimates vary significantly, ranging from 5.2-18 GT carbon dioxide equivalent (CO_2eq), as they include different supply chain stages and greenhouse gasses. Figure 1.3 is included to show that past estimates of food system and agricultural emissions have even more variation than the ones included in this analysis.

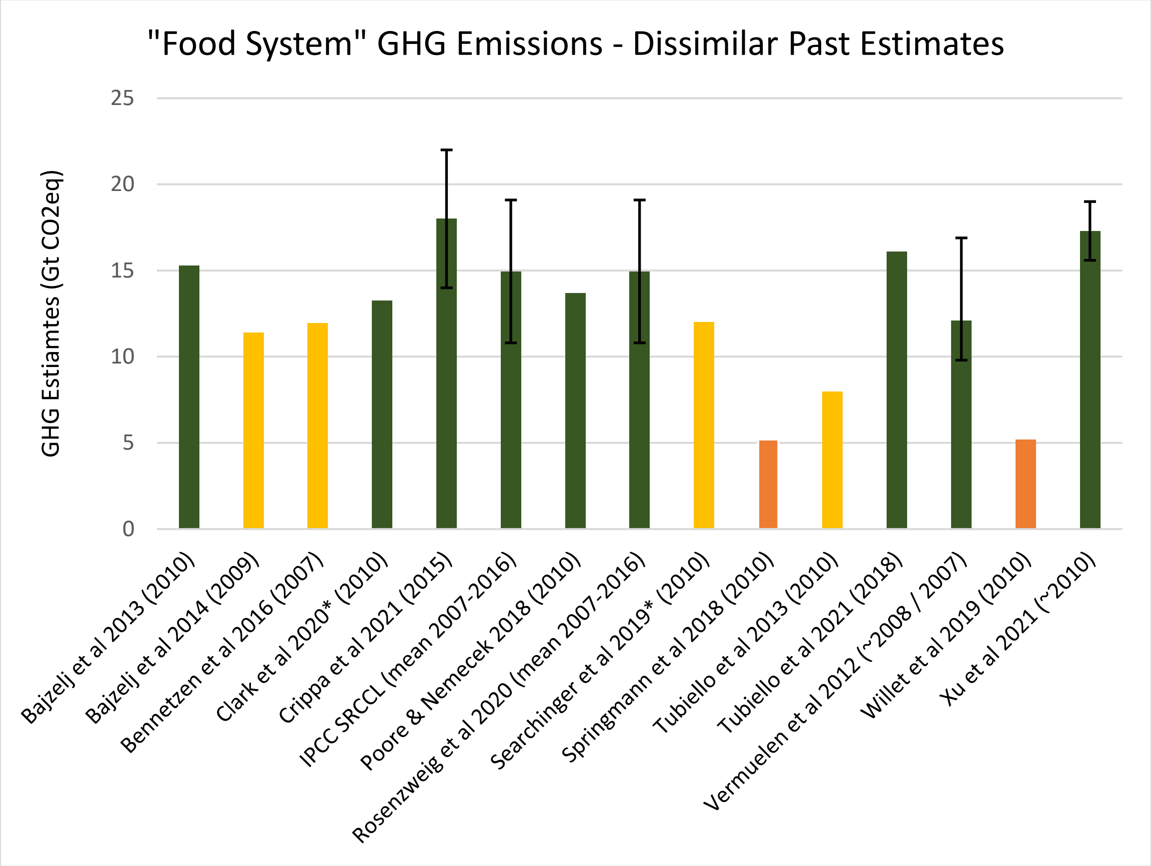

Figure 1.3: Past estimates for "food system" GHG emissions –comparing dissimilar estimates. What is included in these past estimates varies widely –with many of these estimates excluding some greenhouse gasses and emission stages. Here, red bars indicate that only CH_4 and N_2O gasses are included, orange indicates that pre- or post-production emissions are excluded, and green indicates estimates that include LUC, agricultural production, and some pre- and post-production emissions.

The included papers (n=9) vary in the scope of their food system GHG emission estimates. Which stage these activities are grouped into varies from paper to paper. To make a standardized comparison, this chapter breaks emissions into four key stages: land use and land use change (LUC); agricultural production; pre-production; and post-production. What activities are included in each paper's estimate is shown in Table 1.2. The most variation across estimates occurs in the pre-and post-production stages, so these activities are broken down further than LUC and agricultural production. It is important to note that these activities are not inherently additive. Some activities listed are aggregated to reflect the wording of the paper using them.

In addition to including varying food system activities, these estimates also vary in their approaches and assumptions. The state of the science in greenhouse gas estimations has changed over time, and with it so have the carbon dioxide equivalent (CO_2eq) values used for other GHGs. Across the included papers, attributions of deforestation and LUC to the food system ranged from 60-100% where specified. These key differences are highlighted in Table 1.3.

To compare past estimates for food system GHG emissions, I aggregate emissions into three categories: LUC; On-Farm Production; and Pre- and Post-Production. Pre- and post-production are not shown separately as very few studies give disaggregated values for these stages. The specific food system activities and years vary across estimates, and are shown for comparison in Figure 1.4. LUC estimates vary from 20-36%, On-farm production estimates vary from 39-59%, and pre- and post-production estimates range from 12-36% of total food system GHG emissions estimates where all three categories are specified. Total food system GHG estimates range from 12.1-18.4 GT CO2eq, with a mean of 15.13 GT across the 9 past food system estimates included in this analysis. The lowest total food system emissions estimate is Vermeulen et al. (2012) with an estimate of ~12 GT for 2007/2008. Crippa et al. (2021) has the highest food system emissions estimate, with an ~18 GT estimate for 2015

Table 1.2: Stages and activities included in past estimates for global food system GHG emissions. This table describes what is included in past estimations of global food system GHG emissions. These activities may overlap --descriptions of what is included in the post-production stage vary greatly, so where possible, exact language of the paper and supplementary materials is specified for accuracy. DNS = does not specify. AFO = aquaculture feed only

	Bajzelj et al. 2013	Clark et al. 2020	Crippa et al. 2021	IPCC SRCCL	Poore & Nemecek 2018	Rosenzweig et al. 2020	Tubiello et al. 2021	Vermeulen et al. 2012	Xu et al. 2021
LUC	X	X	X	X	X	X	X	X	X
On-Farm Ag. Production	X	X	X	X	X	X	X	X	X
Fisheries & Aquaculture	DNS	X	X	AFO	X	AFO	X	X	
Non-Food Ag. Emissions	DNS		X	X		X	X	DNS	X
Pre-Production	X	X	X	X	X	X	X	X	X
Fertilizer Mining			X	X		X			X
Fertilizer Manufacturing	X		X	X		X	X	X	X
Fertilizer Transportation			X	X		X			X
Pesticide Mining			X	X		X			X
Pesticide Manufacturing			X	X		X		X	X
Pesticide Transportation			X	X		X			X
Post-Production	X		X	X	X	X	X	X	X
International Transport				X					
Domestic Transport				X			X		
Transportation			X	X	X			X	X
International Trade				X					X
Processing	X		X	X	X		X	X	X
Packaging	X		X	X	X		X	X	
Refrigeration			X	X			X	X	
Retail			X	X	X		X	X	
Catering & Domestic Food Management				X				X	
Cooking	X			X					
Solid Food Waste			X	X			X		
Consumer Food Waste				X				X	
Food Incineration				X			X		
Wastewater Treatment			X						
Industrial Wastewater				X			X		
Domestic Wastewater				X			X		
Food Waste					X				
Consumption			X						

Table 1.3: Past estimates for global food system GHG emissions paper summaries. This table summarizes the different years, approaches, and assumptions used to create different food systems GHG emissions estimates. LUC = land use change; DNS = does not specify; LCA = life cycle assessment

	Bajzelj et al. 2013	**Clark et al. 2020**	**Crippa et al. 2021**	**IPCC SRCCL 2019**	**Poore & Nemecek 2018**	**Rosenzweig et al. 2020**	**Tubiello et al. 2021**	**Vermeulen et al. 2012**	**Xu et al. 2021**
Year(s) Estimated	2010	2010	1990-2015	mean 2007-2016	2010	mean 2007-2016	1990; 2018	2007/2008	~2010
Approach	Top-down	Bottom-up	Top-down	Top-down	Bottom-up	Top-down	Top-down	Bottom-up	Bottom-up
Data Sources	EDGAR Emissions Inventory	LCA, UN Population, Diet Composition, & LUC Data	EDGAR-FOOD database	FAOSTAT and USEPA food databases	LCA Data EDGAR Database	FAOSTAT and USEPA food databases	FAOSTAT database	Literature review	Utilizes a model– data integration Framework
Estimates as CO_2eq	AR4 (CH_4 = 25; N_2O = 298)	AR5 (CH_4=28; N_2O =265)	AR5 (CH_4=28; N_2O =265)	AR5 (CH_4=28; N_2O =265)	DNS	AR5 (CH_4=28; N_2O =265)	IPCC SAR (CH_4 = 21, N_2O = 310)	DNS	AR5 (CH_4=28; N_2O =265)
Deforestation Assumption	Does not attribute all LUC to food. DNS amount attributed.	Land is cleared to meet global food & feed demand	100% global deforestation is attributed to food.	LUC is the net CO_2 flux of all LUC.	60% of global deforestation is attributed to food.	LUC given is the net CO_2 flux of all LUC.	100% of net forest conversion is attributed to food.	75% of deforestation & degradation are attributed to food.	DNS
Novelty	Sankey diagram comparing emissions across sectors and activities.	LCA approach	Maps food system emissions over a contiguous time period.	First IPCC report with a FS GHG estimate.	Comprehensive food LCA databases for GHGs, water, land, and more.	It is almost the same data and analysis as the IPCC SRCCL.	Sankey diagram comparing agricultural, land, and FS emissions.	One of the first food system GHG emissions estimates.	Estimates the impacts of plant- and animal-based food production.

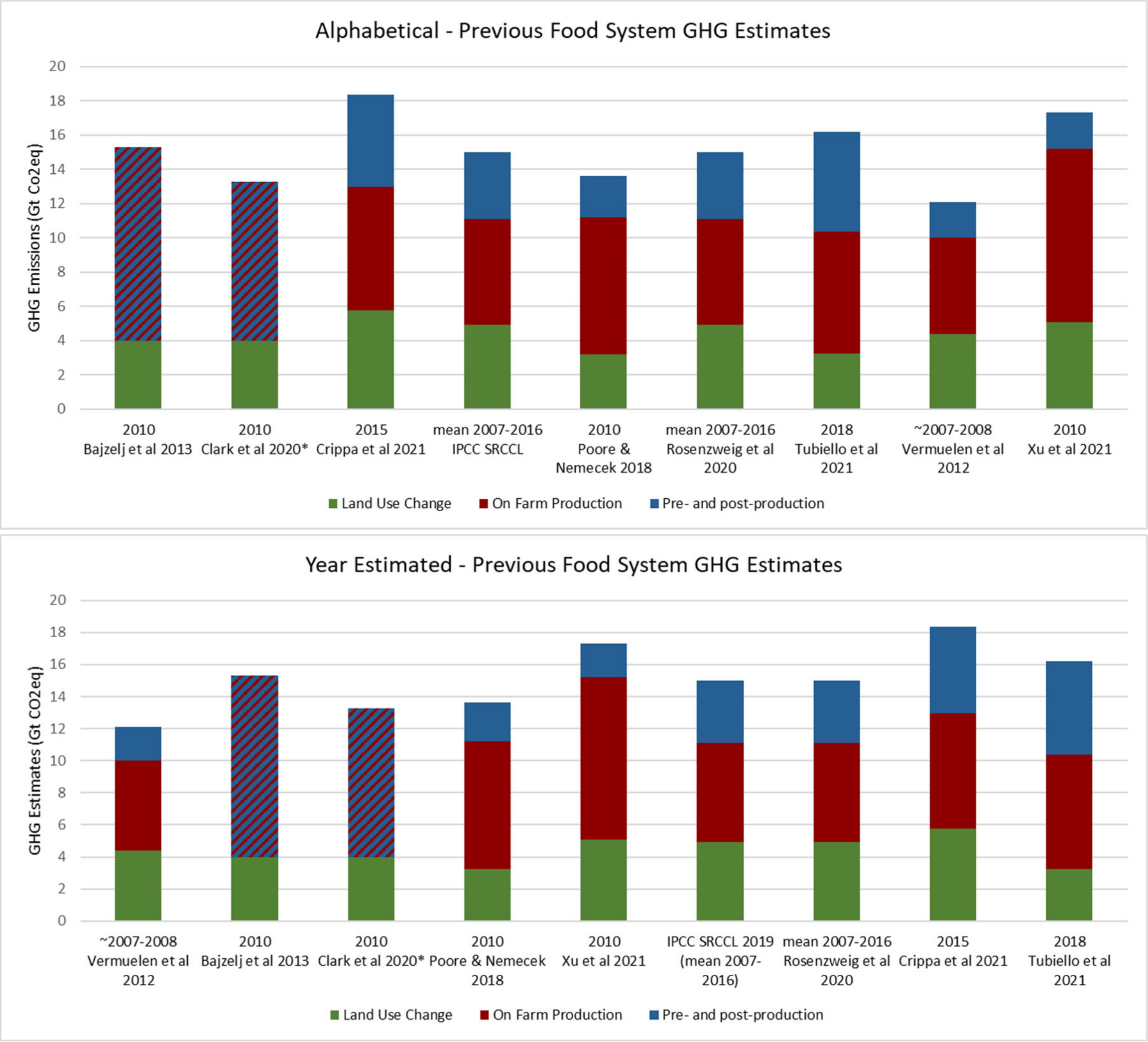

Figure 1.4: Past Estimates of Global Food System GHG Emissions in a) alphabetical order, and b) by period of time estimated. a) This figure displays past estimates for food system emissions broken out by LUC, on-farm production, and pre-and post-production stages by paper in alphabetical order. b) This part of the figure shows the same information, but organizes it by the period of time that the GHG estimate is provided for, not the date of publication.

While there is variance in the time period estimated across these estimates, there is not a statistically significant trend over time. This is in line with other findings, as even over a period of 25-28 years, papers in this area find that there is not a large change in global GHG emissions estimates, with Crippa et al. (2021) noting a food systems change from approximately 16-18 GT CO_2eq from 1990-2015, and Lamb et al. (2021) noting a AFOLU change from 10-11.6 GT CO_2eq for the AFOLU sector from 1990-2018, with emissions increasing less than 1% a year.

Food system GHG emissions for the estimated period of time for each paper's past estimate are compared to total GHG emissions for the same time period are shown in Figure 1.5. For this comparison, total GHG estimates are taken from the 2021 EDGAR Report: *GHG Emissions of All World Countries* (EDGAR, 2021). These food systems percentages may be different from those given in the papers, as total GHG estimates have been updated with each new EDGAR report. I find that food system emission estimates range from 27-37%. This is skewed to the high-end of the IPCC SRCCL's range of 21-37%. The three most recent food systems estimates (published in 2021) are all greater than 30% of total GHG emissions for their year of analysis.

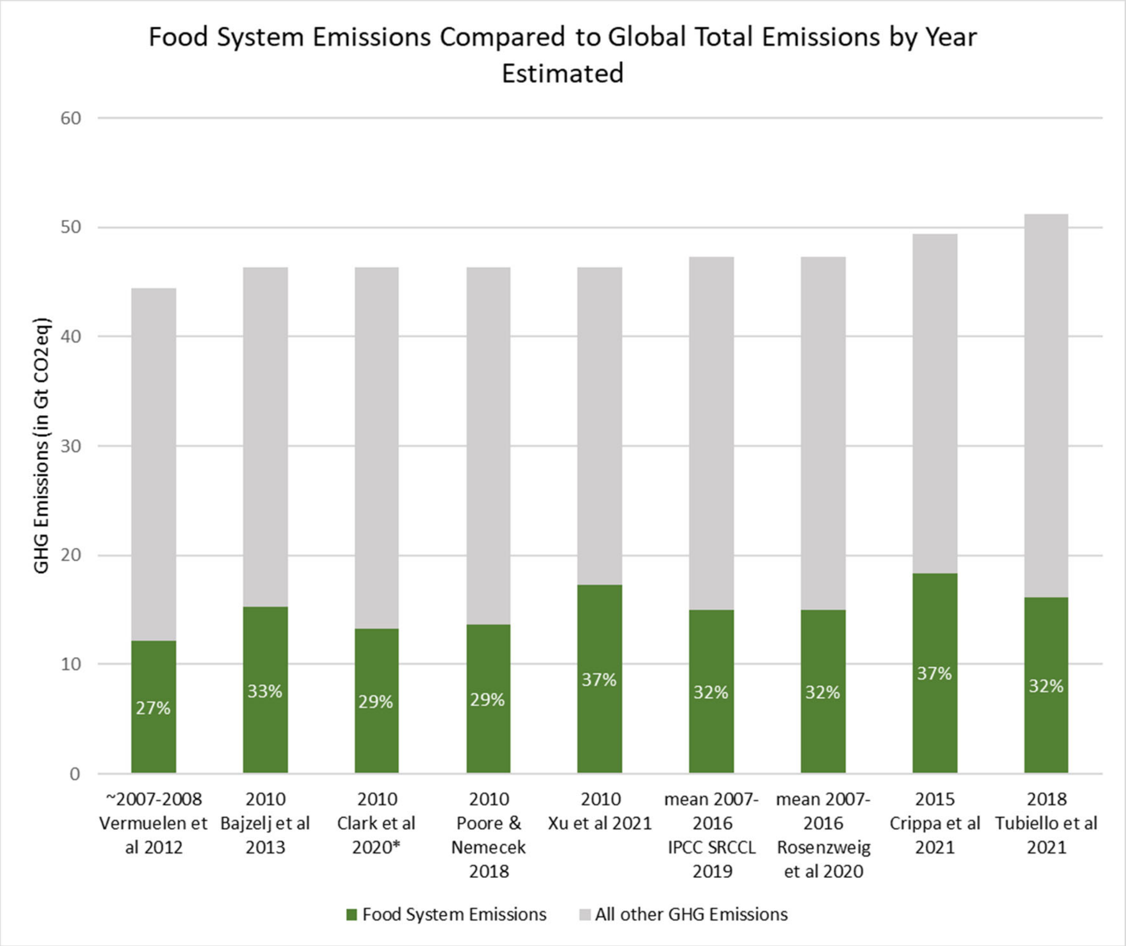

Figure 1.5: This figure displays past estimates for food system emissions compared to Total GHG Emissions estimates taken from EDGAR. Total GHG Emissions are taken for the time period estimated from EDGAR (2021). For example, Tubiello et al. (2021) estimates emissions in 2018, so Total GHG Emissions for 2018 are used for comparison, while the IPCC SRCCL estimates mean emissions from 2007-2016, so this estimate is compared to mean Total GHG Emissions from 2007-2016. Food system emissions estimates range from 27-37% of Total GHG Emissions.

There are four papers that estimate food system emissions in 2010, with a range of approximately 13-17 GT CO_2eq. Even when papers estimate the same year, there are differences in methodology significant enough to have the range for food system emissions to vary between 29-37% of total GHG emissions for 2010.

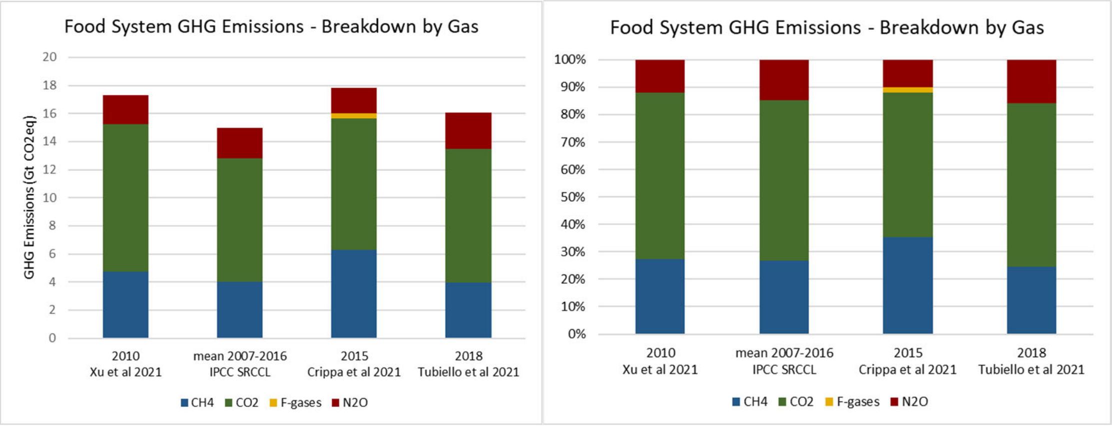

Figure 1.6: Past estimates for global food system GHG emissions broken down by greenhouse gasses. a) Part a displays past food system GHG emission estimates in GT and the contribution of CH_4, CO_2, N_2O, and F-gasses in carbon dioxide equivalents (CO_2eq). b) Part b shows the percent contribution of CH_4, CO_2, N_2O, and F-gasses to total food system emissions in carbon dioxide equivalents (CO_2eq).

Many papers that estimate past food system GHG emissions do not specify the breakdown of emissions across the different greenhouse gasses they include. Of the nine papers included, only four break down emissions into specific gasses. Of these four, only one includes F-gasses. The breakdown of total food system emissions into gasses is shown in Figure 1.6.

The majority of past food system GHG emissions estimates break down their analyses into stages and activities. Xu et al. (2021) takes a novel approach, and attributes emissions across different stages and activities to their end use: plant-based food, animal-based food, and other utilizations. Here, other utilizations include fibers, rubber, and cotton. They find that animal-based foods are responsible for 57% of food system emissions, while plant-based foods and other utilizations are responsible for 29% and 14% respectively. Figure 1.7 displays Xu et al. (2021) food system emissions broken down by stages and activities in part a, and into plant, animal, and other emissions in part b.

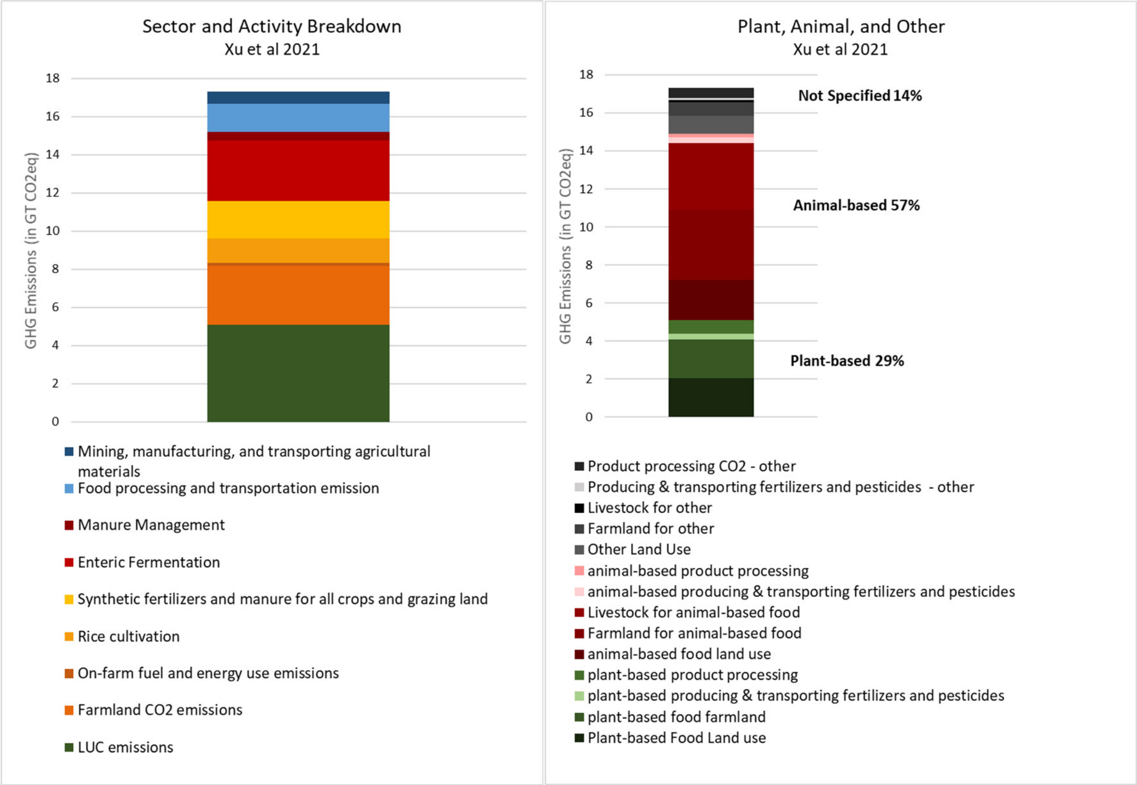

Figure 1.7: Comparing food system GHG emissions by a) sector and activity breakdown, and by b) end use for Xu et al. (2021). This figure shows two different ways of breaking down the 2010 food system emissions estimate from Xu et al. (2021). a) Shows emissions broken out by stage and activity. b) Shows emissions broken down by their end use: for plant-based food, animal-based food, or other.

