Assessing the Sustainability Implications of Expansions and Innovations in Refrigerated Food Supply Chains

by

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Table of Contents

Acknowledgements ii

List of Tables v

List of Figures viii

List of Appendices xiii

Abstract xiv

Chapter 1: Introduction 1

Chapter 2: Critical Research Needed to Examine the Environmental Impacts of Expanded Refrigeration on the Food System 9

Chapter 3: Potential Changes in Greenhouse Gas Emissions from Refrigerated Supply Chain Introduction in a Developing Food System 58

Chapter 4: The Influence of Household Refrigerator Ownership on Diets in Vietnam 96

Chapter 5: Greening the Cold Chain 127

Chapter 6: Comparison of Life Cycle Environmental Impacts from Meal Kits and Grocery Store Meals 158

Chapter 7: Conclusion 204

Appendicies 209

List of Tables

Table 1.1**:** Overview of dissertation chapters and their corresponding analyses 3

Table 2.1: Identified food product studies addressing refrigeration, their scope, and inclusion of non-intrinsic factors as scenarios. Slashes indicate the category is partially addressed, and non-intrinsic factors are presented in bold 18

Table 4.1: GAMLSS Zero Adjusted Gamma model coefficients for refrigerator ownership and per capita expenditure, predicting on the consumption of food types. The first regression coefficients (1) by food type are for the strictly positive portion of the distribution (μ, log-linked) and the second (2) are for the log odds of zero consumption of each food type (ν, logit link). Control variable coefficients not listed for brevity, but full regression outputs are included in Appendix B.3. 109

Table 4.2: Percentage of Households in each VHLSS response year which report consuming no quantity of each food type (kcal/day-adult equivalent) and either do or do not own a refrigerator 114

Table 5.1: Cold chain emissions reduction interventions modeled 139

Table 5.2: Percentage (top) and absolute reductions (bottom) from the baseline emissions resulting from each intervention modeled. Values are shaded to correspond to the magnitude of emissions reductions compared with the baseline. 141

Table 6.1: Monte Carlo Model and Parameter Descriptions 178

Table A.1: Agricultural Production Loss Rate ($R1$) Triangular Distribution Parameters by Region and Food Type (% Loss at each FSC Stage) 214

Table A.2 Postharvest Handling and Storage Loss Rate ($R2$) Triangular Distribution Parameters by Region and Food Type (% Loss at each FSC Stage) 215

Table A.3: Processing and Packaging Loss Rate ($R3$) Triangular Distribution Parameters by Region and Food Type (% Loss at each FSC Stage) 216

Table A.4: Retail Distribution Loss Rate ($R4$) Triangular Distribution Parameters by Region and Food Type (% Loss at each FSC Stage) 217

Table A.5: Demand ($F5$) Normal Distribution Parameters by Region and Food Type (kg food per capita) 218

Table A.6: Demand-Weighted Agricultural Emissions Factor (EA) Normal Distribution by Region and Food Type Parameters (kg CO_2e/kg food) 219

Table A.7: SSA Demand-Weighted Agricultural Emissions Factor (EA) Normal Distribution by Developed Region and Food Type Parameters (kg CO_2e/kg food) 220

Table A.8: Cold Chain Emissions Factor (EC) Normal Distribution Parameters by Region and Food Type Parameters (kg CO_2e/kg food) 223

Table A.9: 365-Day Per Capita Consumption of Each Food Type for Modeled Nationally Recommended Diet for Sub-Saharan Africa 226

Table B.1:Conversion table and food groups 233

Table B.2: VHLSS Summary Statistics (2004-2014) 236

Table B.3: Starchy Staple Foods GAMLSS ZAGA Regression Output 239

Table B.4 Nuts and Seeds GAMLSS ZAGA Regression Output 242

Table B.5: Pulses GAMLSS ZAGA Regression Output 245

Table B.6: Eggs GAMLSS ZAGA Regression Output 248

Table B.7: Flesh Foods GAMLSS ZAGA Regression Output 251

Table B.8: Vegetables GAMLSS ZAGA Regression Output 254

Table B.9: Fruit GAMLSS ZAGA Regression Output 257

Table B.10: Dairy GAMLSS ZAGA Regression Output 260

Table B.11: Average kcal/day/adult equivalent in VHLSS Data (2004-2014).......................... 261

Table C.1: Supply Chain Model Baseline Values 274

Table D.1: Meal Kit Ingredients and Food-Specific Packaging Masses 279

Table D.2: Grocery Meal Ingredients and Food-Specific Packaging Masses 283

Table D.3: Food and Packaging Emissions Characterization Values 290

Table D.4: Food Loss and Waste Rates, Retail Refrigeration Indicator 293

Table D.5: Monte Carlo Simulation Results 294

Table D.6: Meal Kit Median Emissions Contributions by Process 295

Table D.7: Grocery Meal Median Emissions Contributions by Process 297

Table D.8: Additional Environmental Impact Values for the Production of Food and Packaging 307

List of Figures

Figure 1.1**:** Visual representation of the relationship between refrigeration, the food system, and the food-energy-water nexus. Adapted from (Heard and Miller, 2016). 1

Figure 1.2**:** Depiction of the relationship between the cold chain's direct supply chain elements and broader food system factors with their directionality identified. Adapted from (Heard and Miller, 2019). 5