While Xu is novel in that it attributes included pre- and post-production emissions to plant, animal, and other utilizations, Poore and Nemecek (2018) also attributes some of the food system emissions to plant- and animal-based foods. Figure 1.8 below shows 2010 food system emissions broken out into three groups: animal-based, plant-based, and uncategorized emissions. In their analysis, more than 50% of emissions are attributed to animal-based foods, and this is before emissions from savannah burning, processing, transporting, packaging, and retailing are attributed to plant- or animal-based foods.

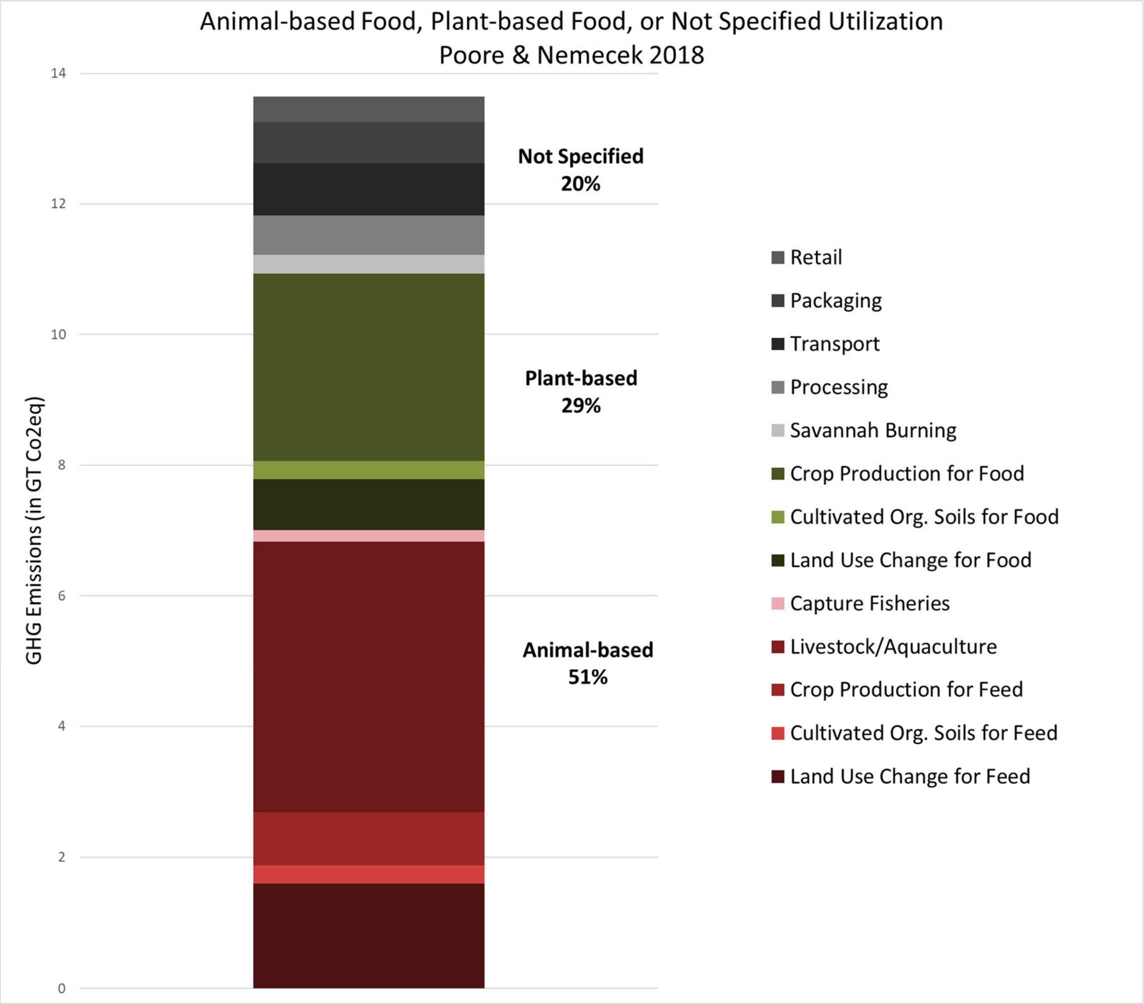

Figure 1.8: GHG emissions breakdown into animal-based, plant-based, and not-specified emissions from Poore & Nemecek. This figure shows a breakdown of food system emissions by 3 key groups: animal-based, plant-based, and uncategorized emissions. Animal-based emissions are shown in different shades of red, plant-based emissions are shown in different shades of green, and not-specified emissions are shown in different shades of gray.

1.4.2 Future Projections

As with past estimates for global food system GHG emissions, projected emissions also include different activities, and have assumptions that vary significantly. Figure 1.9 below is a “catch-all” figure that displays frequently cited “food system” projections from the literature. These estimates are taken from frequently cited publications, and do not meet the defined criteria here for food systems. Springmann et al. (2018) and Willet et al. (2019) do not include any CO_2 emissions in their projections. Springmann et al. (2016) does not include emissions from LUC. Bennetzen et al. (2016) does not include any preor post-production emissions, while Bajzelj et al. (2014) includes only emissions from fertilizer production. Searchinger et al. (2019) and Clark et al. (2020) include emissions up until the farmgate, but do not include any post-production emissions. Creutzig et al. (2021) does not describe their GHG projection methodology.

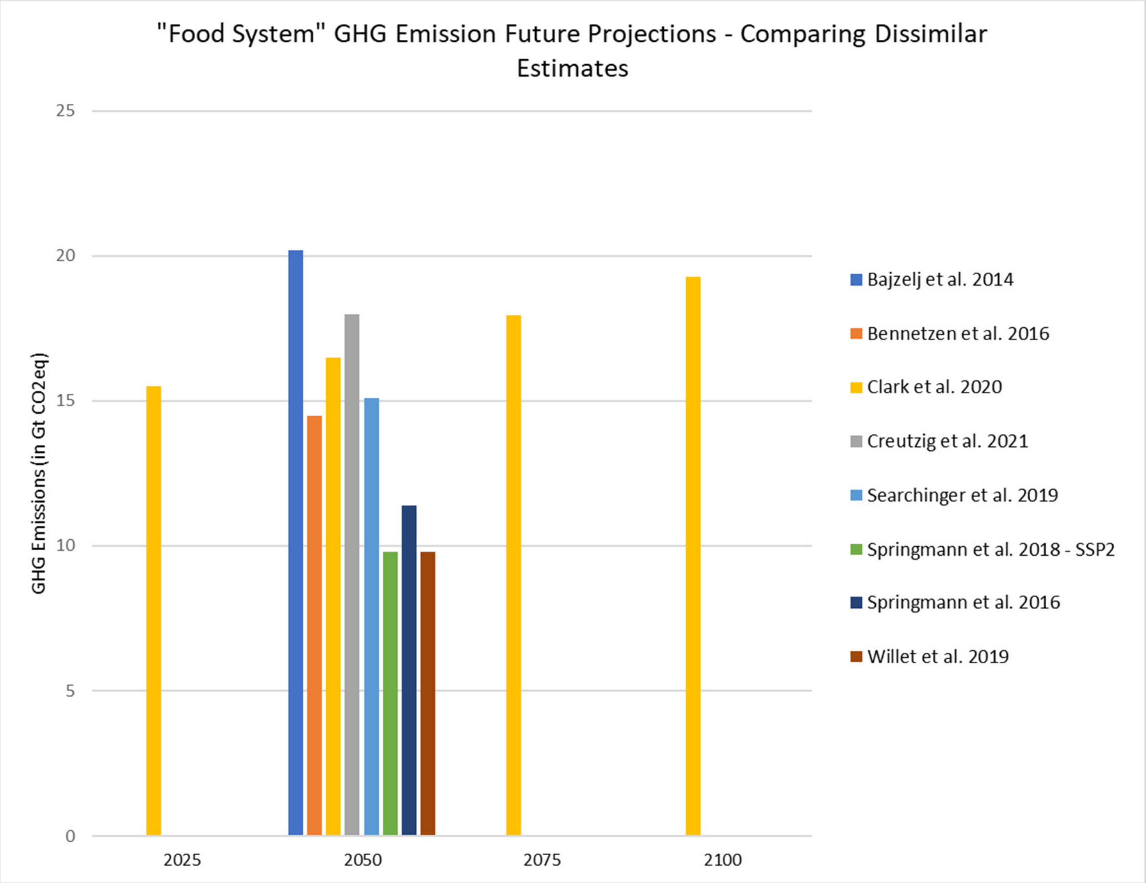

Figure 1.9: Future projections of global "food system" GHG emissions--comparing dissimilar estimates. This figure displays papers that have been described as future projections for food system GHG emissions. What is included in these future projections varies widely –with many of these estimates excluding some greenhouse gasses and emission stages. These differences are discussed further in the body of the text.

To make a more standardized comparison, all of the "food system" emission estimates included in Figure 1.9 that include CH_4, N_2O, and CO_2 in their estimates, are broken down into 4 stages: LUC, on-farm production, pre-production, and post-production. These emissions are compared in Figure 1.10 below. Food system emission future projections for 2050 range from 11.4-20.2 GT CO_2eq. None of these estimates include post-production emissions.

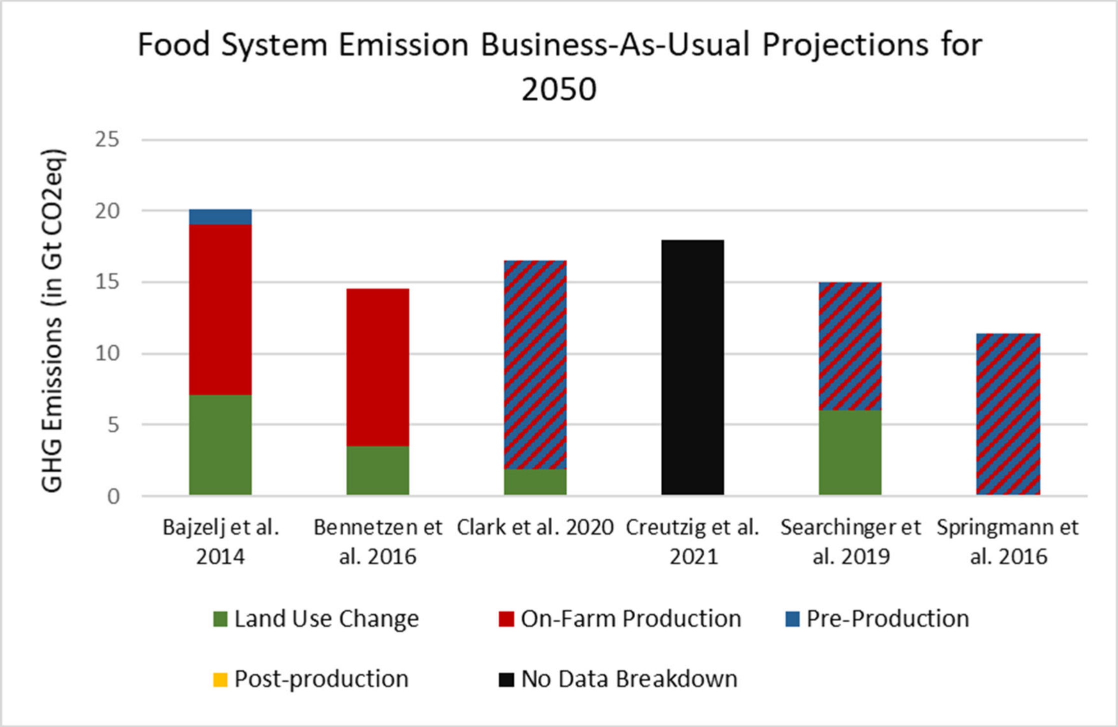

Figure 1.10: Food System GHG Emissions for Business-as-Usual Future Projections in 2050. This figure displays food system GHG emissions future projections for business-as-usual in 2050 broken down into pre-production, LUC, on-farm production, and post-production emissions. None of these estimates include emissions post-farmgate.

1.5 Discussion

There is significant variation in approaches and results in food system GHG emissions estimates and future projections. Understanding consistencies and variation across past, current, and future total food system emission estimates can help inform researchers and policy makers where to focus their efforts in reducing food system emissions.

Recent global food system estimates range from 16.1-18.36 GT CO_2eq, and are all over 30% of anthropogenic GHG emissions, and are on the high end of the 21-37% range popularized by the IPCC Special Report on Climate Change and Land (IPCC SRCCL, 2019; Crippa et al., 2021; Crippa et al., 2021; Xu et al., 2021). All global food system GHG emissions estimates published in 2021 estimate that more than 30% of anthropogenic GHG emissions, with Crippa et al. (2021) estimating 34%, Tubiello et al. (2021) estimating 32%, and Xu et al. (2021) estimating 35%, or 37% when emissions from savannah burning and peatland draining are included.

The ways in which past estimates have broken down their food system GHG emissions estimates may not be sufficient to illustrate the impact of animal-based foods. Xu et al. (2021) finds that almost 10 GT CO_2eq, or 60% of food system GHG emissions, are due to the production of animal-based foods. In their supplementary materials, they break down their estimate into different sub-sectors so that they can compare their estimates with others in this space. Using this breakdown, they find LUC (29%), farmland emissions (38%), livestock emissions (21%), and beyond farmgate emissions to be 12% of total food system emissions for 2010. While not a perfect comparison, Poore & Nemecek (2018) use this same breakdown and find LUC are responsible for 19%, farmland emissions makeup 29%, livestock emissions are responsible for 33%, and beyond the farmgate is responsible for about 19% of food system emissions. Many papers in this space aggregate emissions for agricultural emissions, so it is difficult to tell how much of food system GHG emissions are attributable to animal-based food production (Crippa et al., 2021, Tubiello et al., 2021, Clark et al., 2020, Rosenzweig et al., 2020, IPCC SRCCL, Vermeulen et al., 2012).

Many life cycle assessments and GHG estimates through the farmgate show that animal agriculture dominates GHG emissions (Poore & Nemecek, 2018; Tubiello et al., 2021). Concepts of double climate dividends and carbon opportunity costs show that there are additional GHG costs associated with animal-based food production beyond what is included in the food system emissions estimates analyzed here (Hayek et al., 2020; Sun et al., 2022). Together, this suggests that conventional ways of displaying food system GHG emission data are too aggregated and too incomplete to capture the full GHG costs of animal-based food production.

Past estimates of GHG emissions in the life cycle assessment space have highlighted that the agricultural production stages, and the land-use change associated with production, dominate all other stages in a food’s life cycle, and use this to justify the omission of GHG emissions post-farmgate (Clark et al., 2017; Weber and Matthews, 2008). Recent global estimates of total food system GHG emissions suggest that this might no longer hold true. Crippa et al. (2021) estimates that about 21% of emissions are from transport, processing, packaging, retail, and consumption, and that another 9% of global emissions are from food disposal, with 30% of food system GHG emissions coming from post-production stages. This, in conjunction with the rapid and significant growth in post-production stages show that making this assumption, would fail to capture a significant portion of food's emissions.

Currently, there are no food system GHG future projections that include post-production emissions, nor any that include emissions from F-gasses. Future projections of food systems GHG emissions in 2050 range from 11.4-20.2 GT CO_2eq. Springmann et al. (2016) estimates emissions will be 11.4 GT CO_2eq, but does not include emissions from land use change. While post-production estimates currently comprise a small portion of food system emissions estimates, Crippa et al. (2021) finds strong growth from 1990-2015 in global transport (+67%), processing (+33%), packaging (+67%), retail (+300%), consumption (+50%), and in end of life (+29%), with low- and middle-income countries experiencing even more rapid growth in transport (+200%), processing (+200%), and packaging (+150%). While estimated to only contribute 2% of global food system GHG emissions in 2015, from 1990-2015, F-gas emissions increased by more than 100% globally (Crippa et al., 2021). In industrialized countries, F-gasses are responsible for 8% of food system emissions, and this number has also increased by more than 100% from 1990-2015.

Given the omission of varying greenhouse gasses, stages, and activities in past food system emission estimates and future projections, it is very likely that the contribution of our global food system to climate change is underestimated.

Future work in food system GHG emissions estimation should include new estimations of the mitigation potential of different food system interventions, that include aspects of food systems that have been excluded to date (like post-production emissions and F-gasses), as well as incorporate new methods and findings in this space to determine what specific foods, diets, and actors drive GHG damages. Examples of existing work that show what drives climate damages in food systems include the attribution of deforestation to specific commodities in Pendrill et al. (2019), and the contribution of plant-, animal-, and other- sources of GHG emissions in Xu et al. (2021). Paralleling work done by the World Inequality Lab at the Paris School of Economics on GHG estimates for individuals, future research should also look at the variation of food-specific emissions across different levels of affluence within and across countries.

1.6 Acknowledgements

I thank Nina Domingo, Srinidhi Balasubramanian, Madisen Gittlin, Madeline Faubion, and Jason Hill for their support editing this chapter. I also want to thank Srinidhi Balasubramanian for teaching me how to pay close attention to detail when researching differences across emissions estimates and inventories. I want to give additional thanks to Joseph Poore and Michael Clark for providing insights on their own food system estimation work. This chapter is in preparation for journal submission, under the working citation:

K. Colgan, S. Balasubramanian, J. Hill (forthcoming). Understanding global food system emissions: analyzing key differences in past estimates and future projections. *In preparation.*

Chapter 2: Illustrating the mismatch between the recommendations of key papers in food systems climate mitigation and their calls for food systems transformation

2.1 Summary

The need for rapid and transformative change in food systems to reduce their contributions to climate change is widely recognized. A large number of interventions to achieve this change have been explored by many actors, in many geographic and socioeconomic contexts, across the dimensions of food systems. These interventions are commonly organized and analyzed in various ways, including actor, area of intervention, supply chain stage, level of political intrusiveness, cost, mitigation potential, potential for change, and more. Here, I organize food system mitigation interventions by different systems change frameworks and analyze the recommendations of 12 key papers for one of these—their potential for systems change. I find that despite their calls for food systems transformation, their recommendations to mitigate GHG emissions are primarily food system adjustments (45%) and reforms (46%) rather than transformational changes (9%). Expert recommendations coming from food security reports have the highest proportion of third-order recommendations, with their average recommendation scoring over 2, or a second-order of change. Learning from, and building on, their recommendations could help create more transformative recommendations in food system mitigation. This mismatch highlights the need to utilize systems change frameworks to prioritize currently discussed interventions, and suggest new ones to reduce food systems emissions and transform our food systems.

2.2 Introduction

The need for rapid and transformative change in our food systems to mitigate and adapt to climate change is widely recognized in academic and political literature (Foley et al., 2011; Campbell et al., 2018; Willet et al., 2019; IPCC SRCCL; Clark et al., 2020; HLPE, 2020; SOFI, 2021). A multitude of interventions to achieve this change have been explored and reported in notable works including: the IPCC Special Report on Climate Change and Land, Rosenzweig et al., (2020), and Niles et al., (2018). Beyond climate change mitigation, additional motivations for food system change include health, food security, and nutrition. Willet et al. (2019) discusses the benefits of adopting Planetary Health Diets, while the State of Food Security and Nutrition (SOFI) report and the High

Level Panel of Experts on Food Security and Nutrition (HLPE) report discuss food security and nutrition. These papers include environmental and climate action in their reports, as a stable climate is crucial for achieving food security and stability. Across these, and many other works in this space, mechanisms to mitigate emissions can be characterized by actor, area of intervention, supply chain stage, political intrusiveness, potential for change, cost, mitigation potential, and a host of other variables, by which these interventions can be organized.

Actors in food systems change include governments, community organizations, non-governmental organizations, academic institutions, corporations, farmers, food service providers, grocery stores, restaurants, individuals, and more. In their discussion of altering food environments to prevent type 2 diabetes, Liu et al. (2018) discusses how successful interventions will likely be achieved with a multi-level approach including interventions at the individual, interpersonal, organizational, community, and public policy levels. This actor hierarchy can be extended, and used to organize interventions to mitigate climate change in our food system as well.

These interventions can be organized by components for food security (e.g., availability, access, stability, utilization, agency, and sustainability) food environments (e.g., availability, accessibility, affordability, and attractiveness), as well as food waste hierarchies (e.g., reduce, reuse, recycle, disposal) as used by many food system actors such as the HLPE, FAO, and EPA (HLPE, 2020; EPA, 2021). These specific components are continually evolving as more is learned about what influences people's food decisions, and exact definitions vary with organization and time.

Interventions can also be organized by supply chain stages. Niles et al. (2018) breaks down emissions into the following stages: pre-production; production; post-production; consumption; loss, waste, and disposal. To better highlight the differences in interventions to mitigate climate change, Niles et al. (2018) also organizes these interventions for extensive and intensive production systems in low-and middle-income countries, as well as for high-income countries, highlighting how different interventions will be applied at every stage of the food supply chain depending on their country context.

These interventions can also be organized by their level of intrusiveness. Willet et al. (2019) applies the Nuffield Council of Bioethics Ladder of Policy Intervention to sustainable food systems, and Rust et al. (2020) employs an almost identical framework in their review of interventions to reduce meat overconsumption (Nuffield Council on Bioethics, 2007). These frameworks rank interventions by level of political intrusiveness ranging from doing nothing to eliminating choice.

Interventions to mitigate food system emissions can also be organized by their potential for change. There are many examples of potential for change frameworks including: Avoid, Shift, Improve; Meadows' 12 Leverage Points; Order of Change; and more. Creutzig and Niamir et al. (2021) utilizes an avoid, shift, improve framework to assess the mitigation potential and impacts on human wellbeing of different climate change interventions. One of the most influential systems change frameworks is Donella Meadows', *Leverage points: Places to intervene in a system* (Meadows, 1999). Her twelve-point framework ranges from adjusting constants and parameters to transcending systems paradigms, and highlights that as one moves towards changing paradigms, there is a greater potential for change, but it is harder to achieve that change. Her framework has been applied to work in food systems and sustainability (Abson et al., 2017, Fischer and Riechers, 2019; Slater et al., 2022). Slater et al. (2022) reviews key reports in food systems that call for transformative change, and uses a shortened adaptation of Meadows 12 places to intervene in a system, breaking down recommendations into six leverage points: systems paradigms (power, control, structures, and goals), system rules, information flows, feedback loops, and system elements and adjustment mechanisms. They find that most expert recommendations do not align with transformative change, and instead focus on less impactful leverage points. The authors' backgrounds are in nutrition and focus primarily on a public health lens. Here, I focus on extracting key recommendations from academic papers and reports that both: 1) call for food systems transformation and 2) the mitigation of greenhouse gas emissions in food systems. I analyze how these recommendations align with the paper's calls to transform food systems through an order of change framework. Then, I use the systems change frameworks described above to show how recommendations to mitigate GHG emissions in food systems can be improved through an illustrative example. This chapter seeks to illustrate the mismatch between expert recommendations to mitigate GHG emissions in food systems and their calls for food system transformation, as well as show how systems change frameworks can be used to create more transformative recommendations.

2.3 Methods

Paper Inclusion Criteria:

To perform this analysis, I identified papers that look at both mitigating climate change and transforming food systems. I utilized Google Scholar, SCOPUS, and JSTOR using keyword combinations of “food systems”, “climate”, and “mitigation”. These papers were then screened for relevance looking for a framing or focus on transforming food systems. Words signaling the time-sensitive nature of action such as “urgent” and “rapid”, words showing the comprehensive nature such as “far-reaching” and “Great Food Transformation”, and inclusion of need for change along multiple dimensions of food systems such as production, nutrition and health, land use and governance, environmental sustainability, and livelihoods were used to screen for relevance to food systems transformation. This initial search took place in 2018 and 2019. After that, only recurring publications and academic papers based on their analysis are added, including Rosenzweig et al. (2020), HLPE (2020), and SOFI (2021). For recurring publications, only the most current versions that focus on climate change are included in this analysis. For large reports, the summary documents are used instead of the entire report, as it is likely that fewer people read the whole report, as compared to the summary document. The key papers included in this analysis are shown in Table 2.1 below.

Table 2.1: Included key papers and reports in food systems mitigation. These papers were included for analysis based on their discussion of food systems mitigation and their calls for food systems transformation. SOFI = The State of Food Security and Nutrition. NGOs = non-governmental organizations. IPCC = Intergovernmental Panel on Climate Change. WRI = World Resources Institute. UN = United Nations. UNDP = United Nations Development Program. CIRAD = the French Agricultural Research Center for International Development. INRA = the French National Institute of Agricultural Research. FAO = United Nations Food and Agriculture Organization. CFS = Committee on World Food Security. NASA = the United States National Aeronautics and Space Administration. IFAD = International Fund for Agricultural Development. UNICEF = United Nations International Children's Emergency Fund. WFP = World Food Program. WHO = World Health Organization.

Paper	**Food System Focus**	**Author Coalition**
Foley et al. 2011	Food Security and Sustainability	Academia
Vermeulen et al. 2012	Food Systems and Climate Change	Academia; Research Centers; NGOs
Campbell et al. 2018	Food Systems, Agriculture, and Climate Change	Academia; Research Centers; NGOs
Clark et al. 2018	Diet, Health, Environment	Academia
Niles et al. 2018	Food Systems and Climate Change	Academia; Research Centers; NGOs; Think Tanks; Independent Expert
Loboguerrero et al. 2019	Food Systems, Agriculture, and Climate Change	Academia; Research Centers
IPCC SRCCL 2019 - SPM	Climate Change and Land	IPCC
Searchinger et al. 2019	Food, Land Use, and Greenhouse Gasses	WRI, World Bank, UN Environment, UNDP, CIRAD, INRA
Willet et al. 2019	Healthy Diets, Sustainable Food Systems, and Planetary Boundaries	EAT-Lancet Commission
HLPE 2020 - Executive Summary	Food Security	High Level Panel of Experts on Food Security and Nutrition (HLPE) of the CFS
Rosenzweig et al. 2020	Food Systems and Climate Change	Academia; FAO; NASA; Research Centers; NGOs; Think Tanks; Empraba
SOFI 2021 - In Brief	Food Security	FAO, IFAD, UNICEF, WFP and WHO.

Recommendation Extraction and Coding:

Many of the papers include dimensions beyond climate change in their analyses. For example, Searchinger et al. (2019) centers around food, land-use, and climate goals, while Willet et al. (2019) utilizes a planetary boundary approach for food systems and looks at the effects of food systems interventions on greenhouse gasses, cropland use, water use, nitrogen and phosphorus application, and biodiversity loss. HLPE (2020) and SOFI (2021) are recurring publications that focus on food security, and include sustainability and climate stabilization as key components to achieve global food security. Given this multifaceted focus, food system recommendations extracted from these papers are not always centered around mitigating climate change. The focus of the key papers analyzed here is shown in Table 2.1 above.

To extract paper recommendations, I followed the process outlined in Figure 2.1 below. First, I extracted recommendations from summary papers, if they were provided. If there were no summary tables, recommendations were extracted from headers or bullet points in the text. If these headers and subheaders were greater than five in number, then these recommendations were used. If they were not, recommendations were extracted from the text of the paragraphs relating to their recommendations. This process is non-exhaustive. Many papers include recommendations outside the key tables and paragraphs relating to their recommendations. While imperfect, it is important to note that people reading these papers may skim, or not read in-depth, and might be a better representation of what people take away from the paper.

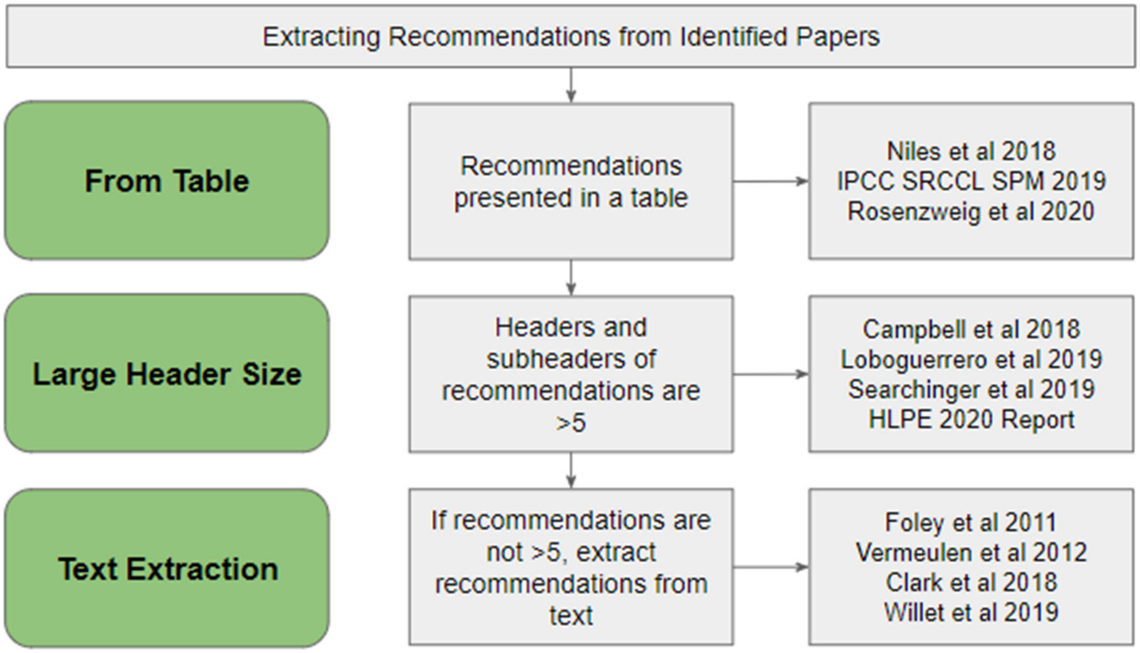

Figure 2.1: Process diagram for extracting recommendations. This figure illustrates the process for extracting recommendations for each identified paper, based on if they were extracted from tables, from paper headers, or if they were extracted directly from the text itself.

Methods for Coding:

After these recommendations were extracted, they were then coded with an order of change ranking utilizing a schema I adapted from Slater et al. (2022). It is important to note that the specific wording, and the way that recommendations are discussed, affects what order of change they are coded as. For example, a recommendation that uses language such as “continued improvements in…”, and “preserving..” will be coded as a first-order change, because these types of adjustments are already occurring in the current food system. Here, like in similar analyses, a lack of specificity in the recommendations results in them being coded as a lower order of change. Context from the paragraphs discussing the recommendations is used to determine the order of change ranking, meaning that it is possible for the same recommendations to have different ranks across papers.

Order of change is one way to think about systems change. The version I use here is simple, there are only 3 levels: first-, second-, and third-order change. **First-order change** is just an adjustment to the system --it makes a small tweak to one part of the whole system to address the identified challenge and is technical in nature. **Second-**

order change is a reformation to the system --it seeks to improve the system by influencing the system's drivers or change behavior but does not significantly change the system. **Third-order change** is a transformation of the system --it radically changes the structure, goals, and/or operations of the system. (Slater et al., 2022; Lawrence et al., 2015; Bartunek & Moch, 1987)

To code these recommendations, I adapted and built on the schema used in Slater et al. (2022). Slater et al. centers their schema around the six governance principles they identify: systems-based transparent approaches; addresses power asymmetries; policy cohesion; inclusivity; adaptiveness & responsiveness; and connectivity. To expand their schema beyond the adoption of healthy, sustainable diets and change it for healthy and sustainable food systems, I include first-, second-, and third-order descriptions of harm reduction and information sharing to standardize my coding across food system recommendations. This schema is shown in Table 2.2 below.

Table 2.2: Order of Change Schema. This table adapts and builds on the schema used in Slater et al. (2022) to create guiding principles to use in the process to assign order of change rankings to key paper recommendations.

Criterion	First-order change (Adjust)	Second-order change (Reform)	Third-order change (Transform)
Problem framing	May not acknowledge a problem, or if the problem exists it is because of technological inefficiencies.	The problem is caused by shortcomings within the system.	The problem is created by a system with flawed social, political, and economic values and poses an immediate threat to wellbeing.
Process for change	Maintains the current structure of power in the system.	Questions the current power structure that shapes the system; looks to include a more diverse group of actor's perspectives.	Moves towards a holistic, systems-approach; encourages revaluation of the design of the system.
Participation of stakeholders	Maintains the current power structures in decision making. Often global in scope.	Brings a wide range of stakeholders into the problem-solving and decision making process.	Centers around inclusivity, empowering people to be engaged in food systems transformation. Community-driven approach.
Governance structure	Projects undertaken within one entity.	Projects and programs across different entities.	Projects and programs integrating all relevant entities (holistic, cross-cutting approach).
Information sharing	Creates additional information to support the adoption of HSDs and HSFSs.	Creates additional information, and provides it to end users to support adoption of HSDs and HSFSs.	Creates additional information and resources for end users, and empowers them to act on the new information to support the adoption of HSDs and HSFSs.
Addressing harm	Calls for reductions or limitation of ongoing harms.	Calls for the cessation of ongoing harms, or calls for restoration of part of the harm done.	Calls for the cessation of ongoing harms, and works to reverse these harms.
Policy approach to achieving food systems change	Utilizes technological improvements to increase the mitigation potential of components in our food system.	Identifies different leverage points in the current system to be reformed to improve food system outcomes.	Utilizes a systems perspective to challenge the current systems purpose and structure, and identify a new purpose and structure that works towards improving food systems outcomes.

The schema was used to create order of change rankings for recommendations relating to various aspects of food systems transformation. Categories were created to illustrate what first-, second-, and third- order change looks like for different aspects of food systems. The categories include land and biodiversity; energy; agricultural production;

dietary shifts; economic, social, & political interventions; food loss & waste; supply chain; research and planning; enabling environments; risk & resilience; and refrigeration. For agricultural production, first-order of change recommendations include adjustments to agricultural production such as: continued improvements of crop and livestock genetics; reductions in the overapplication of farm inputs, and improved manure management. Second-order of change recommendations for agricultural production include reforms to agricultural production such as: shifts away from production of biofuels, livestock feed, and other non-food uses; integrated agriculture; agroecological-approaches; better varieties of crops and livestock; crop diversification; and integrated pest management. Third-order of change recommendations include recommendations like: perennial grains, diverse production systems, and agroforestry. For refrigeration, first-order recommendations are ones that increase efficiency such as regular maintenance routines and improved energy efficiency. Second-order recommendations shift to new technologies that utilize low-GHG refrigerants such as ammonia, CO_2, and Solstice ze, while third-order recommendations are ones that bypass refrigeration altogether, such as passive heating & cooling systems.

Once recommendations are extracted from each paper, they are compared using a ranking system to evaluate if there are trends in the papers and their recommendation averages of the order of change rankings. Third-order recommendations are scored with a 3, second- with a 2, and first- with a 1.

Table 2.3: First-, second-, and third-order change examples for each food system category. The order of change schema was used to create examples for each food system category for each order of change. First-order changes are small adjustments to the current status quo in the designated aspect of food systems. Second-order changes are reforms to the current status quo in the designated aspect of food systems. Third-order changes are transformational shifts in the designated aspect of food systems. HSFS = healthy and sustainable food systems. HSD = healthy and sustainable diets.

Food System Category	First-order change (Adjust)	Second-order change (Reform)	Third-order change (Transform)
Land & Biodiversity	Calls for reductions or limits in land degradation and biodiversity loss.	Calls for restoration of degraded and unused lands.	Calls for stops to natural ecosystem conversion and land degradation, and their restoration.
Energy	Energy is sourced from recovered wastes, or still relies on combustion and release of GHGs. Energy efficiency.	Energy is sourced from marginally better energy sources.	Renewable energy from sources that do not rely on combustion or ecosystem degradation.
Agricultural Production	Solutions that are tweaks to current popular production systems	Shifts away from current production systems.	New systems of production.
Shift Diets	Solutions that focus on shifting one component, or improve one outcome of diets	Solutions that focus on a couple of components or outcomes relating to diets.	Solutions that advance diets that are good for personal, public, and planetary health outcomes.
Specific Economic, Social, & Political Interventions	Expands existing programs.	Adds new policies to improve HSD adoption and move towards HSFSs	Transforms systems to ones that put people and the planet first.
Reduce Food Loss & Waste	Solutions that focus on shifting one component or outcome, with a technical focus.	Solutions that focus on a couple of components or outcomes relating to food loss and waste.	Closed loop food system, all unavoidable food waste is recovered and delivered back to the food system.
Supply Chain	Improves technologies and expands current supply chain components.	Shifts to better modes, methods, and practices of transporting, storing, processing, and retailing food.	Supply chain solutions that do not exacerbate climate change, land degradation, waste, or social inequality.
Research & Planning	Research and planning creates information to support the adoption of HSDs and HSFSs.	Creates additional information, and provides it to end users to support adoption of HSDs and HSFSs.	Creates additional resources with end users, and empowers them to act to advance HSDs and HSFSs.
Enabling Environments	Accelerates and expands existing actions to create HSFSs.	Builds capacity for local networks and organizations to make new, community-driven food systems change.	Community-driven programs across numerous entities, centered in empowerment and social inclusion, that create HSDs and HSFSs.
Risk & Resilience	Creates information to help inform behavior to reduce risk or improve resilience.	Shares information with end users to help inform behavior to reduce risk or improve resilience.	Eliminates detrimental potential effects associated with the risk.
Refrigeration	Improves management of refrigeration systems and cold chains and use high efficiency machines.	Shifts away from current refrigeration systems. Adopt low-GHG refrigerant technologies.	Bypass refrigeration and reduce reliance on cold chains.

2.4 Results

Coding Recommendations

A total of 273 recommendations were extracted from the identified papers in food systems transformation and GHG mitigation. These recommendations are not all unique, as papers make some of the same recommendations (for example: shift diets, reduce food waste). These recommendations can also fall into more than one category. For example, “change dietary and agricultural preferences” in Foley (2011) falls into both the agricultural production and diet shift categories.

I find that most recommendations fall into first- (45%) or second-order (46%) change categories, and very few (9%) are third-order change. This finding is in alignment with Slater et al. (2022). Half of the papers analyzed have only one recommendation that received a third-order of change ranking, and another quarter of the papers only have two recommendations that receive a third order of change ranking. Rosenzweig et al. (2020) has three, third-order recommendations, all of which fall into the agricultural production category. The majority of recommendations ranked as transformational in the HLPE (2020) report focus on creating enabling environments. The SOFI (2021) report has three third-order recommendations, all of which focus on social interventions that focus on transforming systems to reduce conflict and structural inequalities, or shifting diets to improve health and environmental outcomes. The HLPE (2020) report has the highest average for order of change recommendations with a score of 2.5, while the second highest average is 2.3 from the SOFI (2021) report. The rest of the papers included in this analysis average a 2.0 or lower with their average recommendation ranking reform or lower. Across the papers, I find that reports focusing first on food security have the highest proportion of third-order of change recommendations, with 50% of their recommendations coded as transformational. A summary table of the recommendations coding by paper for order of change ranking is shown in Table 2.4 below.

Table 2.4: Recommendations by order of change by key paper. This table summarizes the number of recommendations extracted from each paper, as well as the number of recommendations falling into each order of change. Here, the average order of change of the paper's recommendations are color coded from white to green, where the higher average order of change is denoted with darker green.

	Foley et al. 2011	Vermeulen et al. 2012	Campbell et al. 2018	Niles et al. 2018	Clark et al. 2018	Loboguerrero et al. 2019	Willet et al. 2019	IPCC SRCCL 2019	Searchinger et al. 2019	Rosenzweig et al. 2020	HLPE 15 2020	SOFI 2021	**Total**
Total Recommendations Extracted	**29**	**18**	**8**	**33**	**15**	**9**	**52**	**28**	**22**	**41**	**12**	**6**	**273**
Adjust	15	10	3	20	5	1	20	16	12	20	0	1	123
Reform	13	6	3	12	9	7	31	11	8	18	6	2	126
Transform	1	2	2	1	1	1	1	1	2	3	6	3	24
average	1.52	1.56	1.88	1.42	1.73	2.00	1.63	1.46	1.55	1.59	2.50	2.33	

A total of 362 category tags were extracted from the recommendations. The categories most represented in the recommendations were agricultural production and diet shifts, included in the recommendations of all but one paper. Agricultural production did not explicitly make it into the recommendations of the SOFI (2021) report, while diet shifts were not explicitly included in Campbell et al. (2018) recommendations. Both dietary shifts and improvements in agricultural production are mentioned in both papers. Agricultural production is discussed at length in the SOFI (2021) report, both in how vulnerable production and food security is to climate change, and how climate-smart agriculture practices can help mitigate and adapt to climate change. In Campbell et al. (2018), the mitigation potential of shifting diets and reducing consumption of livestock is discussed in the section on trade-offs, where it highlights the role of livestock consumption in food security in many low-income and rural contexts. It is important to note that just because the extracted recommendations do not fall into a specific category does not mean that these papers do not talk about that category, just that the category did not make it into the key recommendations extracted as the main focus of these papers. For example, food waste made it into the extracted recommendations for only 9 papers, but all 12 papers mention it as a solution --it is just not the focus of their recommendations. A summary table of the recommendations by paper broken into categories is shown in Table 2.5 below.

Table 2.5: Recommendation count by food systems category and by key paper. This table summarizes the number of recommendations extracted from each paper, as well as the number of recommendations falling into each category.

	Foley et al 2011	Vermeulen et al 2012	Campbell et al 2018	Niles et al 2018	Clark et al 2018	Loboguerrero et al 2019	Willet et al 2019	IPCC SRCCL 2019	Searchinger et al 2019	Rosenzweig et al 2020	HLPE 15 2020	SOFI 2021	**Total**	
Total Recommendations Extracted	**29**	**18**	**8**	**33**	**15**	**9**	**52**	**28**	**22**	**41**	**12**	**6**	**273**	Percent of Total
Total Category Tags	**38**	**27**	**12**	**36**	**18**	**15**	**85**	**29**	**26**	**48**	**19**	**9**	**362**	
Land & Biodiversity	6	0	0	0	1	1	7	12	5	1	0	0	33	9%
Energy	0	1	0	2	0	0	0	1	1	2	0	0	7	2%
Agricultural Production	21	8	3	17	4	5	16	8	15	29	1	0	127	35%
Shift Diets	1	2	0	1	10	1	22	1	1	1	4	1	45	12%
Specific Economic, Social, & Political Interventions	9	2	2	1	2	0	25	0	2	2	1	5	51	14%
Reduce Food Loss & Waste	1	1	0	7	1	1	6	2	1	2	0	0	22	6%
Supply Chain	0	1	0	6	0	0	1	2	0	5	0	0	15	4%
Research & Planning	0	1	0	0	0	0	3	0	0	0	1	0	5	1%
Enabling Environments	0	0	4	0	0	2	4	0	0	0	9	1	20	5%
Risk & Resilience	0	9	3	0	0	5	1	3	1	6	3	2	33	9%
Refrigeration	0	2	0	2	0	0	0	0	0	0	0	0	4	1%

The categories least represented in the recommendations were refrigeration (not included in the recommendations of 10 papers), research and planning (9), enabling environments (7), and supply chain (7). If energy and refrigeration are not broken out separately, and are instead included in the supply chain category, it is still not included in the recommendations of 6 papers.

Expanding the Discussion of Interventions

Here, refrigeration is selected as an illustrative example to discuss food system interventions to mitigate GHG emissions. It is selected for its comparatively small scope and relative simplicity, its rapid growth in GHG emissions in recent years, and its projections to continue growing rapidly into the future (Crippa et al., 2021).

In the extraction of key paper recommendations, only Vermeulen et al. (2012) and Niles et al. (2018) include recommendations on improvements in refrigeration and cold chains, with a total of four recommendations identified. Vermeulen et al. (2012) recommends (1) that refrigeration is improved and expanded to help mitigate emissions, ensure food safety, and reduce food waste, and (2) that we reduce our reliance on refrigeration and cold chains to mitigate emissions and improve the resilience of our food system. The first recommendation is coded as an adjustment, or first-order change, while the second is coded as a transformation, or third-order change. Niles et al. (2018) recommends improved refrigerant management (first-order change), and the adoption of low-GHG refrigerants (second-order change). I build on these recommendations using the Nuffield Ladder of Intervention framework (Table 2.6), the abbreviated version of Meadows' Leverage Points framework used in Slater et al. (2022) (Table 2.7), the actor hierarchy used by Liu et al. (2018) (Table 2.8), and the order of change framework in conjunction with a United Nations Environmental Program briefing note to enumerate more potential recommendations around GHG mitigation in refrigeration and cold chains (UNEP, 2019) (Table 2.9).

Table 2.6: Utilizing the Nuffield Ladder framework to enumerate interventions in refrigeration and cold chains. This table shows interventions in refrigeration to reduce food system GHG emissions utilizing the Nuffield Ladder of Policy Intervention framework. These range from most intrusive (eliminate choice) to least politically intrusive (monitor choice).

Nuffield Ladder Ranking	**Example Interventions**
Eliminate Choice	Do not allow purchase of cold chain technologies that use high-global warming potential (GWP) refrigerants
Restrict Choice	Restrict new purchases of refrigerator models to GHG-efficient ones
Disincentivize Choice	Implement a refrigerator tax
Incentivize Choice	Give a credit for disposing of old refrigerators; give a subsidy for GHG-efficient refrigerator purchase
Shift Default Choice	Make smaller refrigerator units the default in new builds; change industry standard to improved refrigerator models
Create New Choice	Create community refrigerator hubs
Clarify Choice	Educate about the energy use, GHG emissions, and maintenance routines of refrigerators
Monitor Choice	Do nothing or analyze current refrigerator use

Table 2.7: Utilizing an abbreviated leverage points framework to enumerate interventions in refrigeration and cold chains. This table shows interventions in refrigeration organized using the shortened version of Meadows' Leverage Points used by Slater et al. (2018), ranked by potential for change. Interventions that change systems paradigm have the greatest potential for change, while system adjustment mechanisms have the least potential for systems change.

Leverage Point	**Example Interventions**
Systems Paradigm	Change the idea that growth in refrigeration is good –make smaller, or fewer, refrigerators desirable, while still reducing food waste
Power, Control, Structures, and Goals	Move to community refrigeration hubs instead of personally-owned units
System Rules	Do not allow units that use high-GWP refrigerants in new builds; limit the number of refrigerators used in single family homes
Information Flows	Share information on the energy use, and GHGs of their refrigerator use with corporations and consumers
Feedback Loops	Negative feedback loop: taxes on refrigerants, energy use. Positive feedback loop: limiting affluence growth to limit demand for one (or multiple) refrigerators
System Elements and Adjustment Mechanisms	Increase energy efficiency of refrigerators

Table 2.8: Utilizing the actor hierarchy framework to enumerate interventions in refrigeration and cold chains. This table shows interventions in refrigeration organized using the actor hierarchy from Liu et al. (2018). These range from the individual level of change to public policy change.

Actor Hierarchy	**Example Interventions**
Public Policy	Governmental policy requiring regular maintenance for industrial refrigeration units; governmental ban of high-GWP refrigerants; free governmental disposal program for old refrigeration units; governmental program for community hub refrigeration; financial incentives for consumers to update their refrigerators
Community	Community hub refrigeration; grassroots initiatives to share knowledge and work to improve refrigerant and energy efficiency of refrigerators; programs to popularize and normalize the use of refrigerant-free cold chain solutions
Organizational	Organizational policy to use the most energy efficient refrigerators; organizational decision to use refrigerators with lower-GWP refrigerants; organizational policy to start reducing refrigeration needs
Interpersonal	Discuss refrigerator energy use, GHG emissions, and ways to improve them in peer groups, with family, friends
Individual	Get a more energy efficient refrigerator; get a refrigerator that uses a refrigerant with a lower-GWP refrigerant; do not own a refrigerator; own fewer refrigerators

Table 2.9: Utilizing the order of change framework to enumerate interventions in refrigeration and cold chains. This table shows interventions in refrigeration and cold chains organized by their order of change potential.