Figure 2.1: The key factors related to the cold chain and their primary categorizations. Intrinsic factors relate to the technology itself, indirect factors are those relating to the technology's adoption and interaction with other systems, and external factors occur independently of the technology's presence. 13

Figure 2.2: A simplified representation of the changes in direct energy use and food waste at different stages of the food supply chain with the introduction of refrigeration. While the refrigeration is anticipated to increase direct energy consumption at all stages of the process, overall changes food waste are unknown, with decreases in the supply chain competing with increased household waste. 40

Figure 3.1: Visual representations of mass flows for food (F), loss rates (R), and losses (L) in the upstream food supply chain to supply 1 kg of food to retail. R values are loss rates in each FSC stage for fruits and vegetables for Sub-Saharan Africa (top) and North America & Oceania (bottom) from Gustavsson et al.(Gustavsson et al., 2011) Each food type has unique food loss rates at each stage; the values for fruits and vegetables are shown here as an example. Emissions

in this study are calculated for the pre-retail portion of the FSC due to data constraints and the role of consumer behavior and retailing heterogeneity in the downstream FSC. Further description of the study boundary and these terms available in Methods. 66

Figure 3.2: Comparison of median emissions added from cold chain introduction and emissions associated with avoided food losses. The calculated values pertain to emissions occurring during the postharvest and pre-retail supply chain (i.e. L_2, and L_3 in Figure 3.1). The calculated difference indicates the direct trade-off between introduced cold chain emissions and avoided food loss emissions for each food type 78

Figure 3.3: Boxplots and histograms of the difference between added cold chain emissions and avoided loss emissions in the postharvest cold chain for both introduction scenarios. Panel A) is a boxplot of the emissions difference per kg of each food type food delivered to retail for the North American scenario, with Panel C) reflecting these emissions for the European scenario. Boxes show the range of values between the 25th and 75th percentiles generated from Monte Carlo Analysis, with the box's line indicating the median. The grey tails are data points generated which fall outside of this interquartile range. Panel B) shows the histogram of total net emissions for the North American scenario's model runs based on a weighted average of food types, with Panel D) showing these results for the European scenario. 81

Figure 3.4: Changes in upstream food supply emissions (kg CO_2e) required to deliver one kg of a representative diet, based on a weighted average of each food type within a typical diet. Percentage differences in emissions are displayed by corresponding food type in the graph. 83

Figure 4.1: Vietnamese refrigerator ownership and average household per capita expenditure (PCE) over 2004-2014 as recorded by the Vietnam Household Living Standards Survey. The right plot boxes encompass the 25th and 75th percentile values of PCE per year, with the black lines extending to the extreme high and low values recorded. The horizontal black lines in the boxes indicate the median PCE value for each group per year. 104

Figure 4.2: Percentage of households reporting ownership of a refrigerator in the Vietnam Household Living Standards Survey. Data from the 2004 survey wave is displayed in the left-most map, 2014 data in the middle, and the percentage change between these survey waves on the right 105

Figure 4.3: Average household kcal/day per adult equivalent of food types examined as measured by the VHLSS between 2004 and 2014. A y-axis break is defined between 1100 and 1700 kcal/Per Adult Equivalent to better-display the changes in consumption of Starchy Staple Foods in conjunction with other food categories. 107

Figure 4.4: Estimated changes in consumption of each food type corresponding with refrigertor ownership or a 200 USD increase in per capita expenditure. Esimates are from GAMLSS ZAGA μ coefficients for each food type, reflecting changes in average kcal/day per adult equivalent consumption of each food group. Statistical significance is labeled at the levels: '***' 0.001, '**' 0.01, and '*' 0.05 110

Figure 4.5: Boxplots of proportions of food consumed from a household's own production (left) or purchased external to the home (right). Proportions are of the food when characterized into monetary values, and displayed for households with or without refrigerators. 116

Figure 4.6: Acquired Dietary Diversity Scores (out of a maximum of 9) by year and refrigerator ownership status in VHLSS data (2004-2014). Error bars represent 95% confidence intervals. 117

Figure 5.1: Depictions of the food supply chain processes for each food type modeled, with key parameters described. A detailed list of all model parameters is included in Appendix C. 132

Figure 5.2.: Emissions reductions per kg food supplied when implementing combinations of the floating head supermarket refrigeration, food loss reduction, and decarbonized electricity emissions interventions modeled 149

Figure 6.1: Visual depiction of the meal kit and grocery meal supply chains examined. 166

Figure 6.2: Total estimated emissions (kg CO_2e) for the five meals studied supplied as a meal kit or via a grocery store. Black lines indicate median emissions for each meal by type, and boxes indicate emissions within the 25th and 75th percentiles of model runs. Grey dots indicate values falling outside of this range, which may be considered outliers. These more-extreme values have an upward bias, reflecting higher-emissions intensity cases to create, supply, and consume meals. 181

Figure 6.3: Median emissions (kg CO_2e) for each contributing element to meal emissions by meal type. MK indicates meal kit and GS indicates grocery store meals. Solid lines surround portions of the supply chain more-directly within a consumers' control. Emissions and contributions are displayed in absolute terms in the upper chart, and by percentage of total emissions in the lower chart. 182

Figure 6.4: Median emissions (kg CO_2e) for contributing elements to meal emissions by meal type if grocery meal ingredients have identical mass to meal kit ingredients. MK indicates meal

kit and GS indicates grocery store meals. Solid lines surround portions of the supply chain more-directly within a consumers' control... 192