Order of Change	Mechanism	Intervention	Examples
Third Order - Transform	Bypass refrigeration	Do not refrigerate things that do not need refrigeration	US eggs; plant-based milks in the refrigerated section
		Utilize passive heating & cooling systems	Evaporative cooling systems on farm; thermally-efficient buildings, transport methods that use passive cooling system
	Transform Consumer Demand	Popularize dry chain alternatives	Movement from frozen to dried and shelf stable foods (mushrooms, vegetables, prepared meals)
Second Order - Reform	Switch Refrigerants	Adopt technologies that use low-GWP refrigerants	Technologies that use ammonia, CO_2, Solstice ze, etc
	Reform Consumer Demand	Aggregate demand	Adopt community cooling hubs
First Order - Adjust	Continue to Increase Refrigerant Efficiency	Adopt refrigerant-efficient technologies	Variable speed compressors
		Adopt refrigerant-efficient practices	Maintain refrigerators and refrigeration units regularly
		Improve building & site design	Use trees for shading, add a reflective coating to packhouse rooftops, etc
		Improve refrigerant waste management	Require technicians who service machines to follow best practices; require recovery of refrigerants upon unit disposal
		Mitigate demand through low-tech solutions	Natural ventilation, natural shading; improved insulation
	Continue to Increase Energy GHG Efficiency in Cold Chains	Change transportation modes	Less roads, more rail
		Adopt efficient control systems	Smart appliances
		Adopt renewable, low-GHG energy sources for electricity	Solar, wind, etc
		Utilize waste energy resources	Utilize waste heat/cold in commercial and industrial processes
	Adjust Consumer Demand	Improve energy efficiency of consumer refrigerators	Adopt best-available refrigerators
		Alter consumer behavior	Smaller refrigerators in homes; adjust acceptable temperatures

2.5 Discussion

Through this analysis, I find that there is a mismatch between key papers in the food systems mitigation space and their calls for urgent and rapid food systems change. Other work in sustainability and food systems support my finding. Abson et al. (2017) finds that many popular interventions for sustainability focus on weak leverage points for systems change. Slater et al. (2022) finds that broad food system reports call for transformation, but that their recommendations focus more on implementing adjustments or reforms to our current food system rather than transforming it. Expert recommendations to mitigate food system emissions follow the same trend, with only 9% of the expert recommendations analyzed here being a third-order, transformational change.

In this analysis, papers and reports that discuss power, demographics, and other related topics in sections other than their recommendations will rank lower than they would if they were included in the recommendation themselves. While this is a limitation of this analysis, it is important to note that if a reader were skimming the papers looking for the main points, this information would likely not have been extracted. An example of this is shown in Niles et al. (2018). This paper has the lowest average ranking recommendations, but they do discuss the influence of power, culture, and demographics on food system outcomes in other parts of their paper. This highlights that in our communications on food system mitigation, we must be explicit in the changes needed in these aspects of our food system recommendations, or readers may miss this crucial information.

The category that the most expert recommendations fell into is agricultural production. Given the historical focus on agricultural production interventions for both climate mitigation and food security, this is not a surprising finding. With time, additional aspects were added to climate estimates in this space, extending from agriculture to Agriculture, Forestry, and Other Land Use (AFOLU). But a comprehensive food system approach that includes GHG emissions post-farmgate is a much more recent approach, so it is understandable that there is a limited discussion of these interventions to mitigate food system emissions (Vermeulen et al., 2012; IPCC SRCCL, Rosenzweig et al., 2020). It does, however, elucidate the need for an expansion of the way experts talk about food system mitigation interventions to ensure that we do not miss large opportunities for change.

Of the identified key literature, reports focused on food security had the greatest proportion of third-order, transformational recommendations. These reports are created by a panel of experts across the UN system and supported by academics, and are recurring publications. The SOFI report is a collaborative report by FAO, IFAD, UNICEF, WFP, and WHO. The first SOFI report was published in 1990, and another one has been published almost every year since. The HLPE is the United Nations body charged with the assessment of global nutrition and food security, and they have published 16 reports so far. Environmentally sustainable food production is a more recent addition to their publications, but is now recognized as a critical component for food security. While it is an unfair standard to hold publications with a small author list, and without this kind of institutional support have just as transformational recommendations, it is important that researchers in food systems mitigation learn from these reports to accelerate our efforts to create more holistic, transformational recommendations. The creation of a similar recurring, collaborative publication in the food systems mitigation space could also help disseminate new understandings and research in this emerging research area as well.

Systems change frameworks have been widely used to discern interventions that will have a greater potential for change. In this analysis, I used the Nuffield Ladder, an abbreviated version of Meadows' Leverage Points used by Slater et al. (2022), the actor hierarchy used in Liu et al. 2018, and an order of change framework to enumerate interventions in refrigeration and cold chains. This intentional process to step back from already-known interventions, and think from a broader systems perspective can help illuminate new recommendations. Utilizing frameworks that have different focuses, such as different actors, different levels of political intrusiveness, and broader systems change can help ensure a wide variety of interventions are generated and cover multiple facets of our society. While Vermeulen et al. (2012) already discusses reducing reliance on cold chains for climate resilience, identifying this type of third-order change for every aspect of our food system can help move the focus from incremental improvements, and more towards disruptive systems change that increase the number of transformative expert recommendations in food systems mitigation. An iterative process that utilizes multiple frameworks that fit the area one is seeking to transform, in conjunction with nonexpert participants can help identify a greater number of interventions for change and help ensure that recommendations are relevant to a broader audience, as well as have a greater potential for change.

It is important to note that interventions with a large potential for change in systems change frameworks do not necessarily align with measured mitigation potential and may not fully illuminate trade-offs associated with an intervention. For example, expanding refrigeration and cold chains has been a popular recommendation to reduce food waste and improve food safety (Vermeulen et al., 2012; Lipinski et al., 2013; Niles et al., 2018). Given that food waste reduction is another aspect of food systems, and another intervention to reduce GHG emissions, efforts to reduce reliance on refrigeration must ensure that we do not increase our food waste, or progress in mitigating emissions in cold chains might be offset or surpassed by an increase in emissions from increased food waste.

While mitigation potential is not included in this analysis, many of the recommendations in the IPCC SRCCL have their mitigation potential included in the report. Many of these interventions to mitigate food system emissions are ranked as first- and second-order changes, and not as a third-order, transformative change. Meadows (1999) notes that small changes to our current system are comparatively easier to achieve than systems transformation, and it is likely that these types of interventions are easier to conceptualize, describe, and analyze than systems transformation. Given the urgent need to drawdown GHG emissions to meet the goals of the Paris Climate Agreement, it is likely that we need advancement interventions that adjust and reform our current system. Food system recommendations must find a balance across incremental and transformative change, while still conveying what the goals of food systems transformation are to decisionmakers.

There is movement towards more holistic and transformative recommendations in the food systems mitigation and broader food systems literature. Slater et al. (2022) finds that over time, recommendations in food systems reports have become more transformative. Work in food systems and climate is moving away from a sole focus on mitigation or adaptation towards cross-cutting solutions that do both (Loboguerrero et al., 2019). We also see a growing focus on centering around people and meeting their needs in more recent reports, as well as movements away from recommendations that rely on actions and altruism of individuals to make change, focusing instead on changing global trade policies, governance structures, and our cultural systems to create enabling environments to affect larger-scale change (Ross et al., 2019; Friel et al., 2020; HLPE, 2020; SOFI, 2021). These advances in the broader food systems field need to be translated into the expert recommendations, in conjunction with a greater focus on the parts of the frameworks that have the greatest potential for change, if we are to transform our food systems to meet the goals of the Paris Climate agreement.

2.6 Acknowledgements

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Chapter 3: Interventions to Mitigate Food System Emissions Can Facilitate or Impede the Achievement of the Sustainable Development Goals

3.1 Summary

The global food system is responsible for over a third of anthropogenic greenhouse gas emissions and will require radical transformation to stay below the 1.5°C and 2°C goals of the Paris Climate Agreement. Extensive effort has been devoted to identifying interventions to mitigate food system emissions but there is a paucity of work studying the effects of these interventions on the United Nations Sustainable Development Goals more broadly. Here I explore how food system mitigation efforts can either contribute to, or impede, the achievement of the UN Sustainable Development Goals (SDGs). I find that many of these interventions are likely to have co-benefits for other environmental-related SDGs, as well as many co-benefits for economic- and livelihood-related SDGs for climate interventions that also focus on agricultural productivity, while advancement on the more justice-centered SDGs is likely only if marginalized and vulnerable populations are empowered and included at the forefront of mitigation policy planning and implementation, and that interventions center around reducing inequalities. Without this inclusion, food system mitigation efforts are likely to exacerbate the existing poverty, hunger, and inequality of our current food system, precluding the achievement of the Sustainable Development Goals. I discuss the need for a portfolio of inclusive, and holistic climate interventions that consider all of the SDGs at the forefront of the policy creation process, and for further investigation into interventions that might support deeper, more comprehensive food systems change that facilitates the achievement of both the Paris Climate Agreement and the Sustainable Development Goals. This work is intended to stimulate conversation around the complexity of this challenge, as well as provide guidance to policymakers and the public.

3.2 Introduction

Other sections of this dissertation focus on sharing the importance of mitigating food system emissions, and what we can do to achieve these emissions reductions. This chapter focuses on the implications of food systems climate action on other aspects of sustainability. In the climate space, there is the general belief that things that are good for climate are also good for sustainability; this sentiment has been echoed by many in key papers and reports in the food systems greenhouse gas (GHG) mitigation space. For example, the IPCC Special Report on Climate Change and Land says, "Most of the response options assessed contribute positively to sustainable development and other societal goals" (IPCC SRCCL, 2019). A recent paper on Project Drawdown's system of solutions says, "Tradeoffs do exist, and they should not be discounted; however, the benefits of the Drawdown "system of solutions" to achieving the SDGs overwhelmingly support their implementation as urgently as possible" (Frischmann et al., 2020). Both of these papers discuss a curated selection of response options or solutions to address GHG emissions, so it is possible that their recommendations minimize trade-offs with the SDGs; however, this is not analyzed in this chapter. In their review of food system and sustainability narratives, Béné et al. (2019) notes that "several recently published high-profile reports underplay those trade-offs", where "those" refers to food system dimensions like food security, nutrition, livelihoods, culture, and sustainability.

There is growing awareness of the hazards of "carbon myopia" in food systems (Harrison et al., 2021). While Harrison et al. (2021) spends much of their time contesting current methods of quantifying GHG emissions in livestock systems, they give a thoughtful discussion of many of the benefits of livestock production including food and income provision, stability in drought conditions, livestock's ability to turn land that is unsuitable for crop production into a source of stable food, and the reliance of many low-income peoples on livestock. This example shows that there are many important dimensions of our food system in sustainability beyond climate change.

To discuss dimensions of sustainability beyond climate action, I use the United Nations Sustainable Development Goals (SDGs) framework, shown below in Figure 3.1. There are 17 SDGs: no poverty; zero hunger; good health and wellbeing; quality education; gender equality; clean water and sanitation; affordable and clean energy; decent work and economic growth; industry, innovation, and infrastructure; reduced inequalities; sustainable cities and communities; responsible consumption and production; climate action; life below water; life on land; peace, justice, and strong institutions; and partnerships for the goals. Targets and indicators are used to measure success on these broad goals, where targets are specific sub-goals and indicators are data that can be used to measure improvement in an area relevant to the target. These goals were designed to be inseparable, so that you cannot achieve one goal without advancing many of the goals.

Figure 3.1: The United Nations Sustainable Development Goals. This figure displays the United Nations Sustainable Development Goals, signed by 193 UN member states. These goals all have corresponding targets. SDG 13: Climate Action is monitored by the UNFCCC and progress on the Paris Climate Agreement framework and goals that were agreed upon at the United Nations 21st Conference of the Parties. The Paris Climate Agreement was created to limit warming to 2°C, with an aspirational target of 1.5°C. Currently, 189 UN parties are signatories.

This inseparability also leads to interactions between the SDGs. Nilsson et al. (2016) explores the impacts of SDGs on each other through a 7-point scale ranging from canceling (-3) to indivisible (+3). This paper has become a key resource in this space, with many using the scale they created, or using the paper as a guiding framework for related analyses. A report by the International Science Council (2017) uses this scale to examine interactions between the SDGs, studying goals 2, 3, 7, and 14 in depth, and finds that there are “no fundamental incompatibilities between goals” (International Science Council, 2017). Another study uses the scale to determine the impacts of SDG targets on other SDG targets in Sweden (Weitz et al., 2018). While Sterling et al. (2020) does not use the scale in their analysis, they use the paper to guide their mapping of Pacific Islands Wellbeing Dimensions to SDGs.

Pradhan et al. (2017) takes a different approach. Instead of using a group of expert opinions, they use correlations of indicator data to determine the trade-offs and synergies between the goals, highlighting the goals in their analysis that conflict most (reduced inequalities and responsible consumption and production; no poverty and responsible consumption and production; and clean water and responsible consumption and production) and are most synergetic (sustainable communities and climate action; no poverty and quality education; and no poverty and gender equality). They find that positive correlations (synergies in their analysis) occur when goals use the same indicators to measure progress, and that most trade-offs result from the "traditional nonsustainability development paradigm focusing on economic growth to generate human welfare at the expense of environmental sustainability" (Pradhan et al., 2017).

This paper is widely cited, and prominent research in the food systems and climate space uses their analysis (Herrero et al., 2020; IPCC SRCCL, 2019). The limitations of using indicator data in identifying trade-offs and synergies between SDGs are well noted in related literature. Sterling et al. (2020) notes that indicators are still not fully developed at the time of their analysis, that they may not be able to measure progress on the target they are used to measure progress on, that we currently have insufficient data for indicators because they are currently unfeasible to measure, and that using these indicators as a primary tool can increase social and environmental harms. Lipper et al. (2020) echoes the lack of reported indicator data by countries in their examination of SDG2: No Hunger, and also notes that indicator data for targets 2.3 and 2.4 are still under development.

Even within one SDG, targets can conflict. In their analysis of trade-offs and synergies between targets in SDG2: No Hunger, Lipper et al. (2020) highlights three key gaps. These are: that much agricultural productivity so far has been at the expense of the environment and sustainable food production; that increasing productivity and incomes for smallholder farmers does not have a direct or positive correlation with reducing malnutrition; and that so far, many increases in agricultural productivity have been at the expense of climate resilience. Due to these shortcomings, they highlight the importance of utilizing metrics for progress that encapsulate information across multiple indicators, targets, and goals like, nutritional yields (Lipper et al., 2020).

An extensive amount of research related to the SDGs across the globe has been conducted. Beyond what is highlighted above, the SDG framework is also used in the IPCC Special Report on Global Warming of 1.5 ºC to show trade-offs and synergies between SDGs and energy supply, energy demand, and land, and an entire chapter of the IPCC Special Report on Climate Change and Land is dedicated to the discussion of decision making relating to sustainable development, though these insights are not well represented in the more widely read Summary for Policymakers (SPM). While they do not use the SDG framework specifically, Creutzig and Niamir et al. (2021) discuss dimensions of wellbeing in their analysis of demand-side solutions to mitigate global GHGs. Beyond academic studies, there are tools measuring the contributions of climate action to the UN Sustainable Development Goals such as the UN Development Program's Climate Action Impact Tool, or CAIT, and the SDG Climate Action Nexus tool, SCAN-tool, supported by Germany's International Climate Initiative (UNDP CAIT; SCAN-tool).

While much work has been done relating to climate change, food systems, and sustainable development, this chapter is novel in that it explores five broad scenarios to achieving food system emissions reductions through a variety of interventions, highlighting the different trade-offs and synergies associated with each intervention. Here, I discuss how interventions in the five food system scenarios modeled in Clark et al. (2020) are likely to affect GHG emissions, as well as the SDGs beyond climate action. These future scenarios include food systems defined by: plant-rich diets, healthy calories, high yields, half food waste, and high-efficiency production. The mitigation potential of these five future food system scenarios is shown in Figure 3.2 below. **This chapter explores how specific interventions to mitigate food system emissions can facilitate or impede the achievement of the UN sustainable development goals through the implementation of five key mitigation strategies: plant-rich diets, healthy calories, high yields, half food waste, and high-efficiency production.**

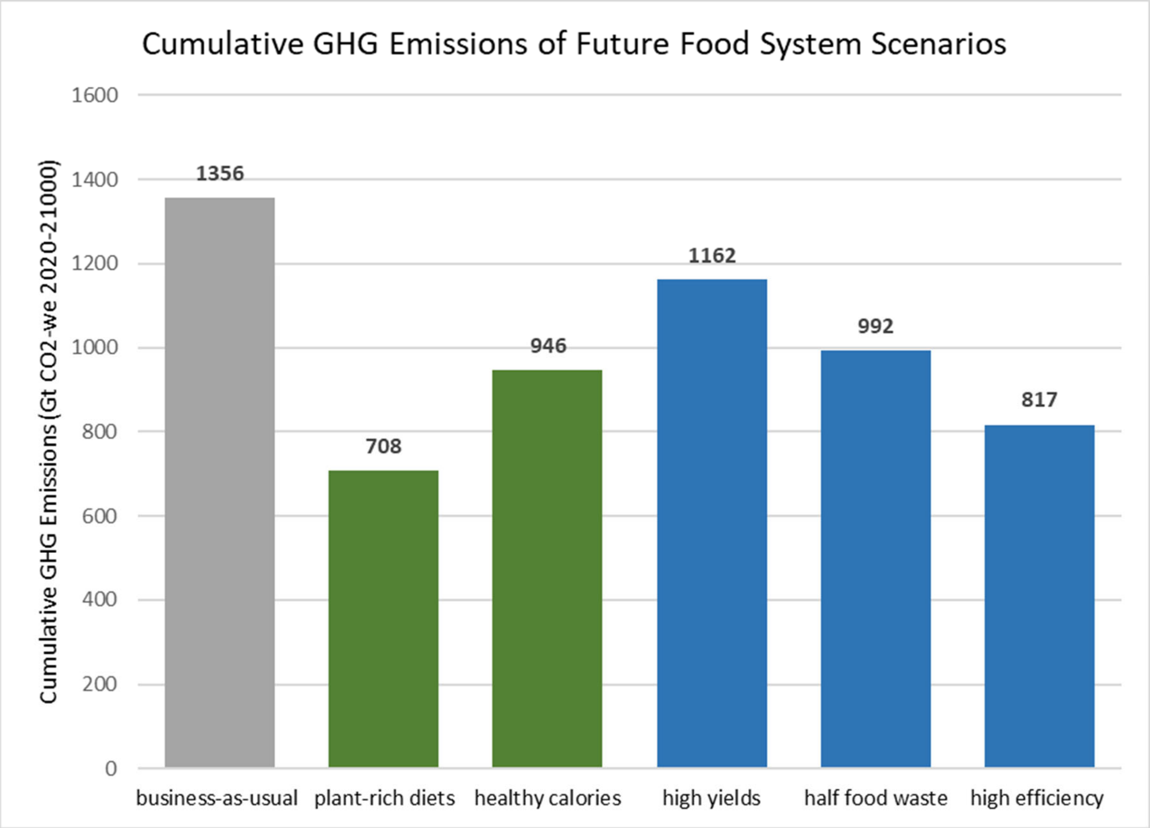


Figure 3.2: Cumulative GHG emissions of future food system scenarios modeled in Clark et al. (2020). This figure illustrates the cumulative mitigation potential of 5 key food system scenarios as estimated by Clark et al. (2020) from 2020-2100: plant-rich diets, healthy calories, high yields, half food waste, and high-efficiency production. Gray bars designate the business-as-usual scenario, green bars represent scenarios that focus on shifting diets, and blue bars denote improvements along the food supply chain. Recreated from Clark et al. (2020).

3.3 Methods

This chapter is framed around the five key mitigation strategies identified in Clark et al. (2020). In their analysis, these five strategies are gradually adopted between 2020 and 2050, and the cumulative mitigation potential of these strategies are compared to the business-as-usual (BAU) scenario between 2020 and 2100.

Clark et al. (2020) uses the UN medium fertility population scenario and life cycle GHG estimates for foods, in combination with diets that continue to follow recent trajectories to project the cumulative GHG emissions associated with the BAU scenario. Dietary trends have shown that as affluence increases, so does caloric consumption, and the consumption of animal-based foods (Bennett, 1941; Tilman et al., 2011). These trends are continued in the BAU diet scenario, resulting in an increased demand for land. Cropland expansion is assumed to emit 333 metric tons of CO_2 through the loss of above-ground carbon storage in biomass and carbon storage in soils. The BAU scenario also assumes that: yields continue to increase at the current rate; food loss and waste rates remain the same; and the GHG emissions associated with food production remain at current levels. More detailed information can be found in Clark et al. (2020).

The plant-rich diet scenario modeled is the cumulative mitigation potential of global adoption of the EAT-Lancet Commission's Planetary Health Diet as defined by Willet et al. (2019). The healthy calories scenario modeled is the global adoption of a BAU diet paired down to a healthy amount of calories. The healthy number of calories used is the number used by the EAT-Lancet Commission, corresponding to the number of calories needed to maintain a body mass index of 22.5 at current average activity levels, or approximately 2100 calories per person per day (Willet et al., 2019). The high yields scenario modeled is the cumulative mitigation potential of yields that are 50% above current maximum potential yields. The half food waste scenario modeled is the cumulative mitigation potential of a 50% reduction in the food lost and wasted globally. The high-efficiency scenario modeled is a 40% reduction in the GHG emissions emitted in the production of each unit of food. More information on the modeling assumptions and the reason behind them can be found in detail in the supplementary materials of Clark et al. (2020).

The Sustainable Development Goals and their targets and indicators were compared to the five future food system scenarios in Clark et al. (2020) to determine the direct modeled benefits and likely co-benefits of their future food scenarios. The research base established in the first two chapters of this dissertation were built on through the additional review of related articles, reports, and other literature, to ascertain how specific interventions to achieve the identified future food system are likely to affect SDGs beyond climate action. This chapter is not exhaustive, but instead illustrates a few of the potential SDG synergies trade-offs that could accompany climate interventions in food systems.

3.4 Results

To understand this analysis, it is important to first know and comprehend the well-established relationships within food systems and sustainability. These relationships are shown in Tables 3.1 and 3.2 below.

Table 3.1: Established social-centered relationships in food systems, climate, and sustainability.

Well-Established Relationships	**Description**	**Sources**
Indigenous Land Tenure & Deforestation	Secure Indigenous land-tenure is shown to reduce deforestation and forest degradation, as well as store more carbon than non-Indigenous managed lands, including conservation lands.	Nepstad et al., 2006; Vergara-Asenjo and Potvin, 2014; Ceddia et al., 2015; Baragwanath & Bayi, 2020; Walker et al., 2020
Increased Land Demands & Loss of Land Tenure	As demand for agricultural lands increase, land tenure is often lost first for women and Indigenous people.	Walker et al., 2020; FAO and FILAC, 2021
Racial Inequities in Food	Between- and within-country disparities in access to land, food, nutrition, and health outcomes are worse for Black-, Indigenous, and people of color due to systems of white supremacy, colorism, racism, and colonization.	Carpenter, 2012; Elsheikh and Barhoum, 2013; Conrad & Zuckerman, 2020; USDA ERS, 2020
Gender Inequities in Food	Women have reduced access to land, credit, knowledge, decision making, and food, and are often charged with food planning and preparation.	Barry et al., 2020; CGIAR, 2021
Natural Resource Extraction & Human Rights	Extracting natural resources for our food system like, phosphate rock mining for fertilizer and fossil fuels to power our tractors, leads to conflict, violence, the displacement of Indigenous people, and human rights violations.	Healy et al., 2019; Smart, 2020; FAO and FILAC, 2021
Affluence & Dietary Emissions	As affluence increases, so does the consumption of animal-sourced foods and total calories, leading to diets with greater GHG emissions. We see that high-income countries have greater dietary emissions than their low-income country counterparts.	Bennett et al., 1941; Tilman et al., 2011; Tubiello et al., 2021
Affluence & GHG Emissions	Beyond dietary and food system emissions, overall GHG emissions also increase with affluence. Emission gaps between wealthy individuals and individuals with the lowest-incomes are vast, with some ultra-wealthy individuals emitting more in one day than many will over their entire lives.	Chancel & Piketty, 2015; Hickel, 2020; Wiedmann et al., 2020; Chancel et al., 2022

Table 3.2 Established environmental-centered relationships in food systems, climate, and sustainability.

Well-Established Relationships	**Description**	**Sources**
Food and Air Pollution	Air pollution occurs in current food production systems from tillage, fertilizer application, and on-farm energy use and contributes to the formation of PM2.5 and premature mortality.	Paulot and Jacob, 2013; Balasubramanian et al., 2021; Domingo et al., 2021
Food and Water Pollution	Interventions that focus on increasing production through the use of fertilizers and livestock waste lead to water pollution from agricultural run-off, resulting in acidification and eutrophication, which creates dead zones.	Diaz and Rosenberg, 2008; Evans et al., 2019
Energy in Food	Energy is in every part of our food system from mining for raw materials, producing agricultural inputs, food processing, transporting our food, cooking, and disposing of food waste.	Vermeulen et al., 2012; Crippa et al., 2021; Tubiello et al., 2021
Animal Agriculture Land Footprint & Climate	Animal-based foods, in particular foods sourced from ruminant animals, have much greater land footprints to produce the same amount of calories and protein than their plant-based and poultry-based counterparts. This production is associated with a loss of carbon storage resulting in carbon opportunity costs with their production, and double climate dividends from movement away from their production.	Poore & Nemecek, 2018; Hayek et al., 2020; Sun et al., 2022
High Yields & Nutrition Delivery	High yields often do not translate to high rates of nutritional delivery. Increasing yields for crops predominantly fed to livestock or used for non-food uses like biofuel production leads to inefficient nutritional delivery to the food system. Countries with the highest yields can also have incredibly low rates of nutritional delivery.	Cassidy et al., 2013; DeFries et al., 2015; DeRuiter et al., 2018; Lipper et al., 2020
High Yields & Land Use	In theory, high-yields can lead to food production systems with smaller land footprints, as more food can be grown on the same amount of land. In practice, we have often seen that as yields increase so does demand for new agricultural land, as farmer’s incomes increase and they can afford to buy and farm more land. This phenomenon is also referred to as Borlaug’s Paradox.	Rudel et al., 2009; Ceddia et al., 2013

The results of each of the five scenarios are displayed in the following format:

1. Description of Clark et al. (2020) modeling results, noting key assumptions
2. Background information on the future scenario
3. Analysis
    a. Overview of the directly modeled benefits
    b. Overview of the likely co-benefits of modeled intervention
    c. Analysis of highlighted interventions and their potential impacts on the SDGs

3.4.1 Plant-Rich Diets

The first strategy analyzed in Clark et al. (2020) is the cumulative mitigation potential of adopting plant-rich diets from 2020-2100. In their modeling, they define plant-rich diets in accordance with the EAT-Lancet Commission's Planetary Health Diet, which is defined in detail in Willet et al. (2019). They find that adopting plant-rich diets would reduce emissions by 648 GT carbon dioxide warming equivalent (CO_2-we) from 2020-2100 from their BAU scenario. Of the 5 strategies analyzed, Clark et al. (2020) finds that this strategy has the largest mitigation potential.

The plant-rich diet scenario in Clark et al. (2020) assumes that the lands no longer needed for agricultural production are abandoned, and that this land sequesters carbon at a rate of 211 metric tons of CO_2 per hectare. It is important to note that abandoned agricultural lands might be used for another purpose, and sequester less carbon. To realize their modeled decreases in GHG emissions, policies will be needed that ensure these lands are not used for another, more emissive end use.

3.4.1.1 Background - why was this strategy selected?

Plant-rich diets vary in composition and are primarily plants, but allow for modest consumption of animal-based foods. These diets are rich in vegetables, fruits, whole grains, legumes, and nuts. Popular examples of plant-rich diets include meat-free diets like vegan and vegetarian diets, and other plant-rich diets such as the EAT-Lancet Commission's Planetary Health Diet, the Mediterranean diet, and the New Nordic Diet (Mithril et al., 2012; Clark et al., 2018; Willet et al., 2019).

Plant-rich diets have significant mitigation potential. They have much lower direct emissions than animal-based foods, as animals are inefficient at converting feed to food, and animal-based foods that are sourced from ruminants have high methane emissions from enteric fermentation. Additionally, animal-based food production has high carbon opportunity costs (Hayek et al., 2020). Lands dedicated to their production could otherwise be reverted back to natural ecosystems that sequester carbon in aboveground biomass and soils. Meat and dairy products require more land (for the production of their feed and forage) than their plant-based alternatives, resulting in carbon opportunity costs from their production that are approximately equivalent to the remaining 1.5°C emissions budget (Hayek et al., 2020). All of the IPCC-projected pathways to 1.5°C require the removal of carbon dioxide (ranging from 100-1000 billion tonnes of CO_2), and only two negative emissions technologies are currently viable at scale: afforestation and soil carbon sequestration (Keyßer & Lenzen, 2021; Minx et al., 2018).

The area of research concerning the achievement of reductions in meat consumption is growing rapidly. In 2020, three of the first reviews in this space were published (Attwood et al., 2021; Harguess et al., 2020; Rust et al., 2020). Rust et al. (2020) identifies barriers to reducing the overconsumption of meat, and highlights interventions to reduce meat overconsumption ranging from providing information to eliminating choice. Harguess et al. (2020) utilizes a framework from Stoll-Kleemann and Schmidt (2016) that identifies eleven factors ranging from personal, socio-cultural, political, to economic that can influence meat eating behavior, to characterize experimental interventions to reduce meat consumption, and in their systematic review they find that 5 of the 11 factors have not yet been tested. Atwood et al. (2020) creates a playbook of actions that food service providers can take to change diner behavior and increase the selection of plant-rich dishes in their establishments through interventions in product, placement, presentation, promotion, and people. These reviews list suggestions to shift diets ranging from individual action to global systems change.

Globally, there is insufficient availability of foods necessary to achieve plant-rich diets. To meet the planet's dietary needs for fruits and vegetables based on guidelines such as the Harvard Healthy Eating Plate, World Health Organization dietary recommendations, and the EAT-Lancet's Planetary Health Diet, we would need to increase production globally, as we currently do not produce enough of these foods to meet global needs (Bahadur et al., 2018; Willett et al., 2019; Mason-D’Croz et al., 2019). Even when these foods are available, they are prohibitively expensive for much of the world’s population (Hirvonen et al., 2019). Thus, significant changes to our food systems are required for widespread adoption of plant-rich diets.

3.4.1.2 Analysis - how do interventions to implement this strategy affect the SDGs?

Direct Modeled Benefits

Given the much smaller proportion of animal-based foods in the plant-rich diet compared to BAU diets, and the much larger GHG footprint of animal-based foods, plant-rich diets adoption leads to progress on SDG13: Climate Action. Additionally, because land requirements are so much higher for the production of animal-based foods than their plant-based counterparts, the adoption of plant-rich diets will facilitate the advancement of SDG15: Life on Land.

Likely Co-benefits

The adoption of plant-rich diets would likely be accompanied by other co-benefits. Reducing animal-based food production would likely reduce water and air pollution damages, advancing progress on SDG3 (3.9), SDG6 (6.3), SDG11 (11.6), SDG12 (12.4), and SDG14 (14.1, 14.3). Shrinking agriculture’s land footprint will help slow deforestation, reduce land degradation and the degradation of natural habitats, helping advance SDG15 (15.2, 15.3, 15.4, 15.5). As agricultural expansion has historically led to the loss of land tenure for women and Indigenous people, stopping this expansion can help slow further regression on SDG1 (1.4), SDG2 (2.3), SDG5 (5.5), and SDG10 (10.2, 10.4). Additional policies will be needed to ensure secure land tenure for women and Indigenous people, so while reducing agricultural expansion is likely to reduce further loss of land tenure, it does not ensure that land tenure is formally recognized. Furthermore, this analysis does not assume that it will advance progress on these goals, so much as stop the projected regression on these goals. Foods associated with improved health outcomes like whole grains, fruits, vegetables, legumes, and nuts generally have low environmental impacts, while foods like red meat have some of the largest environmental impacts and are associated with the greatest increases in disease risk, so adopting a more plant-rich diet is likely to improve health for many, advancing progress on SDG 3. Additionally, as business-as-usual diets and animal agriculture exacerbate 5 out of the 7 drivers for the emergence of zoonotic diseases like COVID19 and the avian flu, the adoption of plant-rich diets are likely to reduce the risk for future pandemics, contributing to macroeconomic stability, and advancing progress on SDG17 (17.13).

Interventions and their Potential Impacts on SDGs

In the discussion of adopting plant-rich diets, I cover three main interventions: greenhouse gas taxes, behavioral nudges to change consumption and procurement, and popularizing plant-rich diets.

The first intervention that I cover here is a GHG tax on food. There will be overlap here with the healthy calories strategy, but we will discuss this type of intervention at length in this section and only mention it briefly in later sections. Taxes are one popular intervention to alter diets and have been used to try and achieve a variety of diet shifts, including reductions in sugar-sweetened beverages (SSB), sodium, and saturated fats (Smed et al., 2016; Baker et al., 2017; Hyseni et al., 2017). GHG taxes on food and taxes on emission-intensive foods, like meat, have been proposed by environmental organizations (Jacobsen, 2013), and studied by academics (Wirsenius et al., 2011; Ripple et al., 2014; Springmann et al., 2017), but have not yet been implemented at scale. A review by Garnett et al. (2015), which evaluates the impact of fiscal policies on food decisions, concludes that taxes generally lead to reduced intake or product reformulation of the taxed product, though the health implications are unclear. Additionally, much research finds that politically feasible levels of taxation will be too small to sufficiently change consumption to realize health goals (Chouinard et al., 2007; Smed et al., 2007; Powell & Chaloupka, 2009). Some researchers also caution against the use of taxes, given the difficulties in predicting what healthy or unhealthy foods people may substitute taxed foods with, and how overall food spending will change (Cornelsen et al., 2015; Hyseni et al., 2017).

Taxes on SSBs have been adopted by a growing list of countries and municipalities, including Belgium, Chile, Mexico, Norway, Saudi Arabia, South Africa, the UK, and the Navajo Nation, as well as many US cities, including Berkeley and Philadelphia (Yazzie et al., 2020; City of Philadelphia, 2021). Evidence from early adopters suggests that the SSB tax is effective in moderately disincentivizing consumption, with households in the lowest socioeconomic levels generally experiencing the largest drop in purchases (Colchero et al., 2017; Roache & Gostin, 2017). In areas where access to a variety of fresh produce, fortified foods, and dietary supplements are not easily accessible, it may be difficult to obtain necessary micronutrients without consuming animal products. Low-income households in all countries should be given careful attention when considering policies that alter food prices, as food expenditures often represent a greater portion of their total budget, making them more vulnerable to sudden shifts in prices (Ivanic & Martin, 2008; Springmann et al., 2017). Springmann et al. (2017) finds that a GHG tax on all foods leads to decreased deaths from reduced red meat consumption in areas currently overconsuming them, but an increase in deaths in low- and middle-income countries from reductions in fruit and vegetable consumption, and overall calories with increased food prices. They also found that GHG taxes on food led to the greatest changes in consumption and GHG emissions in low- and middle-income countries, and only reduced food-related GHG emissions by 9%. Further, the people who are most likely to experience health benefits from an increased consumption of animal products are also those experiencing food insecurity and hunger (Neumann et al., 2002; Randolph et al., 2007). While reducing consumption of calorie-dense, nutrient-poor foods like SSBs may not harm health, it is likely that adding additional costs on foods through a GHG tax would exacerbate hunger and harm the health of many –in particular those who are already vulnerable-- as well make access to other basic services harder as more money must be spent to obtain food (Springmann et al., 2017). This would harm progress on SDG1, SDG2, SDG3, and SDG10.

Target 17.1 focuses on strengthening domestic resources and capacity for revenue collection. If governments were to adopt a GHG tax on food, this would be another source of revenue to help advance SDG17.

Multifaceted interventions that couple taxes on emissive foods in conjunction with subsidies for healthy, low-emission foods, like fruits and vegetables, could reduce food system emissions and improve health outcomes if proper support is provided to people with low socioeconomic status (Springmann et al., 2017; Broeks et al., 2020). If support policies are added that make it easier for people to procure more nutritious diets, then policy portfolios that include GHG taxes could potentially reduce hunger and improve health, advancing progress on SDGs 2 and 3. While subsidies could help make these foods more affordable for more people, they are insufficient to bring about global dietary shifts. Subsidies and taxes do not make low-emission alternatives more locally available or accessible. We do not currently produce enough fruits or vegetables to meet people's dietary needs, and agricultural and food supply chains are slow to respond. It is important to note that increases in food prices disproportionately harm people with low socioeconomic status, while GHG emissions are disproportionately generated by the affluent (Chancel & Piketty, 2015; Headey & Alderman, 2019; Hickel, 2020; Tubiello et al., 2020). Additionally, it is important to note that GHG taxes add costs to foods, but do not directly reduce GHG emissions. In fact, past efforts to implement carbon pricing systems have reduced overall emissions by just 0-2% (Green, 2021).

The second intervention I explore is behavioral nudges to change consumption and procurement. Changing the default food option at catered events to be plant-based can increase their selection, as found by a study of conference meal selection where more than 86% of meals selected were vegetarian by changing the default meal option (Hansen et al., 2021). DefaultVeg, a partnership between the UK Food Plan, Creature Kind, and the Better Food Foundation, champions defaulting to plant-based dishes in academic and corporate settings to promote sustainability and inclusivity. McCarty and Faber (2022) find that defaulting to a plant-based diet in a medium-size corporate office can reduce GHG emissions by more than 75,000 kg of CO_2eq, which is approximately the same GHG emissions as driving an average car 200,000 miles. In addition to reducing GHG emissions, defaulting plant-based increases the inclusivity of food options, as the majority of the world's population is lactose intolerant, and many religious faiths encourage plant-based diets or prohibit the consumption of certain animal-based foods (Storhaug et al., 2017). Changing defaults allows us to change social norms around eating to help improve procurement practices and facilitate sustainable consumption, advancing progress on SDG12 (12.7) and SDG13.

Popularizing plant-rich diets will require improving their attractiveness. What people choose to eat converges with the dietary choices of their families and other close social connections (Christakis & Fowler, 2007). Meat consumption is lower among people with a vegetarian in their social circle, and considerably lower in people in the same household as a vegetarian (Vandermoere et al., 2019). This shows that cultural shifts are important to shift diets. The World Resources Institute's Cool Food initiative works to change culture to make plant-rich eating cool and accessible by working with universities, food conglomerates, and corporations to help increase the number of plant-rich meals served. Marketing and advertising shape food culture. Numerous campaigns have linked meat consumption with masculinity, like "it takes a tough man to cook a tender chicken" in the United States, and "Feed the Man Meat" in Australia (Moberg et al., 2021; Dumbrell & Mathai, 2008). While these campaigns are not the only reason that gender-identity and meat consumption are so related, the connections between gender-identity and meat consumption are apparent. We find that men eat more meat (Prattala et al., 2007; Partearryo et al., 2019) and are less willing to reduce their meat consumption (Tobler et al., 2011; Hansen et al., 2021). Nakagawa and Hart (2019) find that men may eat more meat as a performance of masculinity, and numerous studies highlight that there is an association between meat consumption and perceived "manliness" (Sobal, 2006; Dumbrell & Mathai, 2008; Rothgerber, 2013). Living arrangements and relationships influence food choices, and an Australian study found that men reported eating healthier or being open to eating healthier when their significant other, of which only female partners were mentioned, ate healthier or cooked for them (Carroll et al., 2019). Heteronormative family food practices prevail and women are often still placed in charge of food provisioning (Gatley et al., 2014; Carrol et al., 2019). Changing gender norms and eliminating the association of meat with masculinity could advance climate and public health initiatives, facilitating progress on SDGs 3 and 13 (Nath, 2010; Modlinska et al., 2020). Past campaigns have started to work to equate meat-alternatives with athleticism and masculinity through advertisements, sponsorships (Beyond Meat sponsored LA Lakers, Quorn sponsored Olympians), and public awareness campaigns (Blythman, 2018; Los Angeles Lakers, 2019). Consuming more plant-based alternatives to meat can help decouple economic growth and environmental degradation, advancing progress on SDG8 (8.4) and SDG12 (12.2). Adopting plant-rich diets heavy in highly-processed and corporate-owned meat-alternatives may increase costs of plant-based protein sources, making plant-rich diets even more expensive and unavailable to many, as well as decrease the likely health co-benefits of plant-rich diet adoption, harming SDG2 (2.1) and SDG3 (3.4).

As mentioned in the likely co-benefits section, popularizing plant-rich diets — through whatever interventions --- will likely help reduce land demand and the loss of land tenure that often accompanies it. Complementary policies that work to formally recognize land tenure for women and Indigenous people, and a reformation of existing policies to ensure equal participation and power in agricultural production, can help advance progress on SDG1 (1.4), SDG2 (2.3), SDG5 (5.5), and SDG10 (10.2, 10.4).

Figure 3.3: The direct modeled benefits, likely co-benefits, and the potential of interventions to achieve a plant-rich future food system to help or harm the achievement of the UN Sustainable Development Goals.

3.4.2 Healthy Calories

The second strategy analyzed in Clark et al. (2020) is the cumulative mitigation potential of adopting diets with a healthy amount of calories from 2020-2100. In their modeling, the 2085 calories consumed in the healthy calories scenario are the same proportions of foods in the BAU scenario. Of the 5 strategies analyzed, Clark et al. (2020) finds that this strategy has the third largest mitigation potential.

It is important to note that pathways to adopt diets with healthy calories may not keep the same proportions of foods consumed in the BAU scenario. Average diet composition will have great effects on food system GHG emissions and land use. Clark et al. (2020)

assumes that there is less food produced in proportion with the BAU scenario, resulting in a decrease in the total agricultural land footprint, allowing more carbon to be sequestered on abandoned croplands. While Clark et al. (2020) determines that adopting diets with a healthy amount of calories has significant mitigation potential, other studies do not come to this same conclusion (Creutzig et al., 2021). These potential effects are discussed in more detail below.

3.4.2.1 Background - why was this strategy selected?

To adopt diets with a healthy amount of calories, there are two main ways to intervene: reduce underconsumption and reduce overconsumption. Many strategies and pathways to eliminate hunger and malnutrition have been proposed, but hunger has been increasing globally since 2015, and COVID19 has worsened hunger dramatically (SOFI, 2019; SOFI, 2021). In 2020, almost one in three people did not have adequate access to food, and 928 million people suffered from severe food insecurity. At the same time, over two billion people are overweight or obese (WHO, 2021). Micronutrient deficiencies -- also known as hidden hunger -- affect over 2 billion people globally, regardless of whether they are under- or overweight (Dary & Hurrell, 2006; Muthayya et al., 2013; FAO, IFAD, UNICEF, WFP, & WHO, 2018).

Generally, we find that sustainable and healthy foods go hand-in-hand, with a few key exceptions (Clark et al., 2019). Plant-based foods, like whole grains, fruits, vegetables, nuts, legumes, and vegetable oils high in unsaturated fats are consistently linked with health and environmental benefits, as well as some lower environmental impact animal foods, like fish. Unprocessed red meats have the highest relative environmental impacts of the foods studied in Clark et al. (2019), followed closely with processed red meats, as well as the highest risk for mortality. SSBs have very low relative environmental impacts, but are associated with higher relative risks for mortality, while nuts are associated with higher relative environmental impacts (due to their scarcity-weighted water use), and lower relative risks for mortality (Clark et al., 2019).

What one eats to make up a healthy amount of calories influences the environmental impacts associated with one's diet. One could eat a diet associated with the lowest risks of mortality, eating a diet rich in foods like shrimp, salmon, chicken, avocados, and nuts, but have high water, land, and GHG footprints associated with them (Poore & Nemecek, 2018; Clark et al., 2019). It takes much less land and water, and emits far fewer greenhouse gasses, to overshoot one's caloric needs with foods like potatoes, refined grains, and sugar sweetened beverages (Poore & Nemecek, 2018; Clark et al., 2019). This difference in emissions is the main reason that other work does not find that caloric overconsumption has a significant mitigation potential (Creutzig & Niamir et al., 2021).

3.4.2.2 Analysis - how do interventions to implement this strategy affect the SDGs?

Direct Modeled Benefits

By definition, a healthy calorie diet eliminates hunger, achieving SDG2 (2.1). Bringing calorie consumption to a healthy level would also help to reduce premature mortality from non-communicable diseases, advancing progress on SDG3 (3.4). GHG emissions reductions resulting from agricultural overproduction would be avoided, and the land footprint associated with it would decline, advancing SDG13 and SDG15. Though they are not included in Clark et al. (2020), post-harvest emissions associated with the rest of the food chain activities, like packaging, transportation, retailing, and food preparation are also likely to decline, progressing SDG13.

Likely Co-Benefits

Adopting diets with a healthy amount of calories globally, would likely be accompanied by other co-benefits. Reducing agricultural overproduction would likely reduce water and air pollution, advancing progress on SDG3 (3.9), SDG6 (6.3), SDG11 (11.6), SDG12 (12.4), and SDG14 (14.1, 14.3). As with a plant-rich future food system, shrinking agriculture’s land footprint will help slow deforestation, reduce land degradation and the degradation of natural habitats, and advance progress on SDG15 (15.2, 15.3, 15.4, 15.5). Stopping agricultural expansion can help slow the loss of land tenure for women and Indigenous people, and further regression on SDG1 (1.4), SDG2 (2.3), SDG5 (5.5), and SDG10 (10.2, 10.4). Additional policies will be needed to ensure secure land tenure for women and Indigenous people, so while reducing agricultural expansion is likely to reduce further loss of land tenure, it does not ensure that land tenure is formally recognized; this analysis does not assume that it will advance progress on these goals, but instead stop further regression on these goals.

Interventions and their Potential Impacts on SDGs

In the discussion of adopting diets with a healthy amount of calories, I cover 5 main interventions: school feeding programs, expanded social protection programs, taxes, improving access to food through improved transportation and walkable cities, and transforming zoning laws.

Homegrown school feeding programs are used widely, and vary greatly. Through these programs, schools purchase locally-produced foods to use in the meals they serve to students and create a stable, daily meal for school-aged children as well as reliable markets for farmers. Brazil's National School Feeding Program is multifaceted, and in addition to procuring from local family farms, they also have an education component that promotes school gardens, nutrition, and the human right to food. This program is expansive, ensuring that over 40 million students are fed each school day (FAO, 2018). The Homegrown School Feeding Program implemented in rural Kenya has achieved a $2.74 boost in local cash incomes for every $1 transferred to a school for food purchases (SOFI, 2019). In Minnesota, we have the Farm to Schools program, through which the Minnesota Department of Agriculture reimburses school districts for their purchases of Minnesota-grown foods (MDA, 2022). Homegrown school feeding programs implemented procurement practices to reduce underconsumption, food price volatility, local market instability, global poverty, and increase access to education, advancing progress on SDG1 (1.3, 1.a), SDG2 (2.1), SDG4 (4.1), and SDG12 (12.7).

Social protection programs have been proposed and implemented to eliminate hunger and underconsumption, including strengthening the human right to food, social safety nets, cash-based transfers, declaring access to basic services a human right, and more. Hunger and underconsumption are often the result of poverty and the inability to afford food, so interventions that center around poverty elimination are also likely to advance SDG2 (SOFI, 2021). The UN Food and Agriculture Organization has resources on how to implement the right to food in legislation change, budgeting, assessment and monitoring, and education (FAO, 2022a; FAO, 2022b). Expanding social protection programs is the goal of targets 1.3 and 10.4, so strengthening these types of programs would advance progress on SDG1 and SDG10. The Shock-Responsive Safety Net for Human Capital Project is the national cash-based transfer program to alleviate poverty, and it was expanded to use remote mobile money transfers to reduce the detrimental economic effects of floods, COVID19, and locusts, without the need for in-person banking services (WFP, 2021). Social protection policies can be designed to also help the vulnerable recover from climate disruptions, advancing progress on SDG1 (1.5) and SDG13 (13.1). Cash-transfers are not always an appropriate solution, so in-kind food supplies can be used to ensure people's caloric needs are met, as is done by Prosperidad Social and the World Food Program for Indigenous and migrant communities in Colombia (WFP, 2021). Creative design to ensure that the most vulnerable populations' needs are met will advance SDG1, SDG2, SDG5, and SDG10. Social protection programs can be used to meet people's immediate needs, but if governments and NGOs decide to cut programs or reduce their financial support, these advancements on the SDGs may not be long-lasting.

As discussed in the plant-rich diet section above, unless coupled with mechanisms to transfer wealth, or other policies to make up for the loss of income, food taxes are regressive, and will harm progress on SDG1, SDG2, and SDG10. If taxes are used to reduce any facet of overconsumption, in particular ones that limit the consumption of foods associated with low environmental impacts, the taxes may not end up resulting in GHG emissions reductions. These types of taxes may shift consumption to more polluting, and land-intensive foods, undoing the predicted environmental benefits of the intervention and potentially harming SDG3, SDG6, SDG11, SDG12, SDG13, SDG14, and SDG15.