Figure 6.5: Percentage difference between emissions (kg CO_2e) for an average meal kit or grocery store meal calculated when each parameter of interest is fixed to 25% greater or less than its median value (or as otherwise noted) and other parameters held at their median values...... 194

Figure A.1: Sensitivity of model parameters to uncertainty. Filtered to include factors whose different between their 95th percentile and/or 5th percentile values and median varies by 10% or greater. 224

Figure A.2: Changes in upstream food supply emissions (kg CO_2e) required to deliver one kg of food, based on a weighted average of each food type within the modeled Nationally Recommended Diet. Percentage differences in emissions are displayed by food type in the graph 228

List of Appendices

Appendix A: Supporting Information for Chapter 3 209

Appendix B: Supporting Information for Chapter 4 231

Appendix C: Supporting Information for Chapter 5 2612

Appendix D: Supporting Information for Chapter 6 276

Abstract

Refrigeration transforms food systems. The global integrated refrigerated supply chain, or "cold chain," impacts numerous sustainability outcomes, from energy consumption and greenhouse gas (GHG) emissions, to consumer diets and producer behavior. This dissertation seeks to understand refrigeration's systems-level sustainability implications: first, how this technology influences environmental outcomes and human behavior, but also how adoption and use patterns feed back into how this technology impacts its users and the broader environment.

This dissertation begins by building an understanding of the current cold chain's influence on sustainability. Chapter 2 reviews the existing literature on refrigeration, finding the cold chain remarkably understudied in the sustainability literature. One key environmental tension identified is the trade-off between GHG emissions added from cold chain operation, and the cold chain's ability to decrease food loss. Chapter 3 compares changes in pre-retail GHG emissions from cold chain operation and food loss rate changes when introducing a refrigerated supply chain into the Sub-Saharan African food system. This study finds cold chain introduction resulting in a net GHG increase of 10% in a scenario reflecting a North American development scenario and 2% in a European development scenario. This analysis also models refrigeration's influence on food demand and agricultural production: finding an increase of 10% over the baseline when modeling a North American diet, or a 15% reduction with a European diet. Given the substantial influence diet has on food system sustainability, Chapter 4 explores the particular

role that refrigeration plays in consumer diet. This study moves beyond Chapter 3's assumption of convergence to Western diets in development, using data from the Vietnam Household Living Standards Survey and a regression model to isolate the effects of refrigeration from socio-economic variables. In this case study, household refrigerator ownership is statistically significantly associated with lower consumption of starchy staple foods, nuts and seeds, and pulses; and higher consumption of meat and dairy.

Having investigated how refrigeration currently influences emissions and diet, this dissertation's final chapters examine improvements and innovations in refrigerated supply chains. Motivated by a Chapter 3 finding that the cold chain adds more pre-retail emissions than it saves through food loss reduction, Chapter 5 assesses interventions to decrease cold chain emissions. This study builds a more-refined, process-based cold chain model, reflecting a fully-developed refrigerated food supply chain. The largest decreases result from decarbonized electricity, improved supermarket refrigeration systems, or reductions in pre-consumer food loss. The largest emissions reduction from a single intervention is 1.20 kg CO2e/kg (39%) for frozen fish supplied from using decarbonized electricity, and the largest from a tested combination is 1.61 kg CO_2e/kg frozen fish from combining decarbonized electricity with a CO_2NH_3 supermarket refrigeration system. The final chapter assesses the environmental improvements offered by an innovation in the cold chain: meal kit services. Meal kits are pre-portioned ingredients delivered to consumers, circumventing brick-and-mortar retailing. This study finds average grocery store meal GHG emissions exceeding those for an equivalent meal kit by 33%. Reductions in food waste emissions are found to exceed emissions missions added through extra packaging, and that direct-to-consumer delivery provides additional emissions reductions.

This dissertation examines several key sustainability implications of cold chain expansion and innovation. The complex interactions between cold chain technology and consumer behavior underscores the need to take a systems perspective when examining sustainability outcomes from future food supply chain developments.

Chapter 1

Introduction

Refrigeration creates transformative changes in a food system. On a basic level, refrigeration allows for the increased capacity to store perishable food items: lowering spoilage rates by reducing and maintaining temperature. An integrated refrigerated supply chain, or "cold chain," presents the capacity to reduce food loss and waste through spoilage reduction, as well as the capacity for supplying and consuming different quantities of food types. However, the operation of cold chains presents notable environmental burdens: through energy consumption and refrigerant emissions releases (James and James, 2013). Refrigeration is a transformative technology (Miller and Keoleian, 2015): fundamentally altering the food supply chains in which it is situated, and also allowing for shifts in consumer diets and producer practices. A simplified depiction of the interactions between refrigeration and elements of the food-energy-water nexus is shown in Figure 1.