Changing the relative accessibility of different foods is central to shifting diets. Food deserts, or the unavailability of healthy options, impact health outcomes, as do food swamps, or areas where high-calorie, nutrient-poor foods are more prevalent than healthier food options. One US study found that the presence of food swamps are better predictors of obesity than are food deserts, with greater effects felt in areas with higher income inequality and low resident mobility (Cooksey-Stowers et al., 2017). Making healthy, nutritious diets more accessible through expanded offerings and improved transportation and city-planning will be needed to help reduce underconsumption, overconsumption, and micronutrient deficiencies (Willet et al., 2019; Havewala, 2021).

Expanding and reducing barriers to use public transportation and the creation of walkable neighborhoods and cities can help increase food access, while reducing the use of single passenger vehicles, and the environmental and human health damages that accompany them, advancing progress on SDG3 (3.9), SDG11 (11.6), and SDG12 (12.2, 12.4). Adopting electrified public transportation that runs on renewable energy will help advance progress on SDG7 (7.3). If the adoption of these renewable energy-powered transportation systems in low-income countries are facilitated through technology transfer, concessionary financing, and international cooperation, this would also advance SDG1 (1.a), SDG7 (7.a, 7.b), SDG9 (9.1), SDG10 (10.b), SDG12 (12.a), and SDG17 (17.2, 17.3, 17.6, 17.7). Engaging vulnerable people, women, children, people with disabilities, and the elderly to help shape these programs to meet their needs would advance progress on SDG10 (10.2), SDG11 (11.2, 11.3), and SDG16 (16.7). Extending education and employment opportunities to work in renewable energy, public transportation, and healthy diet sectors for local community members can help advance progress on SDG4 (4.3, 4.4) and SDG8 (8.2, 8.3), and ensuring equal opportunities, eliminating discriminatory policies, and taking affirmative action to employ women, low-income, youth, and marginalized people directly in these sectors can help advance SDG4 (4.5), SDG5 (5.1), SDG8 (8.5, 8.6), and SDG10 (10.1, 10.2, 10.3) as well.

Access alone is likely to be insufficient to achieve healthy calorie diets. Similarly, only reducing access to unhealthy foods is also likely to be insufficient (Sturm and Hattori, 2015). Interventions are needed that both increase access to healthy foods and decrease the relative offering of calorie-rich, nutrient-poor foods. One proposed intervention is to transform zoning laws to eliminate food swamps, decreasing the number of food outlets that serve calorie-rich, nutrient-poor foods, and increasing the number of food outlets serving healthy foods in the neighborhoods where people live and work (Willet et al., 2019; Havewala, 2021). With this type of policy intervention, there is greater opportunity for creative solutions, such as adding additional criteria for plant-rich and culturally-relevant foods, or adding ownership and employment requirements to reduce inequalities, advancing goals SDG1 (1.4), SDG5 (5.1), SDG8 (8.5, 8.6), and

SDG10 (10.2, 10.3). Furthermore, economic support for these types of food outlets can be garnered by the adoption of suitable and equitable procurement practices by governments, educational institutions, and corporations, advancing SDG8 (8.3), SDG10 (10.2), and SDG12 (12.7).

Figure 3.4: The direct modeled benefits, likely co-benefits, and the potential of interventions to achieve healthy calorie diets to help or harm the achievement of the UN Sustainable Development Goals.

3.4.3 High Yields

The third strategy analyzed in Clark et al. (2020) is the cumulative mitigation potential of achieving high yields from 2020-2100. In their modeling, they define high yields as “50% above current maximum potential yields”. They find that achieving high yields would reduce emissions by 194 GT CO_2-we from 2020-2100 from the BAU scenario. Of the 5 strategies analyzed, Clark et al. (2020) finds that this strategy has the lowest mitigation potential.

It is important to note that land no longer needed to meet food demand in high-yielding food systems is not automatically reverted back to natural ecosystems and restored. In fact, we have seen the opposite relationship occur. Often as yields increase so do demands for new agricultural lands, as farmer's incomes increase and they can afford to buy and farm more land; this phenomenon is called the Borlaug Paradox (Rudel et al., 2009). Similar effects have been observed in other contexts like fuel use and for improvements in technology's energy efficiency (Alcott, 2005; Kuijer & Bakker, 2015). Policies are needed to ensure that increases in yields do not lead to accelerated agricultural expansion, and instead lead to a smaller agricultural land footprint.

3.4.3.1 Background - why was this strategy selected?

Historical increases in yields are largely attributed to the Green Revolution, through the adoption of synthetic fertilizers, implementation of industrial monoculture cropping systems, and improvements in genetics (Pingali et al., 2012). Subsidy programs for fertilizers and seeds have been adopted by many countries to help increase yields and promote local and national food security (Druilhe & Barreiro-Hurlé, 2012). Many development assistance programs have focused on bringing these types of production systems into low-yielding areas to try and reduce yield gaps (Druilhe & Barreiro-Hurlé, 2012). Though Green Revolution innovations and actors are often credited with saving millions, if not billions, of lives, these production systems and technology transfer systems are not without their faults (Erisman et al., 2008).

For some people, most often low-income and subsistence farmers, the caloric gains associated with increased production from Green Revolution production techniques have been accompanied by a decline in dietary diversity and micronutrient consumption, as nutrient-rich traditional foods were displaced by high-yielding staple crops (Lipper et al., 2020). Increased yields and global demand for export of these commodities has led to the conversion of natural ecosystems to agricultural lands, decreasing the lands available to harvest wild foods from (Gibbs et al., 2010; Sunderland & Vasquez, 2020). Many rural dwellers, often the world's poorest, rely on wild foods to meet their nutritional needs, with many remaining groups of hunters and gatherers having better dietary diversity and health than their more agrarian counterparts (Dounias & Froment, 2006; Reyes-Garcia et al., 2019; Sunderland & Vasquez, 2020).

Adoption of these production systems is expensive and cost prohibitive for many (Pingali et al., 2012; USDA/NASS, 2022). The farming inputs associated with Green Revolution production systems significantly increase the price of production as synthetic fertilizers, seeds, and pesticides are manufactured and distributed by international agricultural and pharmaceutical corporations (Dutta, 2012). As seeds are patented, they must be purchased every year, with seed saving leading to prosecution by the corporations providing the seeds (Peavey, 2014). Additionally, these industrial cropping systems often lead to bare soil, resulting in increased soil erosion, water, and air pollution (Montgomery, 2007; Erisman et al., 2013). These production systems are also less resilient, as they rely on monocultures, leading to higher susceptibility to insect outbreaks and increased rates of disease development (Altieri et al., 2015). Loss of diversity in crop production has also been shown to decrease food security at the national level (Renard & Tilman, 2019). Women gained less from the Green Revolution, as efforts to transfer technology were centered around men, and barriers to participate in farming, like a lack of land tenure and access to credit, were plentiful (Doss, 1999; McIntyre et al., 2009; Pinglai et al., 2012).

Due to these growing concerns, there is a growing public awareness and demand for alternative production systems. Agroecological, regenerative, and organic production practices, integrated cropping systems, silvopastures, agroforestry, perennial grains, and other systems that work to diversify the agricultural landscape, have gained in popularity in academic and community spaces as they work towards more circular production systems and utilize Indigenous and local knowledge (IPCC SRCCL, 2019).

3.4.3.2 Analysis - how do interventions to implement this strategy affect the SDGs?

Direct Benefits

When producing a given amount of food, high yields result in less agricultural expansion and land clearing, reducing the emissions associated with this land use change, and requiring a smaller land footprint to meet food demand, working to achieve SDG13 and SDG15.

Likely Co-benefits

Higher yields on one farm are likely to lead to more food available to the family for direct consumption or sale, helping to reduce poverty and hunger, as well as improve health, working to achieve SDG1, SDG2, and SDG3. However, these improvements by early adopters might not be sustainable. As more farmers adopt practices to increase yields, supply may increase suddenly, leading to local surpluses that depress prices; this means that even if farmers have a bumper crop, they may not break even due to price increases for these high-yielding production technologies, exacerbating poverty and declines in other SDGs that come from poverty such as hunger, poor health, and decreased access to education, harming progress on SDG1, SDG2, SDG3, and SDG4.

In the scenario modeled in Clark et al. (2020), higher yields mean less land is needed to meet global food demand. The avoided negative side effects of decreased agricultural land demands that have been discussed in earlier sections are also relevant here on SDG1, SDG2, SDG10, and SDG15. However, this analysis highlights only a cessation of further regression, and not the advancement of these goals. Many interventions to achieve higher yields in the past have been too expensive for small-scale and low-income farmers, and have excluded women, hindering the achievement of SDG2 (2.3), SDG5 (5.5), and SDG10 (10.1, 10.2, 10.3). Furthermore, as fertilizers are often applied on a per unit of land basis (i.e., pounds of nitrogen per acre, kilograms of potassium per hectare), the negative effects of nutrient losses that accompany them, like air and water pollution, can be reduced by reducing the land that they are applied to, helping to advance SDG3 (3.9), SDG6 (6.3), SDG11 (11.6), SDG12 (12.4), and SDG 14 (14.1). Many of the predominant methods to close yield gaps and achieve higher yields resort to an excessive application of fertilizers, as well as leaving bare soils and increasing reliance on tilling, which drives damages to the environment and human health, harming progress on SDG3 (3.9), SDG6 (6.3), SDG11 (11.6), SDG12 (SDG12.4), SDG14 (14.1), and SDG 15 (15.1, 15.2). Reduced land used for agriculture could mean reduced air, water, and soil pollution from reduced use of these inputs, but the benefits of reduced land demand could be overwhelmed by the intensity of pollution on high-yielding production systems.

While land is used more efficiently in high-yield scenarios, other natural resources like water, metals to produce machinery, nitrogen, phosphorus, and potassium may not be, making the impacts on SDG8 unclear.

These social, environmental, and economic trade-offs show that there are no clear co-benefits of adopting high-yield food systems, and that their net impacts on SDGs are unclear. The effects of adopting high-yield production practices are likely to vary by location, scale of production, and length of time.

Interventions and their Potential Impacts on SDGs

In this chapter, I focus on 3 main approaches to achieve high-yielding food systems: fertilizer use, information communication technologies, and agroecological production practices.

Improving the use of fertilizers is one of the predominant interventions discussed in achieving high-yielding agricultural production systems. Many countries have implemented policies that subsidize seeds and fertilizers to increase their use and to increase yields in order to help reduce hunger, ensure national food security, and increase export production to grow their economies, advancing progress on SDG1 (1.1), SDG2 (2.1, 2.2, 2.3), SDG8 (8.1), and SDG17 (17.11) (Druilhe & Barreiro-Hurlé, 2012). In the past, this has led to the expansion of agriculture onto marginal lands less suited for agriculture, resulting in lower yields, and greater environmental degradation, as well as the loss of natural areas to forage wild foods from, harming progress on SDG2 (2.1, 2.2), SDG3 (3.9), SDG6 (6.3), SDG8 (8.4), SDG11 (11.6), SDG12 (12.4), SDG13, SDG14 (14.1), and SDG15 (15.1) (Montgomery, 2007; Diaz & Rosenberg, 2008; Druilhe & Barreiro-Hurlé, 2012; Balasubramanian et al., 2021). Many of these programs targeted men and excluded women, increasing economic inequality, and harming progress on SDG5 (5.5).

Other approaches to alter fertilizer use have been more successful at decoupling fertilizer use and environmental pollution. Fertilizer microdosing is using a small amount of fertilizer on just-planted or young seeds to ensure that it has a large impact with little waste (Searchinger et al., 2019). Small-scale farmers have used the approach to increase grain yields by 44-120%, and increase incomes by 50-130% (Aune & Bationo, 2008; Vanlauwe et al., 2010; Searchinger et al., 2019). Agricultural extension programs have been used in China to increase yields while reducing fertilizer use, achieving 15-18% reductions in fertilizer use and 14-22% reductions in GHG emissions, all while increasing yields by 11% (Cui et al., 2018). These types of context-specific approaches to alter fertilizer use can be used to advance progress on SDG1 (1.1), SDG2 (2.1, 2.2, 2.3), and SDG8 (8.4).

Information and communication technologies (ICT) are technologies that share information; common examples include mobile phones, computers, televisions, and radios. ICT have been used in food systems to share knowledge to help increase farmers' access to best management practices, locations of storage and processing facilities, market prices, and input availability information (Aker & Mbiti, 2010). ICT may also be used to promote high-yielding, low-emission techniques, while providing long-term cost benefits to farmers. The Katalyst program in Bangladesh utilized mobile phones to share information on fertilizer best practices and is credited with reducing farmers' fertilizer expenditures by 25%, while increasing crop yields by 15% (IFPRI, 2018). Reducing costs and improving the yields of small-scale, and low-income farmers can help advance progress on SDG1 (1.1, 1.4), SDG2 (2.1, 2.3), and SDG3. Programs that focus on optimizing fertilizer through precision agricultural techniques that reduce fertilizer use are likely to reduce GHG emissions, air pollution, and water pollution, helping advance SDG3 (3.9), SDG6 (6.3), SDG11 (11.6), SDG12 (12.4), SDG13, and SDG14 (14.1). Increasing yields while decreasing emissions will help advance SDG8 (8.4) by working to decouple economic growth and environmental degradation. Beyond fertilizer use, ICT can be used to help share price data in real time, helping ensure small-scale farmers get fair prices, as well as connect them with markets helping to reduce poverty and hunger, advancing progress on SDG1 (1.1) and SDG2 (2.1, 2.3). Designing programs that target the adoption of ICT by women can help advance progress on SDG5 (5.b).

Agroecological production practices have also been used to increase yields. Agroecology describes agricultural methods and production systems that utilize ecological principles to increase productivity, stability, sustainability, and equitability, through an interdisciplinary lens (Conway, 1985). This is a broad category that includes many facets like: integrated pest management, crop diversification, perennial agriculture, and agroforestry. Agroecological approaches often blend together different styles of farming, including characteristics of both organic and conventional systems, as well as intensive and extensive production methods. These methods focus on whole-system productivity and reducing the environmental externalities of agricultural production systems.

Agroforestry approaches have been traditionally practiced or expanded in many parts of Africa to increase yields, improve food security, and restore degraded lands. The natural regeneration of trees in desertified agricultural lands has been promoted to add firewood, fruit, and livestock fodder, with some leguminous trees improving soil fertility and adding nitrogen to the soil (Garrity et al., 2010). Intercropping with the leguminous tree, *Faidherbia,* is common in the Sahel region of Africa, and is practiced in Senegal, Mali, Burkina Faso, Niger, Chad, Sudan, Ethiopia, as well as in northern Ghana, Nigeria, and Cameroon (Boffa, 1999; Garrity et al., 2010). This practice has been associated with yield increases of 37% in groundnuts, 49-153% in millet, and between 36-200% in sorghum (Rhoades, 1995; Boffa, 1999; Garrity et al., 2010). Intercropping with *Gliricidia,* has been used to stabilize maize yields in Malawi and Zambia (Sileshi et al., 2012). Malawi's Agroforestry Food Security Program has provided over 40% of Malawi's districts with tree seeds, nursery materials and training for a range of agroforestry species (Garrity et al., 2010). Experiments conducted in East and Southern Africa reveal that the adoption of such agroforestry practices may increase maize yields from 0.9 tonnes/ha to 1.8-2.7 tonnes/ha without the use of synthetic nitrogen fertilizers and may go beyond 4 tons/ha with the application of a quarter-dose of mineral fertilizer (Akinnifesi et al., 2010; Sileshi et al., 2010). Using indigenous species in agroforestry can help contribute to the maintenance of genetic diversity of plants, as well as restore desertified and degraded lands, advancing progress on SDG2 (2.4) and SDG15 (15.1, 15.3). Increasing yields with agroforestry can help advance SDG8 (8.4) by working to decouple economic growth and environmental degradation.

High-income countries also benefit from agroecological approaches. Experimental research plots at Iowa State University's Marsden Farms have demonstrated that coupling integrated crop-livestock systems with increased crop diversity has resulted in decreased reliance on synthetic agrichemicals, reduced nutrient pollution, decreased energy use, and reduced GHG emissions, while maintaining the same farm productivity and profitability of a conventional corn-soybean rotation (Hunt et al., 2017; Davis et al., 2012).

Exploration and implementation of large-scale permaculture production systems and managed food forests could also advance SDGs as these types of agroecological production systems will increase the diversity of plants, and are likely to have greater system stability, higher rates of GHG sequestration, and improved nutritional yields than their monoculture counterparts, advancing progress on SDG2 (2.4, 2.5), SDG13, and SDG15 (15.2, 15.5). Advancing research on the yields and nutritional delivery of other agroecological production systems like permacropping systems and managed food forests can help advance SDG9 (9.5).

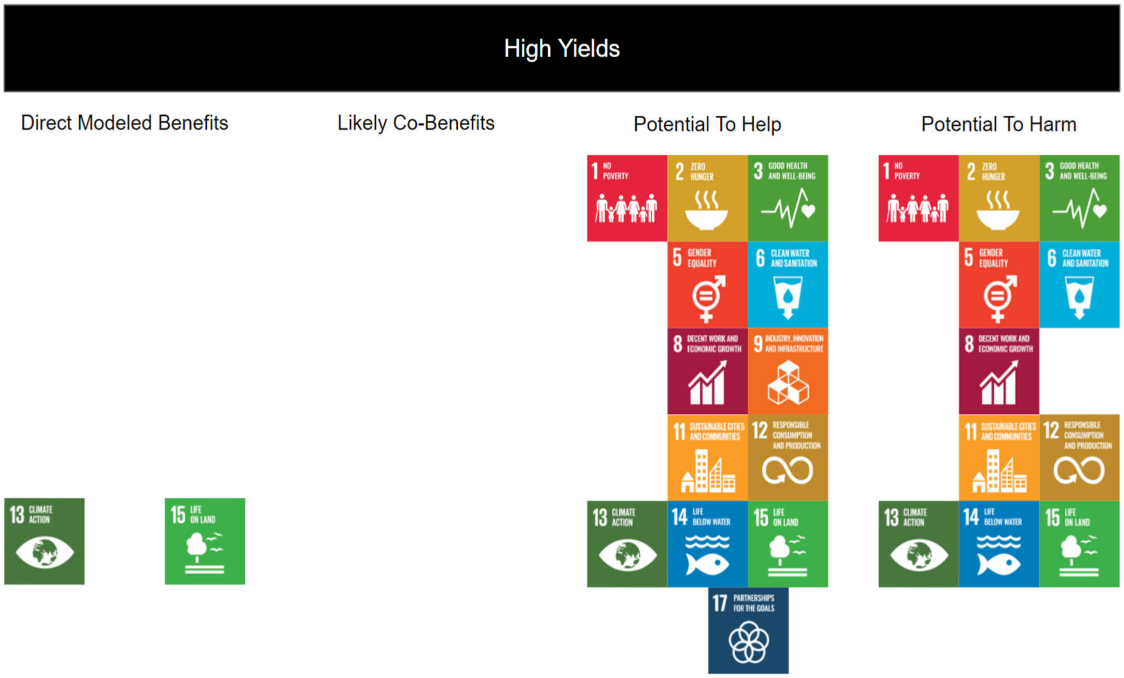


Figure 3.5: The direct modeled benefits, likely co-benefits, and the potential of interventions to achieve a high-yielding future food system to help or harm the achievement of the UN Sustainable Development Goals.

3.4.4 Reduced Food Loss & Waste

The fourth strategy analyzed in Clark et al. (2020) is the cumulative mitigation potential of reducing food loss and waste from 2020-2100. In their modeling, they define reducing food loss and waste as a 50% reduction from their BAU scenario. They find reducing food loss and waste would reduce emissions by 364 GT CO_2-we from 2020-2100 from their BAU scenario (Clark et al., 2020). Of the 5 strategies analyzed, Clark et al. (2020) finds that this strategy has the fourth largest mitigation potential.

It is important to note that reducing food loss and waste in our modeling scenario results in less agricultural production and a smaller agricultural land footprint. This relationship is not inherent, as policies will be needed to ensure that reduced food waste translates to less agricultural production and a smaller agricultural land footprint to ensure that the modeled GHG emission reductions are achieved.

3.4.4.1 Background - why was this strategy selected?

Today, roughly 30% of all food produced is lost or wasted throughout the food system (Gustavsson et al., 2011). Reducing food waste in both high- and low- income country contexts will be necessary to slow agricultural expansion into the future as food demand increases, and these waste reduction strategies vary by context.

In low-income countries, over 40% of food loss and waste occurs at post-harvest and processing levels due to poor access to harvesting techniques, as well as to cooling and storage facilities (Gustavsson et al., 2011). Though technological solutions to reduce post-harvest losses in low-income nations already exist, many have not been implemented due to the lack or absence of market infrastructure, adequate transportation, materials and tools, information, and government regulation and legislation (Kitinoja et al., 2011; Kumar & Kalita, 2017). In more industrialized countries, the retail and consumer levels dominate food waste, with per capita food waste in North America and Europe at a volume 8-20 times greater than in sub-Saharan Africa, as well as south and southeast Asia (Gustavsson et al., 2011; Foley et al., 2011).

Much work has been done in academic, governmental, and non-governmental spaces to create solutions to reduce food loss and waste. Reviews in this space abound, ranging from broad coverage (Lipinski et al., 2013; Ishangulyyev et al., 2019; Kim et al., 2019;

Spang et al., 2019; Alvarez de los Mozos et al., 2020), to more specific topics like household food waste (van Gefffen et al., 2019; Schanes et al., 2018), behavioral changes (Reisch et al., 2021), grassroot initiatives (Mariam et al., 2020), food waste evaluation (Goossens et al., 2019) and US policy (Walia & Sanders, 2017). In addition to many academic reviews, many food waste hierarchies exist that categorize food waste reduction strategies from most preferable to least, varying slightly, but starting first with preventing food waste, and ending with disposal to landfills, sewers, or incinerators (US EPA, 2021; European Commission, n.d.; UK GOV, 2021). Another key resource in this space is the ReFED database of solutions, which identifies key levers and includes stakeholder-specific resources to reduce food loss and waste (ReFED, 2021).

3.4.4.2 Analysis - how do interventions to implement this strategy affect the SDGs?

Direct Modeled Benefits

To meet the same food demand, reducing food loss and waste will reduce the GHG emissions associated with the production of the lost and wasted food, accelerating progress on SDG13: Climate Action. Reducing food loss and waste is not its own SDG, but it is instead covered in the targets of SDG11 (11.6) and SDG12 (12.3, 12.5). In the reduced food loss and waste section modeled in Clark et al. (2020), there is a smaller agricultural land footprint, as less production is needed to meet global food demand, advancing progress on SDG15.

Likely Co-Benefits

As the life of food is extended, and less is lost on-farm, hunger would likely be reduced through the shortening of lean seasons and stretching out food budgets further, helping to improve nutrition and health outcomes, advancing progress on SDG2 and SDG3. If all else is the same, to meet the same amount of food demand with waste reductions, fewer resources are required, which potentially decreases water and air pollution, accelerating progress on SDG3 (3.9), SDG6 (6.3), SDG 11 (11.6) and SDG14 (14.1, 14.3), as well as additional targets on SDG12 (12.2, 12.4). Shrinking agriculture's land footprint will help slow the degradation of lands and natural habitat, facilitating progress on SDG15 (15.2, 15.3, 15.4, 15.5). Stopping agricultural expansion can help slow the loss of land tenure for women and Indigenous people, and further regression on SDG1 (1.4), SDG2 (2.3), SDG5 (5.5), and SDG10 (10.2, 10.4). Additional policies will be needed to ensure secure land tenure for women and Indigenous people, so while reducing agricultural expansion is likely to reduce further loss of land tenure, it does not ensure that land tenure is formally recognized, so this analysis does not assume that it will advance progress on these goals, but instead stop further regression on these goals. Much of the interventions to reduce post-harvest losses center around technology adoption and infrastructure improvements, so it is likely that reducing food loss and waste will help achieve progress on SDG8 (8.2, 8.4) and SDG9 (9.1, 9.4, 9.5).

Interventions and their Potential Impacts on SDGs

In the discussion of reducing food loss and waste, I cover 4 main interventions: expanding cold chains, reducing reliance on refrigeration, improving infrastructure to reduce post-harvest losses, and food-coating requirements.

The GHG emissions mitigated by reducing food waste through the expansion of cold chains may be less than the GHG emissions associated with their adoption (Vermeulen et al., 2012; Niles et al., 2018). The GHG emissions from refrigeration and cold chains in food systems are not well known, and these cold chains can be energy-intensive, which could slow progress on SDG13.