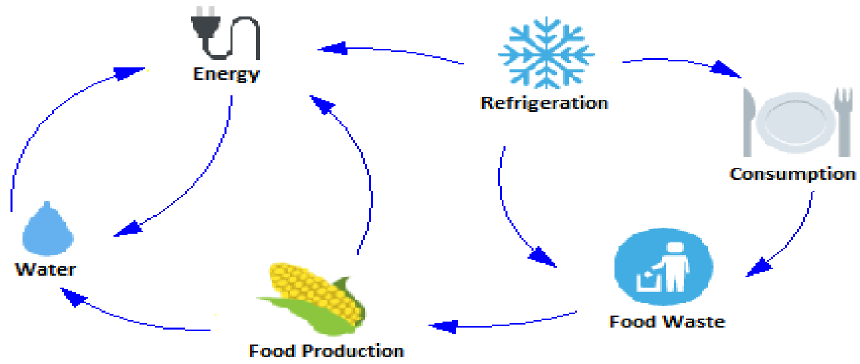

Figure 1.1**:** Visual representation of the relationship between refrigeration, the food system, and the food-energy-water nexus. Adapted from (Heard and Miller, 2016).

Refrigeration is associated with notable environmental impacts: comprising 1% of global greenhouse gas (GHG) emissions (James and James, 2010) and representing 3-3.5% of GHG emissions in developed economies such as the UK (Garnett, 2007). The cold chain is noted as a hallmark of industrialized countries with advanced food system infrastructure, (Parfitt et al., 2010) and has been described as ubiquitous for a modern food system: embedded in every stage of a product's life cycle (Garnett, 2007). As such, considerations of not just direct, but also indirect and external factors associated with refrigerated supply chains is necessary when modeling their environmental impacts.

Despite its connections to facets of sustainability ranging from food security to emissions releases, refrigeration and the cold chain are remarkably understudied in the academic literature (Heard and Miller, 2016). That being said, the impacts of 'cooling' (including both space cooling and refrigeration) have recently started to attract greater interest by international environmental organizations. Most examinations of refrigeration are technical in nature, quantifying refrigeration's energy consumption, refrigerant leakage, or other contributions to greenhouse gas emissions (James and James, 2013). Others have incorporated the role of refrigeration in either a view of levels of food supply chain sophistication in economic development (Parfitt et al., 2010) or qualitatively in the context of changing retail environments and consumer behavior in the food system (Garnett, 2007). In contrast with previous contributions to the literature, this dissertation takes a systems perspective: examining not only the direct emissions impact of refrigeration in a food supply chain, but also exploring the improvement potentials of select interventions and innovations, as well as this technology's relationship to consumer behavior, infrastructure, and the broader food-energy-water nexus.

The introduction of refrigeration into developing food supply chains is the adoption of a mature technology in emerging markets, while innovations in these supply chains correspond with the introduction of an emerging technology into both mature and developing markets (Bergerson et al., 2019). These scenarios each carry their own characteristics and necessary considerations for modeling and assessment. The breadth of methods and study designs employed to examine these topics reflect a systems view of refrigeration, with the specific goals, scopes, and variables assessed as part of this dissertation summarized in Table 1.1.

	Objective	Scope	Outcomes Measured
Chapter 1	Introduction	N/A	N/A
Chapter 2	Review how academic literature has assessed the environmental implications of refrigeration and identify key research gaps	Entire food supply chain, as well as indirect and external interactions	N/A
Chapter 3	Model the effects of cold chain introduction in a developing food system	Pre-retail food supply chain	Greenhouse gas emissions/kg food supplied to retail
Chapter 4	Determine the influence of refrigerator ownership on diets in Vietnam	Household	Kcal/day-adult equivalent of food types
Chapter 5	Assess the relative effectiveness of interventions to decrease cold chain emissions	Pre-consumer food supply chain	Greenhouse gas emissions/kg food supplied to consumer
Chapter 6	Compare the life cycle greenhouse gas emissions of meal kits and grocery store meals	Cradle-to-grave	Greenhouse gas emissions/meal
Chapter 7	Conclusion	N/A	N/A

Table 1.1**:** Overview of dissertation chapters and their corresponding analyses

The research presented in this thesis has been published, or is currently under consideration at the following journals with these co-authors:

- **Chapter 2:** Heard BR, Miller SA. "Critical Research Needed to Examine the Environmental Impacts of Expanded Refrigeration on the Food System." *Environmental Science & Technology*, 50(22), p. 12060-12071, 2016. 10.1021/acs.est.6b02740

- **Chapter 3:** Heard BR, Miller SA. “Potential Changes in Greenhouse Gas Emissions from Refrigerated Supply Chain Introduction in a Developing Food System.” *Environmental Science & Technology*, 53(1), 2019. pp 251–260. DOI: 10.1021/acs.est.8b05322
- **Chapter 4:** Heard BR, Thi HT, Burra DD, Heller MC, Miller SA, Duong TT, Jones AD. “The Influence of Household Refrigerator Ownership on Diets in Vietnam.” *Economics & Human Biology* (Under Review).
- **Chapter 5:** Heard BR, Miller SA. “Greening the Cold Chain.” In preparation for *Environmental Science & Technology*.
- **Chapter 6:** Heard BR, Bandekar M, Vassar B, Miller SA. “Comparison of Life Cycle Environmental Impacts from Meal Kits and Grocery Store Meals.” *Resources, Conservation and Recycling* 147, pp 189–200, 2019. DOI: https://doi.org/10.1016/j.resconrec.2019.04.008

Dissertation Chapter 2 reviews the literature addressing the environmental impacts of refrigeration in the food system. This paper draws on the life cycle assessment-informed framework for assessing transformative technologies developed by (Miller and Keoleian, 2015). Corresponding to this framework, this paper examines not just the factors intrinsic to refrigeration as a technology, but also its interactions with indirect and external factors. The extent to which certain food types and certain parts of the food supply chain are addressed in the literature examined is discussed, and key research needs are identified and summarized.

One key tension identified when reviewing and assessing the literature on refrigeration is the trade-off between the direct GHG emissions added from refrigerated supply chain operation (e.g. energy use, refrigerant release) and the potential to reduce food loss (which contains embodied GHG emissions from its production and supply up to the point of loss). Chapter 3 begins by studying this trade-off: comparing the emissions added through cold chain operation and emissions saved from food loss changes when cold chain introduction is modeled for the Sub-Saharan African food system. Expanding from this comparison, the indirect effects of cold chain introduction on elements of the food system are examined, depicted in Figure 1.2. The effects of the cold chain on food demand (reflecting diet shifts) and agricultural production are modeled, with resulting emissions changes assessed.

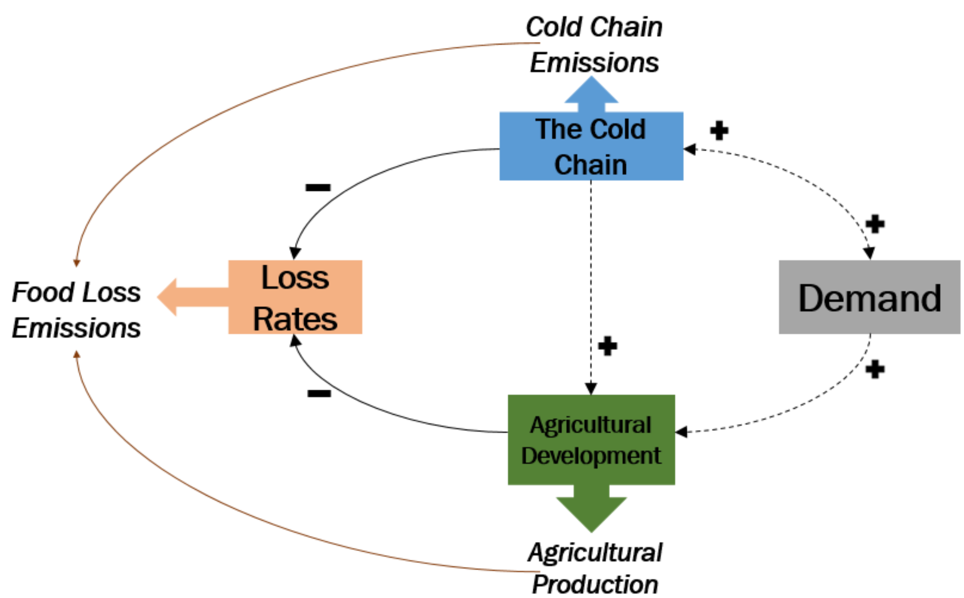

Figure 1.2**:** Depiction of the relationship between the cold chain's direct supply chain elements and broader food system factors with their directionality identified. Adapted from (Heard and Miller, 2019).

The way in which Chapter 3 models diet shifts reflects an assumption of dietary convergence: that with socio-economic development, diets in developing countries will resemble those currently seen in the Global North. This assumption may not be appropriate for all contexts, and the diet shifts modeled are influenced by multiple social and economic factors, not just the presence of refrigeration. Chapter 4 is a study which addresses both of these limitations, presenting a specific and detailed analysis of the influence of refrigerator ownership on household diets in Vietnam. Using Vietnamese household survey data, a multiple regression model is defined which isolates the influence of socio-economic variables, creating a statistical model which directly associated the presence of refrigeration in a household with changes in their consumption of major food groups. This analysis allows for the specific connection between refrigeration and diet to be quantified, and for the dietary shifts enabled by refrigeration to be viewed in the context of sustainable diets (Jones et al., 2016).

Given that Chapter 3 finds that the cold chain is likely to add more emissions through its operation than it saves through food loss reductions, Chapter 5 assesses potential interventions and improvements for decreasing direct emissions from refrigerated supply chains. This analysis develops a more-refined model of a refrigerated food supply chain, reflecting one typically seen in the Global North. This model follows 1 kg food from production, through processing, storage, refrigerated transportation, and grocery retailing. Interventions to decrease greenhouse gas emissions associated with supplying fresh broccoli, frozen broccoli, fresh chicken, frozen chicken, apples, fresh fish, frozen fish, and milk are evaluated, informing an assessment and discussion of the most-impactful cold chain interventions for emissions reductions.

Chapter 6 examines how the specific environmental burdens associated with supplying food refrigerated food may change with innovations in supply chain logistics. This study involves a comparative life cycle assessment of meal kits and more-typical grocery store meals. Comparing meal kit and grocery meal supply chains provides insights into the environmental impacts of e-commerce and direct-to-consumer delivery, as well as the trade-off between packaging and consumer food waste from pre-portioning ingredients. The findings from this comparative analysis reveal the extent to which different refrigerated supply chain elements contribute to a meal's emissions burden, and identify potential means for reducing environmental burdens.

Refrigerated food supply chains create the capacity for major structural shifts in our food system: from their direct environmental impacts from operation and food waste, the diet shifts they may prompt, to the alternative supply chain structures they enable. These changes have notable implications for sustainable development goals, nutrition, and the environmental impacts from emerging products and supply chain structures. This dissertation investigates these topics in an effort to further our knowledge on an understudied topic with important sustainability implications.