Food waste can also be reduced through enhanced storing practices that do not rely on refrigeration. Improving post-harvest infrastructure in handling, processing, packaging, and transportation can reduce food waste as well as increase economic productivity, contributing to progress on SDG8 (8.4) and SDG9 (9.1). Evaporative coolers that do not use refrigerants or electricity are low cost (e.g., some cost only $2 to produce) and can be reused for years, have been used to extend the shelf-life of foods like tomatoes and guavas from only two to 20 days (Lipinski et al., 2013). Reusable plastic crates have been used to reduce losses and damages in the handling and transportation of produce due to poor road and infrastructure conditions (Rapusas & Rolle, 2009; Lipinski et al., 2013). Hermetically sealed metal silos and storage bags like the Purdue Improved Crop

Storage (PICS) bag have been used to reduce losses in storage as well as retain nutritional quality of cereal grains and beans (Kimenju & de Groote 2010; Momanyi et al., 2021). Small-scale early adopters in local markets may have their increased harvests translate to increased incomes, advancing progress on SDG1 (1.1) and SDG2 (2.3). If these food loss solutions are implemented by farmers producing primarily to meet their own food needs, improved storage can lead to increased food and nutrition security, and improved health outcomes, advancing progress on SDG2 (2.1, 2.2) and SDG3. Food loss and waste solutions will vary by type of food produced, and what solutions work best will depend on the community.

Improving education on best practices to harvest, dry, process, and store foods has resulted in significant reductions in local food loss in the past (from a greater than 40% grain loss to a less than 1% through the WFP Zero Food Loss Initiative) (Costa, 2015). If efforts to eliminate gender disparities in these educational efforts are pursued, these interventions could also advance SDG5, in addition to progressing SDG4 (4.4, 4.5, 4.7). If efforts are not made to include people of all gender identities, people with disabilities, Indigenous people, and vulnerable people, this would hinder the advancement of SDG4 (4.5), SDG5 (5.5), and SDG10 (10.3). However, if policy reforms are undertaken to focus these programs on low-income, and people who have been historically excluded, this could facilitate the advancement of SDG1 (1.4), SDG 4(4.4, 4.5, 4.7), (SDG5 (5.5), and SDG10 (10.1, 10.3, 10.4).

If efforts to expand this infrastructure are supported by technology and financial transfers from high-income countries working to fully meet their official development assistance (ODA) commitments, this will advance progress on SDG9 (9.a) and SDG17 (17.2 and 17.6). If these efforts are supported by building up domestic research and development, focusing on capacity building, this will advance SDG9 (9.b) and SDG17 (17.18).

Government requirements or corporate promises to only sell produce with coatings (like those created by Apeel Sciences and Mori) to increase their shelf life will increase food prices for consumers if there are no other policies put in place (Apeel, 2020; Mori, 2020). The effect of increased food prices on hunger could be greater in the reduction of hunger that would accompany increasing the shelf life of food, especially if the upfront costs of food procurement decreases people's access to basic services and harms health, impairing progress on SDG1 (1.1, 1.4), SDG2 (2.1, 2.2), and SDG3.

Figure 3.6: The direct modeled benefits, likely co-benefits, and the potential of interventions to reduce food loss and waste to help or harm the achievement of the UN Sustainable Development Goals.

3.4.5 High-Efficiency

The fifth strategy analyzed in Clark et al. (2020) is the cumulative mitigation potential of achieving high-efficiency agricultural production systems from 2020-2100. In their modeling, they define high-efficiency as a 40% reduction in the GHG emissions associated with the production of one unit of food. They find that achieving high-yields would reduce emissions by 539 GT CO_2-we from 2020-2100 from their BAU scenario. Of the 5 strategies analyzed, Clark et al. (2020) finds that this strategy has the second largest mitigation potential.

3.4.5.1 Background - why was this strategy selected?

As awareness of the impacts of the food system's contribution to climate change continues to grow, and governmental and corporate actions to reduce agricultural emissions also grow, there is likely to be continued investment into the research and deployment of high-efficiency production systems with low emissions per unit of food produced. There are a variety of approaches to create high-efficiency production systems. Precision agriculture is one of the most discussed solutions in this area, focusing on data-utilization to improve efficiency of agricultural production. Techniques vary greatly, and are pushed by corporate dealers (Erickson et al., 2017; Lowenberg-DeBoer & Erickson, 2019). Climate-smart agriculture is another prominent approach that focuses on improving three main dimensions: agricultural productivity, adaptive capacity, and GHG mitigation (Campbell et al., 2014). In livestock production, emissions can be reduced by improving feed and getting animals to market faster, using methane-inhibiting feed additives, on-field nitrification, and urease inhibitors, as well as improving manure management (Maia et al., 2016; Grossi et al., 2018). Agricultural extension programs have been used to reduce GHG emissions, with one program in China increasing yields by >10%, while reducing fertilizer applications by >15%, and overall emissions by 10-20% across maize, rice, and wheat crops (Cui et al., 2018). Targeting smallholder farmers can help increase their productivity and incomes, advancing progress on SDG 2 (2.3). Policy tools have also been used to regulate fertilizer use like the European Nitrate Directive and Ohio's weather-dependent fertilizer restrictions to reduce water pollution, with GHG emissions reductions as a co-benefit, advancing progress on SDG6 (6.3) and SDG13 (European Commission, 2021; Ohio Department of Agriculture, n.d.). As this is a growing research area, it is likely that many more approaches and techniques to achieve high-efficiency production systems will be proposed and trialed in the future.

3.4.5.2 Analysis - how do interventions to implement this strategy affect the SDGs?

Direct SDG Benefits

As modeled in Clark et al. (2020), high-efficiency production results in significant reductions to GHG emissions from agricultural production, contributing to SDG13.

Likely Co-benefits

It is likely that these types of GHG efficiency interventions will also contribute to the efficient utilization of natural resources, reducing pollution to air, water, and soil, and decoupling economic growth from environmental degradation to help advance progress on SDG3 (3.9), SDG6 (6.3), SDG8 (8.4), SDG11 (11.6), SDG12 (12.2, 12.4), and SDG14 (14.1, 14.3). As energy is used in every stage of the food supply chain, it is likely that interventions in food systems to increase efficiency will include movements towards more efficient, and cleaner sources of energy, advancing progress on SDG7 (7.2, 7.3).

Interventions and their Potential Impacts on SDGs

In the discussion of high-efficiency production systems, I cover 3 main interventions: sustainable sourcing requirements, eating a local diet, and buying unpackaged foods.

Expanding and increasing the rigor of sustainable sourcing requirements can result in reduced food supply chain emissions. Agricultural corporations' total emissions, especially those in meat and dairy, are often dominated by their food sourcing emissions, with up to 90% of these corporations’ emissions originating from their supply chain (Lazarus et al., 2021). Examples of sustainable sourcing requirements include corporate sourcing goals and Voluntary Sustainability Standards (VSS). Interest in VSS --standards developed to achieve sustainable and equitable production outcomes-- is growing within industry, government, and nongovernmental organizations alike. Fairtrade, UTZ Certified, Bonsucro, and Rainforest Alliance are just a few of the widely-recognized standards in coffee, cocoa and sugar markets (IPCC SRCCL, Smith et al., 2019; Dietz et al., 2019). More standards and certifications relating to food and land are highlighted in Table 7.3 of the IPCC Special Report on Climate Change and Land. The benefits of VSS will be determined by the specific standards set, the limitation of indirect environmental and social impacts associated with production, as well as the efficacy of interventions to improve lands in production (Smith et al., 2019). Sourcing requirements are being used by agrifood corporations like General Mills, Cargill, PepsiCo, and Land O’Lakes to set goals to reduce the GHG emissions of the ingredients they source. To achieve these goals, these companies are sourcing from regenerative agricultural lands, helping their suppliers adopt best management practices, and increasing the use of precision agriculture techniques. Expanding and increasing the rigor of sustainable sourcing requirements, VSS and alternative trade networks are some of the proposed strategies to improve sustainable production and consumption, get higher prices for farmers, and increase potential for ecotourism, advancing progress on SDG2 (2.3), SDG3 (3.9), SDG6 (6.3), SDG8 (8.4, 8.9), SDG11 (11.6), SDG12 (12.4), SDG13, SDG14 (14.1), and SDG15 (15.1, 15.2, 15.3).

In the past, Transnational Alternative Agrifood Networks (TAAFNs) have been used as an alternative to multinational, corporate-owned food chains. TAAFNs strive to create fair social, economic relationships and production practices that are ecologically sound (Goodman, 2003; Renard, 2003). Hatanaka (2010) finds in their interviews with farmers, warehouse owners, university researchers, NGOs, and government officials in Indonesia that these networks have not achieved these improvements. They found that farmers were working longer hours, chemical-free production practices were more labor-intensive, and increased documentation and paperwork were particularly arduous for workers that were illiterate. Interviewees reported that people in the global North set the terms, while farmers in the global South deal with the burden, and that they were not involved or included in the development of the standards. Additionally, as they felt that the requirements were unfair, farmers would sometimes disregard the requirements (Hatanaka, 2010).

Farmers' ability to produce products that meet these specifications will depend on their capacity and access to farming resources like land, finance, and technical support. Who can respond the fastest to consumer demand, and comply with government regulations will likely determine which producers benefit most from sustainable sourcing requirements. Given the current unequal participation in agriculture, this inequality is likely to continue, or worsen, if policies are not specifically put in place to intervene. Adding sustainable sourcing requirements will likely exacerbate inequality, poverty, hunger, and poor health, hindering progress on SDG1 (1.4), SDG2 (2.1, 2.3), SDG3, SDG5 (5.5) and SDG10. If policies are put in place to improve education access, increase literacy and numeracy, ensure safe and fair working conditions, include all farmers in sourcing requirement design, center around improving conditions for low-income workers, eliminate the pay and opportunity gaps across genders and for people with disabilities, ensure equal access to financing and resources, and upgrade food infrastructure, in efforts to expand sustainable sourcing, this could advance progress on SDG1 (1.4), SDG4 (4.4, 4.5, 4.6), SDG5 (5.1, 5.a), SDG8 (8.5, 8.8), SDG9 (9.4), SDG10

(10.1, 10.2, 10.3, 10.4) and SDG16 (16.b). In the creation and implementation of sustainable sourcing requirements, including and listening to actors in low-income countries, as well as mobilizing financial and technical assistance to build capacity within these countries, could advance progress on SDG10 (10.6), SDG16 (16.7, 16.8), and SDG17 (17.3, 17.7, 17.9, 17.16).

If sustainable sourcing requirements are made by governments and it costs farmers more to comply, or differentiated products sell for higher prices, people not benefiting from increased incomes from higher food prices that instead have to pay more for their food may experience increased hunger and poverty, harming progress on SDG1, SDG2, and SDG3.

If corporations and governments work to minimize costs in their efforts to improve the GHG efficiency of production or reduce the emissions of their product sourcing it is likely to exacerbate existing inequalities. Focusing on cost-effectiveness will likely result in the creation of programs that require less staffing power to run, that allow one technology or solution to be widely implemented, or focus on getting large-scale producers to make the GHG emissions reductions first. This might leave out small-scale producers from support programs, hindering efforts to increase their incomes, and potentially forcing them out of business, harming progress on SDG2 (2.3) and SDG10 (10.1, 10.4).

While Clark et al. (2020) does not include post-farm gate stages in their analysis, there are trade-offs associated with these interventions to improve GHG efficiency as well. One popular proposition that we hear in high-income country contexts is to reduce the impact of one’s food purchases is to reduce food miles and eat local. Food transportation is responsible for only about 5% of global food system emissions (Crippa et al., 2021). While shipping food by air does have much higher emissions than shipping by boat, rail, or road, only 0.16% of food is transported by air, with the majority of internationally traded commodities transported across the ocean by boat (Poore & Nemecek, 2018). If foods that are often transported by plane due to their highly perishable nature, like asparagus and berries, are swapped for local ones not produced in hothouses, there could be a potential for GHG emissions reductions. Overall, reducing GHG emissions from transport is unlikely to have a significant impact on one’s overall dietary GHG emissions, and unlikely to significantly advance progress on SDG13.

Additionally, if efforts to buy local lead to more animal agricultural production around cities, this could worsen air quality and lead to premature mortality, harming progress on SDG3 (3.9) and SDG11 (11.6).

On the other hand, there are many scenarios where local diets facilitate the achievement of the SDGs, including climate action. If the local food is produced in ways that help maintain ecosystems, promote genetic seed diversity, and are resilient to climate change, local diets could advance SDG2 (2.4, 2.5), SDG3 (3.9), SDG6 (6.3), SDG13, and SDG14 (14.1). If eating novel local foods is a motivator for people to eat a healthier, more plant-rich diet, eating a more local diet could help advance progress on SDG3 (3.4, 3.9), SDG6 (6.3), SDG8 (8.4), SDG13, and SDG14 (14.1). Demand for a locally-produced, plant-rich diet could help facilitate movement towards foods with high nutritional yields, and away from inefficient corn and soy production (Cassidy et al., 2013). If demand for eating a local diet leads to the creation of new, plant-rich diet infrastructure (e.g., a plant to process beans into tofu or tempeh), this would advance progress on SDG9 (9.1). Furthermore, if this infrastructure is powered by renewable energy sources, this could also contribute to SDG7. If local foods are procured through an on-site tour, with an educational component on the benefits of plant-rich diets, this could advance progress on SDG4 (4.7) and SDG8 (8.9). If individuals, companies, and governments procure local foods from small-scale suppliers from people who have previously not been allowed to benefit from food production in the same way, like Black-, Indigenous-, and women-owned farms, this can work to advance SDG5 (5.5), SDG10 (10.1, 10.2, 10.3) and SDG12 (12.7). Buying food produced on land collectives can help secure land tenure for those who have been excluded from it, advancing progress on SDG2 (2.3) and SDG8 (8.3).

Large shifts away from importing foods from low- and middle-income countries could have negative effects on their economies and would harm progress on goal SDG17 (17.11). Policies will be needed to support significant changes in global trade patterns to ensure wellbeing of producers in these countries, especially if they are producing for an export market and not a locally demanded food, and global macroeconomic stability, or interventions in high-income countries to eat local food is likely to harm progress on SDG1, SDG2, SDG3, and SDG17 (17.11, 17.13).

Another commonly proposed strategy to reduce the impacts associated with one's diet is to not buy packaged foods. Packaging comprises about 5% of total food system emissions, but this percentage is heterogeneous across food types (Crippa et al., 2021; Poore & Nemecek, 2018). For some fruits and vegetables, packaging can account for 10-22% of the food's emissions, and for wine and beer, packaging can account for more than 40% of the product's emissions (Crippa et al., 2021; Poore & Nemecek, 2018). Much research in mitigation and packaging looks at the role packaging plays in reducing food waste, and given that production emissions, land use, and land use change account for 71% of global food system emissions, this focus is warranted. Dilkes-Hoffman et al. (2018) finds that in food life cycle assessments, emissions from food waste dominate emissions from food packaging no matter the packaging material, and that biodegradable packaging can actually increase overall emissions if it leads to an increase in food waste, harming progress on SDG11 (11.6), SDG12 (12.3, 12.5), and SDG13. Additional research is needed to find packaging solutions that simultaneously reduce packaging, food waste, and have low GHG emissions. Given the significant differences in emissions hotspots along the supply chain by food types, commodity- and product-specific solutions will be needed. Bolstering sustainable research and development systems will advance SDG8 (8.3) and SDG9 (9.5).

The need for resilient, shelf-stable products will increase as climate change progresses and natural hazards occur with greater frequency, causing disruptions to food production, supply chains, and energy systems. Reusable packaging and circular economy approaches could be used to both reduce reliance on single-use packaging and extend the shelf life of food, reducing waste and advancing progress on SDG11 (11.6) and SDG12 (12.4). Germany uses the Pfand system to monetarily incentivize customers to return their bottles, shipping bottles of the same shape and material back to the producers that use them, where they are then washed, refilled, and sent back to market (Ibiapina et al., 2021). Programs like these can decrease demand for natural resource extraction and the human health and environmental damages that accompany it, advancing progress on SDG1 (1.4), SDG2 (2.1), SDG3 (3.9), SDG6 (6.3), SDG13, SDG14 (14.1), SDG15 (15.1), SDG16 (16.1). Life cycle assessments will be needed to ensure that these programs actually achieve their intended environmental benefits, and that they do not lead to increases in local air pollution, GHG emissions, fossil fuel consumption, or water use, otherwise these efforts could hinder the achievement of

SDG3 (3.9), SDG6 (6.4), SDG7, SDG11 (11.6), and SDG13. Municipalities can institute pilot programs to reduce food packaging that suit the specific needs of their municipalities using various approaches to advance SDGs like: taxes to generate revenue with SDG17 (17.1), sustainable infrastructure with SDG9 (9.1, 9.4, 9.5), or education, employment, and entrepreneurial policies to reduce inequalities with SDG4 (4.3, 4.4, 4.5), SDG5 (5.5), and SDG10 (10.1, 10.2, 10.3, 10.4).

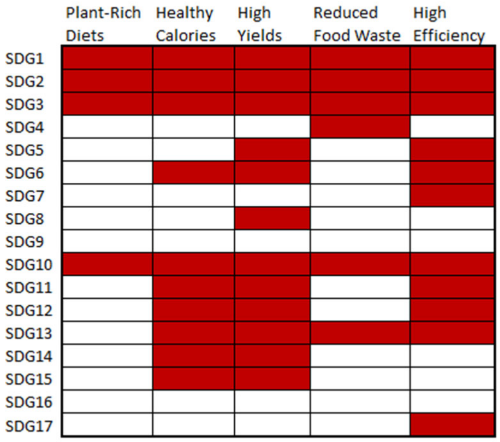
Figure 3.7: The direct modeled benefits, likely co-benefits, and the potential of interventions to achieve a high-efficiency future food system to help or harm the achievement of the UN Sustainable Development Goals.

Taking the summary figures from each of the five future food system scenarios, we can compare and contrast the potential of interventions to achieve each of these futures. Table 3.2 shows the direct modeled benefits and likely co-benefits of the food system scenarios modeled in Clark et al. (2020). The potential of interventions to achieve the future food scenarios modeled in Clark et al. (2020) to help or harm the achievement of the UN Sustainable Development Goals is shown in Table 3.3.

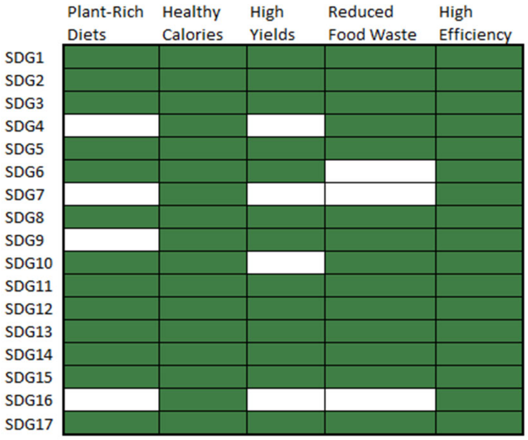
Table 3.3: Summary of the direct modeled benefits and likely co-benefits of the Clark et al. (2020) future food scenarios. This table shows the direct modeled benefits (shown in dark green) and the likely co-benefits (shown in light green) of the five future food system scenarios modeled in Clark et al. (2020). This table shows that there are many likely environmental and environmental-health benefits (SDG 3, SDG6, SDG11, SDG12, SDG14, and SDG15) associated with interventions to reduce food system GHG emissions. Additionally, there are some likely economic and livelihood benefits (SDG8, SDG9, SDG12, SDG17) of these future food scenarios.

	Plant-Rich Diets	Healthy Calories	High Yields	Reduced Food Waste	High Efficiency
SDG1					
SDG2		■			
SDG3	▨	■		▨	▨
SDG4					
SDG5					
SDG6	▨	▨		▨	▨
SDG7					▨
SDG8				▨	▨
SDG9				▨	
SDG10					
SDG11	▨	▨		■	▨
SDG12	▨	▨		■	▨
SDG13	■	■	■	■	■
SDG14	▨	▨		▨	▨
SDG15	■	■	■	■	
SDG16					
SDG17	▨				

Table 3.4: Summary of the potential of interventions to achieve the future food scenarios modeled in Clark et al. (2020) to help or harm the achievement of the UN Sustainable Development Goals. Here, red shows the potential to harm, while green shows the potential to help achieve the SDGs. Of the highlighted interventions, there are fewer trade-offs associated with switching to plant-rich diets or reducing food waste, but more potential synergies with high-efficiency interventions. Interventions in all future food scenarios have the potential to harm progress on SDG1, SDG2, SDG3, and SDG10 if they are not pro-poor in design, as targets in all four of these areas focus on the inclusion and wellbeing of low-income people.

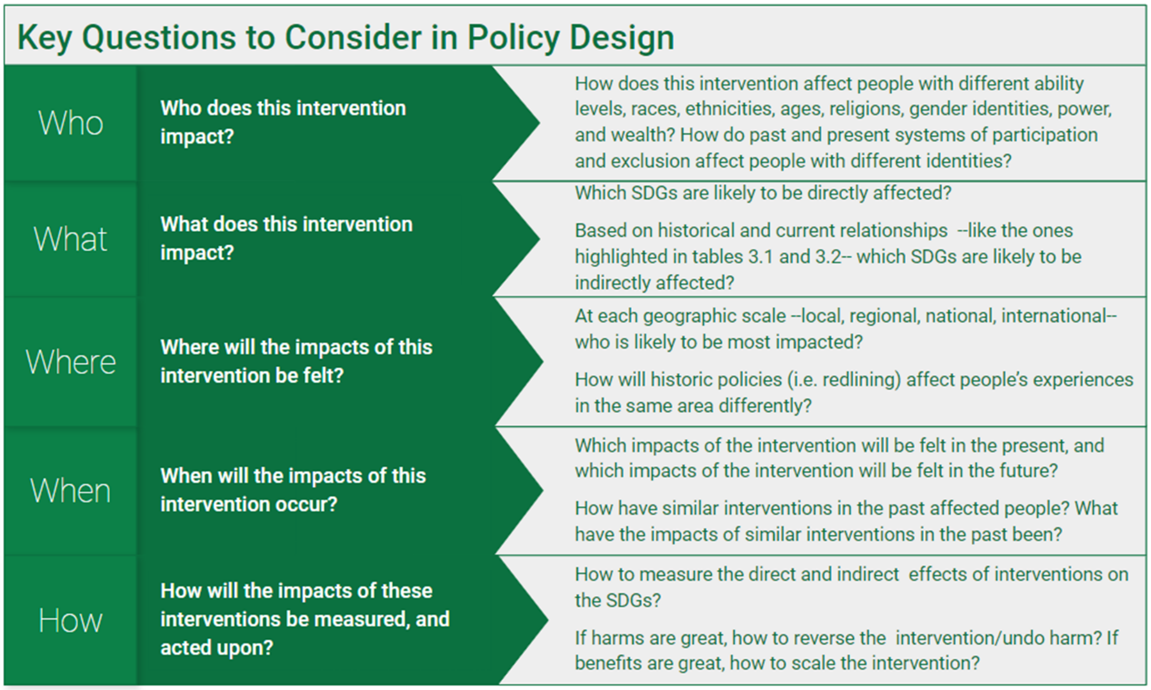


	Plant-Rich Diets	Healthy Calories	High Yields	Reduced Food Waste	High Efficiency
SDG1	🟥	🟥	🟥	🟥	🟥
SDG2	🟥	🟥	🟥	🟥	🟥
SDG3	🟥	🟥	🟥	🟥	🟥
SDG4				🟥	
SDG5			🟥		🟥
SDG6		🟥	🟥		🟥
SDG7					🟥
SDG8			🟥		
SDG9					
SDG10	🟥	🟥	🟥	🟥	🟥
SDG11		🟥	🟥		🟥
SDG12		🟥	🟥		🟥
SDG13		🟥	🟥	🟥	🟥
SDG14		🟥	🟥		
SDG15		🟥	🟥		
SDG16					
SDG17					🟥



	Plant-Rich Diets	Healthy Calories	High Yields	Reduced Food Waste	High Efficiency
SDG1	🟩	🟩	🟩	🟩	🟩
SDG2	🟩	🟩	🟩	🟩	🟩
SDG3	🟩	🟩	🟩	🟩	🟩
SDG4		🟩		🟩	🟩
SDG5	🟩	🟩	🟩	🟩	🟩
SDG6	🟩	🟩	🟩		🟩
SDG7		🟩			🟩
SDG8	🟩	🟩	🟩	🟩	🟩
SDG9		🟩	🟩	🟩	🟩
SDG10	🟩	🟩		🟩	🟩
SDG11	🟩	🟩	🟩	🟩	🟩
SDG12	🟩	🟩	🟩	🟩	🟩
SDG13	🟩	🟩	🟩	🟩	🟩
SDG14	🟩	🟩	🟩	🟩	🟩
SDG15	🟩	🟩	🟩	🟩	🟩
SDG16		🟩			🟩
SDG17	🟩	🟩	🟩	🟩	🟩

Many of the identified interventions can have both positive and negative impacts on the achievement of the SDGs depending on their design. To help reduce the potential of these GHG mitigation interventions, decision-makers should think about the direct and indirect effects of their proposed interventions on each of the SDGs. Figure 3.8 below highlights a few key questions to consider in the design of interventions to mitigate food system emissions and advance progress on the other SDGs. This is a non-exhaustive list, and is just one example of different ways to think about the potential impacts of interventions to mitigate GHG emissions in food systems.



Key Questions to Consider in Policy Design

Who	**Who does this intervention impact?**	How does this intervention affect people with different ability levels, races, ethnicities, ages, religions, gender identities, power, and wealth? How do past and present systems of participation and exclusion affect people with different identities?
What	**What does this intervention impact?**	Which SDGs are likely to be directly affected? Based on historical and current relationships --like the ones highlighted in tables 3.1 and 3.2-- which SDGs are likely to be indirectly affected?
Where	**Where will the impacts of this intervention be felt?**	At each geographic scale --local, regional, national, international-- who is likely to be most impacted? How will historic policies (i.e. redlining) affect people's experiences in the same area differently?
When	**When will the impacts of this intervention occur?**	Which impacts of the intervention will be felt in the present, and which impacts of the intervention will be felt in the future? How have similar interventions in the past affected people? What have the impacts of similar interventions in the past been?
How	**How will the impacts of these interventions be measured, and acted upon?**	How to measure the direct and indirect effects of interventions on the SDGs? If harms are great, how to reverse the intervention/undo harm? If benefits are great, how to scale the intervention?

Figure 3.8: Key questions to consider in the policy design of interventions to mitigate greenhouse gas emissions in our food systems.

3.5 Discussion

The urgency for climate action in food systems to both mitigate food system GHG emissions and adapt to an increasingly variable climate is well-established in academic literature (Vermeulen et al., 2012; Bajzelj et al., 2014; IPCC SRCCL, 2019; Loboguerrero, 2019; Clark et al., 2020). To have a chance at meeting the 1.5°C and 2°C goals of the Paris Climate Agreement, we will need to work to achieve GHG emissions mitigation on multiple food system fronts including: dietary shifts, improved production, and reduced food waste (Bajzelj et al., 2014; Clark et al., 2020). This analysis demonstrates that interventions across dietary shifts, agricultural production systems, and food loss and waste will require suites of complementary policies that target SDGs beyond climate action specifically if they are to achieve the emissions reductions modeled in Clark et al. (2020).

In addition to acting to mitigate climate change, if we are to achieve the goals of the UN Sustainable Development Goals, we need to simultaneously transform our food systems to improve the lives of people, protect our planet from environmental pollution and degradation, and build partnerships to expand peace and prosperity (International

Council for Science, 2017; IPCC SRCCL, 2019). This idea echoes the IPCC 1.5°C Special Report which states, “a reductive focus on specific SDGs in isolation may undermine the long-term achievement of sustainable climate change mitigation”. Considerable trade-offs and synergies across the achievement of the SDGs alone exist (Nilsson et al., 2016; Pradhan et al., 2017; Sterling et al., 2020). Here we illustrate in detail, that interventions to mitigate GHG emissions in food systems also have the ability to facilitate or harm the achievement of the SDGs.

In this analysis, we find that the potential impacts of a mitigation intervention on the SDGs varies widely. It varies by intervention design, with governmental support, and over time. Approaches that promote local ownership, community design, and the equitable inclusion of those that have historically been excluded or not allowed to participate equally (i.e., low-income people), in order to advance their wellbeing are explicitly required to advance many targets across the SDGs including: SDG1 (1.1, 1.2, 1.3, 1.4, 1.5, 1.b), SDG2 (2.1, 2.3), SDG3 (3.d), SDG4 (4.1, 4.2, 4.3, 4.5, 4.6, 4.a), SDG5 (5.1, 5.5, 5.a), SDG6 (6.1, 6.2, 6.b), SDG7 (7.1), SDG8 (8.5, 8.7, 8.8), SDG9 (9.2, 9.3, 9.a), SDG10 (10.1, 10.2, 10.3, 10.4, 10.5, 10.6, 10.a, 10.b), SDG11 (11.2, 11.3), SDG13 (13.a, 13.b), SDG14 (14.7, 14.a), SDG16 (16.7, 16.8, 16.a, 16.b), and SDG17 (17.6, 17.9, 17.18). Targets across the SDGs also discuss domestic and international government financing, technology sharing, knowledge sharing, and capacity building to implement interventions to achieve these goals. Nilsson et al. (2016) highlights how perceived importance of interventions to policymakers and governments affect the realized trade-offs and co-benefits. Active participation in decision and policymaking of all affected people has been shown to result in greater total benefits, in particular when these efforts are centered around the inclusion and empowerment of the poorest and most vulnerable (Jansujwicz et al., 2013; Coenen & Coenen, 2009; Hurlbert, 2015; Gupta and Vegelin, 2016; IPCC SRCCL).

Through the discussion of GHG taxes on foods to reduce food system emissions, this analysis shows that who changes behavior from the implementation of interventions may not always be the people driving climate damages, and that particular attention must be given to low-income people to ensure interventions do not exacerbate existing inequalities in food systems. The focus in this discussion of healthy calorie diets focused on eliminating hunger, and not reducing overconsumption, is one of the reasons that this future food system scenario was found to be so beneficial to the achievement of the SDGs beyond climate action. This is because this analysis focuses on increasing resource access to low-income and vulnerable populations. If the focus were changed to center on interventions that decrease the overconsumption of calories, there would be less progress on the SDGs, as many SDGs focus on the empowerment of vulnerable and historically excluded people. This highlights that different interventions to achieve the same broad future food system scenario can have very different impacts on the SDGs.

A recurring theme across all five scenarios analyzed here is that progress on justice-related targets (listed above) are unlikely to be achieved unless policies are put in place that accompany GHG mitigation interventions that directly center around the inclusion of people who have been historically excluded. As the section on high-efficiency production systems shows, it is possible to achieve GHG reductions without directly advancing justice, and this pathway to reduced food system emissions could be more cost-effective. However, not including marginalized people is likely to not only fail to advance progress on justice-related targets, but due to inequalities in our current food system, is likely to harm the achievement of these goals.

The benefits of interventions to the SDGs are likely to vary with time. In the section on increasing yields, it is discussed about how early adopters will likely see increased incomes, but that these benefits might be short-lived if additional policies or interventions to are not present that ensure that local surpluses from improved productivity do not lead to decreased incomes, jeopardizing previous progress on SDGs. There are likely other temporal aspects of interventions to mitigate food system emissions, and future work will be needed to ensure that progress on the sustainability goals is long-lasting.

While not discussed in this analysis, the current inequality of wealth and power in our global society can lead to corruption and elite capture, when public resources are hoarded to benefit a few individuals at the cost of the wellbeing of the greater community, ultimately affecting who can adopt these mitigation interventions, how these interventions are implemented, and who is allowed to benefit from these interventions (IPCC SRCCL). Reducing inequalities in power and wealth is just one part of creating policy environments that facilitate the success of climate interventions. Enabling policy environments that consider long-term implications, human and financial resources, and government coordination are needed to ensure that interventions are part of a comprehensive strategy to achieve their intended results (IPCC SRCCL, 2019).

Great care must be taken in the specific design of interventions to ensure that they do not harm the wellbeing of people or our planet. This analysis shows that despite suggestion in prominent academic works to the contrary, mitigation efforts in food systems to meet the Paris goals are likely to perpetuate systems of inequality, exacerbating poverty, hunger, violence, and environmental degradation, unless concerted efforts are made to include and empower vulnerable populations at the forefront of mitigation policy planning and implementation. These results align with the work of others in this space, with the IPCC Special Report on Climate Change and Land finding that: "to be effective, truly sustainable, and to reduce or mitigate emerging risks, SDGs need knowledge dissemination and policy initiatives that recognize and assimilate concepts of co-production of ES in socio-ecological systems, cross-scale linkages, uncertainty, spatial and temporal trade-offs between SDGs and ES that acknowledge biophysical, social and political constraints and understand how social change occurs at various scales", where ES stands for ecosystem services.

This analysis is not exhaustive, and only begins to scratch the surface of the potential trade-offs associated with climate interventions in food systems. With enough time and creativity, it seems plausible that one could find ways that any intervention proposed could be implemented in such a way that it facilitates or harms the advancement of every SDG, including climate action itself. Mitigating food system GHG emissions in a way that facilitates the achievement of all SDGs will require a thoughtful and expansive portfolio of justice-centered interventions.

3.6 Acknowledgements

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Chapter 4: Dissertation Conclusion

This dissertation summary chapter includes the motivation, key findings, policy implications and applications, and areas of future research for each of the three preceding chapters. Additionally, the last section of this chapter provides a short summary of the three chapters and outlines the main message of this dissertation as a whole.

4.1 Understanding global food system emissions: analyzing key differences in past estimates and future projections - Chapter 1 Summary

4.1.1 Motivation, Justification, and Research Contribution

Popular press and research articles on the contribution of our food systems to climate change have increased dramatically over the last few years. To date, there has not been a systematic review of research articles' estimates of global food system GHG emissions, nor a comparison of their estimation approaches. Chapter one is a first of its kind synthesis of existing global food system GHG estimates for both past estimates and future projections that compares the methodologies, defined system boundaries, and results of global food system GHG emissions estimates.

4.1.2 Summary of Key Findings:

- There is significant variation in the approaches and results of past estimates and future projections for food system GHG emissions.
- Recent estimates for past global food system GHG emissions are on the high end of the range for food system emissions estimates given in the IPCC Climate Change and Land Special Report.
- The majority of papers display food system GHG emission data in ways that are too aggregated to show what proportion of GHG emissions plant- and animal-based foods are responsible for, as well as what is ultimately driving climate damages from our food system.
- There are no food system GHG emission future projections that include post-production emissions or emissions from F-gasses.

- Past estimates and future projections for food system GHG emissions are likely to be underestimates, as they often exclude differing gasses, stages, and activities in the food system.

4.1.3 Policy Implications and Applications

Chapter one highlights the need for urgent action to mitigate food system emissions at each supply chain stage of our global food system, and the growing proportion of post-agricultural production emissions. Decision-makers can use this knowledge as motivation for greater support for food system change and climate mitigation efforts. Additionally, this chapter calls to attention the need for more data transparency, and better data sharing policies to ensure the accurate understanding of these food systems estimates, and discusses the limitations and omissions of both past estimates and future projections of global food system GHG emissions estimates.

How the knowledge gained from this chapter will be applied and operationalized will vary greatly. In academia, this knowledge can be used to justify more thorough analyses of the GHG emissions associated with different foods, agricultural production systems, and food supply chains, with more analysis-specific emissions estimates for post-production stages becoming the new norm. Industry may use this knowledge to reduce their GHG footprints, or may downplay the impacts of high-emission foods like beef, instead highlighting their efforts to adopt renewable energy in their processing, transport, and packaging, and greenwash these emissions-intensive foods. Climate advocacy organizations could use this knowledge to call for more effort to mitigate emissions from food at every level of governance and at every food supply chain stage.

4.1.4 Future Research

One of the greatest future research needs identified in this chapter is the need for better communication of study results. Some of these studies are too aggregated to show what is ultimately driving emissions, which makes it difficult for decision-makers to know where to intervene. Other studies provide data that is too disaggregated to be readily useful to decision-makers, and would require strong technical skills as well as time to carry out additional research to determine where to intervene. Work that shows what specifically drives emissions can show policy- and decision-makers where to intervene in a system to affect the greatest change.

More refined estimates for individual- and community- GHG estimates of food systems are needed that are not just per-capita averages from global- and country-level emissions estimates. Future research in this area should look at the variation of food-specific emissions across different levels of affluence within and across countries. Key questions to motivate future research in this space include: how does affluence affect dietary emissions; how do the food-emissions of the ultra-wealthy compare to the average person in their community, and what drives these similarities or differences; and, do food-specific emissions follow trends in broader climate damages?

Future research in mitigating food system GHGs should analyze co-benefits and potential trade-offs of climate interventions through a more comprehensive and holistic process, and include the potential impacts on: social (gender, socioeconomic status, education access, inequalities, etc), environmental (air pollution, water pollution, land use, etc), and economic (decent work, innovation, etc) goals.

4.2 Illustrating the mismatch between the recommendations of key papers in food systems climate mitigation and their calls for food systems transformation - Chapter 2 Summary

4.2.1 Motivation, Justification, and Research Contribution

The need for rapid, and transformative changes to mitigate the greenhouse gas emissions from our food systems is widely recognized, and a tremendous number of interventions to reduce these emissions have been proposed. Other work in sustainability and food systems has utilized systems change theories and frameworks to identify a mismatch between expert recommendations and recommendations for transformative change. Chapter two compiles these frameworks, and undertakes a new application of order of change theory to determine if this trend holds in the food systems and climate change mitigation space.

4.2.2 Summary of Key Findings:

- Experts in food systems and climate change call for transformation and greenhouse gas mitigation in our food systems.
- These recommendations focus predominantly on agricultural production, with few recommendations discussing other aspects of the food systems, like refrigeration, research and planning, enabling environments, and supply chains.
- There is a mismatch between calls for food systems transformation and the order of change of their recommendations, with the majority being reforms and adjustments to the current food system, while few of the recommendations are transformational.
- Reports focused on food security have the highest proportion of transformational recommendations of the identified papers.
- We can use existing systems of change frameworks to help address this mismatch, and create more transformational expert recommendations in food systems GHG mitigation.

4.2.3 Policy Implications and Applications

Chapter two shows that the majority of current recommendations to mitigate food system emissions are not transformational, but that we can change this by utilizing systems change frameworks to create better recommendations and expand the discussion space of possible solutions. In chapter two, four different systems change frameworks (see Tables 2.6-2.9) are used to illustrate how recommendations to mitigate GHG emissions from refrigeration could be expanded. These tables can be used for each food system category identified in this dissertation, by different aspects of our food system, and by different food systems actors to create a much larger discussion space in possible solutions to mitigate food system emissions. Spending more time and resources discussing identified recommendations with the greatest potential for systems change can help ensure that newly identified and adopted recommendations are transformational.

Stakeholders can use and apply these systems change frameworks to create new recommendations to address the current deficit of transformational expert recommendations in different areas of our food systems. Potential stakeholders who could use these frameworks include: non-governmental organizations, community groups, think tanks, political groups, policy makers, and industry, who can use these frameworks to ideate new plans, campaigns, and policies to mitigate GHG emissions in food systems. These frameworks can be built on, and modified, to align with the values and goals of each stakeholder.

4.2.4 Future Research

While this chapter enumerates additional potential interventions to mitigate emissions from refrigeration, more work is needed to create transformational recommendations for every aspect of our food system. The frameworks identified in chapter two can be expanded upon and modified, and future research can create new systems change frameworks to further advance work to create transformative recommendations. Recommendations are likely to vary significantly by stakeholder, context, and consideration of other aspects of sustainability and wellbeing.

Expert recommendations from food security-focused reports are currently the most transformational, and experts in other areas of our food system can learn from the organizations, collaborations, and processes that produce these reports. More effort should be placed on learning from existing work outside one’s area of expertise, and listening to practitioners and community members that know the needs of their communities to create recommendations that are place-based and community-driven to help ensure that interventions to mitigate GHG emissions are sustainable and just.

4.3 Interventions to Mitigate Food System Emissions Can Facilitate or Impede the Achievement of the Sustainable Development Goals - Chapter 3 Summary

4.3.1 Motivation, Justification, and Research Contribution

Much research in the climate change space focuses on how to mitigate emissions in food systems, but very little focuses on how interventions to mitigate GHG emissions in our food systems will affect other dimensions of sustainability. Chapter three focuses on how proposed interventions to mitigate food system emissions might affect the UN Sustainable Development Goals. This chapter is unique in that it takes a more systematic approach to discussing the potential trade-offs and synergies associated with different interventions to achieve emissions reductions in five broad scenarios: plant-rich diets, healthy calories, high-yields, reduced food loss and waste, and high-efficiency production.

4.3.2 Summary of Key Findings:

- Interventions to mitigate food system emissions can facilitate or hinder the achievement of the SDGs, depending on their design.
- The prevailing impacts of a given food system mitigation intervention on the SDGs will vary with policy design, scale, time, geography, culture, and governmental support.
- Many food systems mitigation interventions have likely co-benefits for environment-related and economic and livelihood-related goals.
- Advancement on the more justice-centered SDGs is likely only if policies center on reducing inequalities, and marginalized and vulnerable populations are empowered and included at the forefront of mitigation policy planning and implementation.

4.3.3 Policy Implications and Applications

Chapter three reminds us that intent is not impact, and that well-intentioned efforts to mitigate GHG emissions may have larger negative effects on other aspects of sustainability and wellbeing, and fail to achieve the GHG emissions reductions they are designed to achieve. This chapter finds that interventions to mitigate food system GHG emissions are only likely if they are holistic and center around justice. This knowledge can be used by policymakers, advocacy organizations, community groups, and academics to create more thoughtful and inclusive policies, policy design processes, advocacy campaigns, and research. Figure 3.8 highlights a few key questions to consider in the design of interventions to mitigate food system emissions and advance progress on the other SDGs.

To support its analysis, this chapter includes summary tables (Tables 3.1-3.2) of existing relationships in food systems and sustainability. Decision-makers can use these relationships to help ensure efforts to mitigate food systems are not accompanied by new or additional harms, or that these harms are minimized. Researchers and students in food systems can use these tables to learn more about relationships in sustainability beyond their current area of expertise.

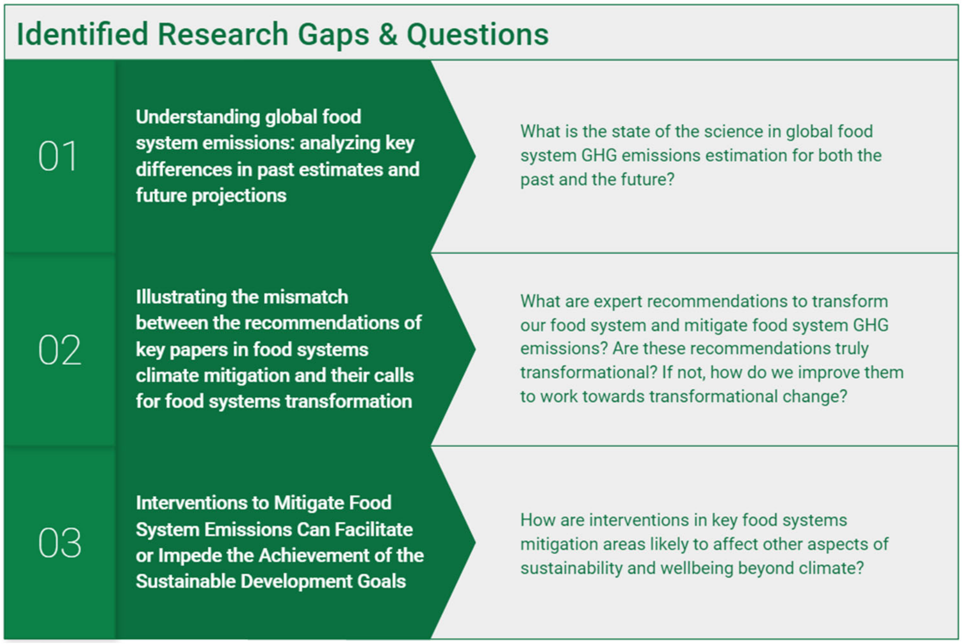
4.3.4 Future Research

This chapter highlights the need for thoughtful and inclusive research and policy design. Lasting interventions are often ones that are place-based and community-driven and this knowledge should be incorporated into academic research. Examples from this chapter show the inseparability of climate and the UN Sustainable Development Goals, highlighting the need for transdisciplinary research that advances multiple goals at the same time, as well as considers the potential harms of the proposed solutions on the other SDGs.

The UN Sustainable Development Goals are international by nature. Future research should help connect pilot, and smaller-scale interventions to larger sustainability goals and frameworks. Multi-criteria metrics for success are necessary to ensure that climate interventions are not harming other dimensions of sustainability, and are aligned with other global goals.

4.4 Dissertation Summary Conclusion

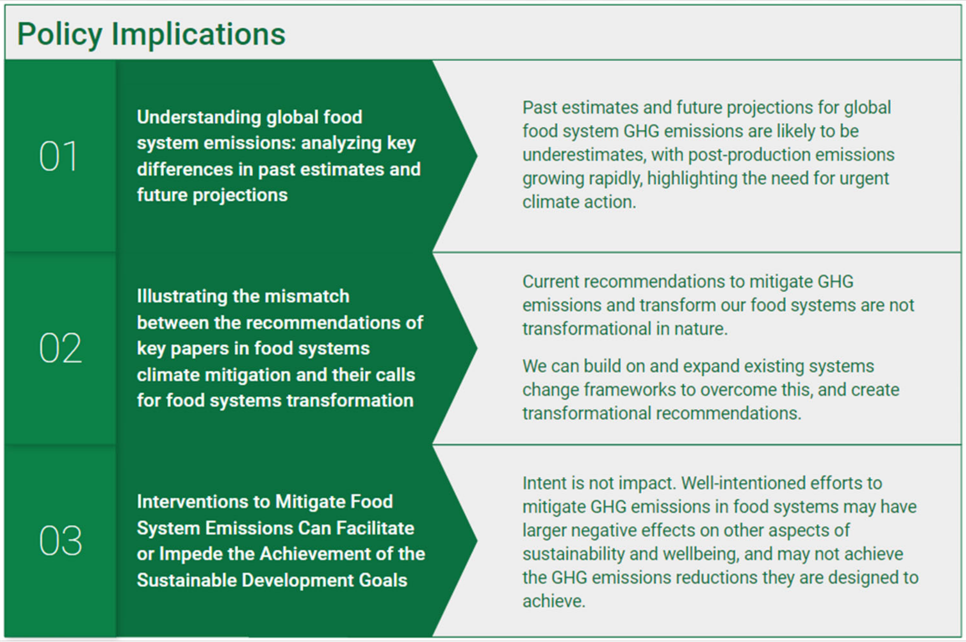
This dissertation makes a unique contribution to the literature. The questions that each chapter strives to answer and the gap that each chapter strives to fill are summarized in Figure 4.1 below, and the major policy implications of each chapter are shown in Figure 4.2.



Identified Research Gaps & Questions

01	Understanding global food system emissions: analyzing key differences in past estimates and future projections	What is the state of the science in global food system GHG emissions estimation for both the past and the future?
02	Illustrating the mismatch between the recommendations of key papers in food systems climate mitigation and their calls for food systems transformation	What are expert recommendations to transform our food system and mitigate food system GHG emissions? Are these recommendations truly transformational? If not, how do we improve them to work towards transformational change?
03	Interventions to Mitigate Food System Emissions Can Facilitate or Impede the Achievement of the Sustainable Development Goals	How are interventions in key food systems mitigation areas likely to affect other aspects of sustainability and wellbeing beyond climate?

Figure 4.1: Identified Research Gaps and Questions for Each Dissertation Chapter.



Policy Implications

01	Understanding global food system emissions: analyzing key differences in past estimates and future projections	Past estimates and future projections for global food system GHG emissions are likely to be underestimates, with post-production emissions growing rapidly, highlighting the need for urgent climate action.
02	Illustrating the mismatch between the recommendations of key papers in food systems climate mitigation and their calls for food systems transformation	Current recommendations to mitigate GHG emissions and transform our food systems are not transformational in nature. We can build on and expand existing systems change frameworks to overcome this, and create transformational recommendations.
03	Interventions to Mitigate Food System Emissions Can Facilitate or Impede the Achievement of the Sustainable Development Goals	Intent is not impact. Well-intentioned efforts to mitigate GHG emissions in food systems may have larger negative effects on other aspects of sustainability and wellbeing, and may not achieve the GHG emissions reductions they are designed to achieve.

Figure 4.2: Policy Implications for Each Dissertation Chapter.

Together, these chapters emphasize the ever-growing body of research that discusses the importance of food systems transformation to meet climate and sustainability goals. This dissertation highlights the need for radical changes in the way that academics and policy makers discuss food systems and climate change, including the ways academic researchers estimate food system GHG emissions, food system experts recommend

GHG emissions interventions, and the design of interventions to mitigate GHG emissions in our food systems.

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