1.1 References

Bergerson, J.A., Brandt, A., Cresko, J., Carbajales-Dale, M., MacLean, H.L., Matthews, H.S., McCoy, S., McManus, M., Miller, S.A., Morrow III, W.R., Posen, I.D., Seager, Th., Skone, T., Sleep, S., 2019. Life cycle assessment of emerging technologies: Evaluation techniques at different stages of market and technical maturity. J. Ind. Ecol. 1–15. doi:10.1111/jiec.12954

Garnett, T., 2007. Food Refrigeration: What is the Contribution to Greenhouse Gas Emissions and How Might Emissions Be Reduced? (No. April 2007), FCRN Working Paper.

Heard, B.R., Miller, S.A., 2019. Potential Changes in Greenhouse Gas Emissions from Refrigerated Supply Chain Introduction in a Developing Food System. Environ. Sci. Technol. 53, 251–260. doi:10.1021/acs.est.8b05322

Heard, B.R., Miller, S.A., 2016. Critical Research Needed to Examine the Environmental Impacts of Expanded Refrigeration on the Food System. Environ. Sci. Technol. 50, 12050–12071. doi:10.1021/acs.est.6b02740

James, S.J., James, C., 2013. Sustainable Cold Chain, in: Tiwari Brijesh K., Norton, T., Holden, N.M. (Eds.), Sustainable Food Processing. John Wiley & Sons, Ltd, pp. 463–496. doi:10.1002/9781118634301.ch19

James, S.J., James, C., 2010. The food cold-chain and climate change. Food Res. Int. 43, 1944–1956. doi:10.1016/j.foodres.2010.02.001

Jones, A.D., Hoey, L., Blesh, J., Miller, L., Green, A., Shapiro, L.F., 2016. A Systematic Review of the Measurement of Sustainable Diets. Adv. Nutr. An Int. Rev. J. 7, 641–664. doi:10.3945/an.115.011015

Miller, S.A., Keoleian, G.A., 2015. Framework for analyzing transformative technologies in life cycle assessment. Environ. Sci. Technol. 49, 3067–3075. doi:10.1021/es505217a

Parfitt, J., Barthel, M., Macnaughton, S., 2010. Food waste within food supply chains: quantification and potential for change to 2050. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 365, 3065–81. doi:10.1098/rstb.2010.012

Chapter 2

Critical Research Needed to Examine the Environmental Impacts of Expanded Refrigeration on the Food System

Heard BR, Miller SA. "Critical Research Needed to Examine the Environmental Impacts of Expanded Refrigeration on the Food System*.*" *Environmental Science & Technology*, 50(22), p. 12060-12071, 2016. 10.1021/acs.est.6b02740

Abstract

The unbroken global refrigerated supply chain, or cold chain, is rapidly expanding in developing countries. In addition to increasing the energy intensity of the food system, the expanded cold chain may facilitate changes in the global diet, food waste patterns, food production and distribution, and shopping habits. The sustainability impacts of many of these changes chain are unknown, given the complexity of interacting social, economic, and technical factors. The current literature surrounding the environmental impacts of refrigeration in the food system focuses on the direct impacts of energy use and coolant emissions, and lacks a critical evaluation of the accompanying systemic societal changes that potentially carry greater environmental impacts. This review examines the cold chain as a transformative technology, identifying key intrinsic, indirect, and external factors that will favorably, unfavorably, or ambiguously impact the environmental profile of the food system. The review identifies key interactions and feedbacks between the cold chain, food production and consumption decisions, infrastructure development, and the global environment which are largely unexamined and in need of empirical data. Viewing cold chain expansion from this broader perspective is essential to understanding

the changing impacts of the food system in developing countries and may inform future sustainability planning.

2.1 **Introduction**

A critical yet relatively unexplored dimension of the food-energy-water nexus is the expansion of the cold chain into developing countries. The cold chain encompasses integrated refrigeration across the entire food supply chain, and is a key component of the global storage and distribution system for perishable goods. The cold chain is an essential part of the modern food system (Garnett, 2007; Salin and Nayga Jr., 2003), by preventing losses due to spoilage (Bogataj et al., 2005) and preserving product value. The cold chain integrates all elements of the food system, beginning with cold storage shortly after harvest, through processing, distribution, transportation, and household consumption (Joshi et al., 2009), The cold chain encompasses a spectrum of climate controlled environments, including environments for frozen foods, chilled foods, and foods stored at low humidity ambient temperatures. The term cold chain is used synonymously with refrigeration throughout this paper. While this paper views the cold chain primarily through the lens of its relationship to the global food system, it also plays a critical role in the provision of other important goods such as vaccines (Fu et al., 2008).

Despite the term “cold chain” not being well-known by consumers (Ovca and Jevšnik, 2009a), it is involved in a substantial part of the developed world’s food system. (Jul, 1985) estimated that 31% of the world’s food supply chain may be refrigerated, a figure which is undoubtedly much larger today, but unfortunately with no recent estimate available in the literature. Meanwhile, less than 25% of meat and 5% of fruits and vegetables pass through the cold chain in China.

However, these figures can be expected to increase as time progresses and economies develop. Cold chain capacity increased by more than 50% in India, and by 66% in Brazil, and by 20% in China between 1998 and 2008 (Yahia, 2010), with continued expansion since then. The current cold chain market is valued at $167 billion USD in 2015 and is expected to grow 7% per year due to increased demand in emerging markets (Markets and Markets, 2015).

The cold chain consumes a notable quantity of energy (D Coulomb, 2008; James and James, 2010). Refrigeration consumes approximately 15% of the world's electricity (James and James, 2010), and is responsible for 3-3.5% of greenhouse gas (GHG) emissions for the UK (Garnett, 2007). Food consumption is one of the most impactful common activities when viewed from a product life cycle perspective (Carlsson-Kanyama et al., 2003); therefore, changes in the food system for developing countries present significant sustainability implications.

2.2 **A Life Cycle Assessment Framework**

This paper encompasses social and behavioral factors along with environmental impacts to examine the sustainability implications of an expanded cold chain. A typical way to analyze the sustainability impacts of a technology like refrigeration would use the framework of a life cycle assessment (LCA). LCA is an approach that examines the environmental impacts of goods and services throughout their production, consumption, and end-of-life stages (Rebitzer et al., 2004;Miller and Keoleian, 2015). The goal of LCA is to capture the full environmental footprint of a product or technology, which in turn, allows for the identification of what drives its environmental impacts, and where there are key areas for improvement. The benefits of integrating social factors and people's decision-making into LCA have been identified (Jørgensen, 2013;Miettinen and Hamalainen, 1997) with the goal of presenting results which are usable and beneficial to producers, consumers, and society. There have also been efforts to connect both of these additional focuses into traditional LCA methodologies (Dreyer et al., 2006; Weidema, 2005; Tillman, 2000) with the aim of achieving this additional scope, while also adhering to its traditional engineering-based framework.

The availability of refrigeration facilitates purchasing, retailing, and behavioral choices in a society which would otherwise not be present or possible. The changes facilitated by the cold chain affect the environmental impact of the food system in ways that are favorable (e.g. extended shelf-life for products), unfavorable (e.g. increased energy consumption for refrigeration), and uncertain (e.g. amount of food waste). Due to the complexity of these changes, it is unclear whether an expanded cold chain will increase or decrease the aggregate environmental impact of the global food system. This paper provides a comprehensive examination of different facets of the cold chain and suggests research areas where greater data and analysis are needed, using an LCA framework that was developed for analyzing transformative technologies. (Miller and Keoleian, 2015) identify ten factors that may influence the environmental impacts of a transformative technology, grouping these as: (1) intrinsic to technology design and performance; (2) indirect influences brought about by the technology's adoption and its interactions with existing systems; and (3) external factors which occur independently of the technology's deployment. Figure 2.1 illustrates the intrinsic, indirect, and external factors that affect the environmental impacts associated with the cold chain.

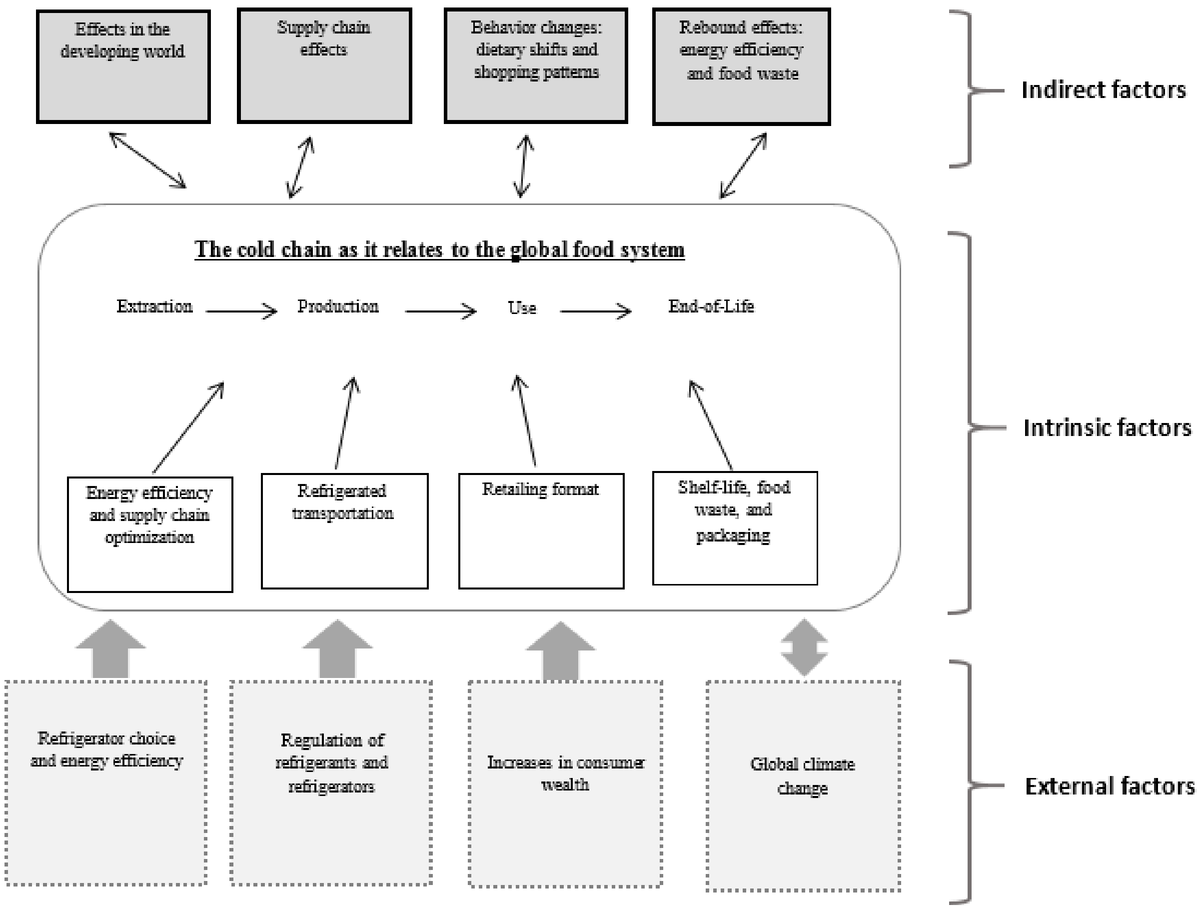

Figure 2.1: The key factors related to the cold chain and their primary categorizations. Intrinsic factors relate to the technology itself, indirect factors are those relating to the technology's adoption and interaction with other systems, and external factors occur independently of the technology's presence.

LCA have traditionally examined manufactured products, but have been increasingly used to analyze agricultural systems as well. Methodological issues in applying the LCA framework to agricultural systems have been identified and addressed within the literature, providing an advantageous perspective through which to view production systems, accounting for often-overlooked portions of a system and related improvement strategies (Heller and Keoleian, 2003).

A framework has been put forward for conducting consequential LCAs for agricultural systems, addressing the significant role that system delimitation has on study results, and how to best incorporate factors such as changes in demand and production which are not addressed in attributional LCAs of this system (Schmidt, 2008).

Due to food's complexity and multi-functionality, choosing an appropriate functional unit is difficult. The choice of functional unit will have an important influence on the results obtained from an LCA (Weber and Matthews, 2008). A detailed examination of food functional units used in the literature is provided with references to key studies by (Schau and Fet, 2008). When examining the impacts of refrigeration, the representative meal consumed by a household may serve as an appropriate functional unit for examining environmental impacts, especially considering the potential for shifts in diet, consumption levels, and other behavior changes. Other common choices of functional unit may include energy (kcal), household food expenditures ($), mass of a particular product (kg), or nutrient (g).

A substantial number of LCAs related to food products include refrigeration within the scope and boundaries of their analysis (Amienyo et al., 2013; Andersson et al., 1998; Beccali et al., 2009; Berlin, 2002; Blanke and Burdick, 2005; Blengini and Busto, 2009; Eide, 2002; González-García et al., 2013; Heller and Keoleian, 2011; Hospido et al., 2009; Ingwersen, 2012; Iribarren et al., 2010; Peters et al., 2010; Point et al., 2012; Roy et al., 2008; Thoma et al., 2013; Zhu and van Ierland, n.d.; Ziegler et al., 2003; Zufia and Arana, 2008), largely accounting for the role refrigeration plays in affecting the energy consumed in a food product's lifetime. Non-intrinsic factors are sometimes, but not frequently, addressed in LCA studies. When these factors are addressed it is in the form of scenario analysis for LCA results, many of which do not address post-production (retail and consumer phase) factors like those related to society and behavior. The frequency of discussion of non-intrinsic factors, and to which parts of the supply chain it is often applied, is summarized and presented in Table 1.

A review paper examining life cycle assessments of a number of food products was conducted by (Roy et al., 2009), identifying and summarizing aspects and results of different LCAs by their relationship to the food system. A similarly widely-scoped summary of life cycle assessments related to different food types is presented by (Mogensen et al., 2009).

	Food Type	Agricultural Production	**Agriculture Scenarios**	Pre-consumer Transportation	Processing/Packaging	Capital Goods and Equipment	**Production Scenarios**	Distribution/Retail Storage	Consumer Transportation	Household Storage and Use	**Post-Production Scenarios**
Grains											
Blengini & Busto (2009)	Rice	/	**X**	X	X	/					
Fruit											
Beccali et al. (2009)	Citrus-based products	X		X	X			X	X	X	
Blanke & Burdick (2005)	Apples	X		X	X		**X**	X	X		
Ingwersen (2012)	Pineapple	X	**X**	X	X		**X**	X			
Vegetables											
Hospido et al. (2009)	Lettuce	X		X	X	X	**X**				
Roy et al. (2008)	Tomatoes	X		X	X	/	**X**	X			

Meat											
Peters et al. (2010)	Beef and Sheepmeat	X	**X**	X	X						
Zhu & van Ierland (2003/2004)	Pork and Novel Protein Foods	X	**X**	X	X		**X**	X	X	X	
Seafood											
Iribarren et al. (2010)	Mussels	X		X	X	X		X		X	
Ziegler et al. (2003)	Cod fillet	X	**X**	X	X		**X**	X	X	X	
Dairy											
Berlin (2002)	Semi-hard cheese	X		X	X						
Eide (2002)	Milk	X		X	X		**X**	X	X	X	
González-García et al. (2013)	Yogurt	X					**X**			X	**X**
Heller & Keoleian (2011)	Milk	X		X	X	X	**X**	X	X	X	

Thoma et al. (2013)	Milk	X		X	X			X	X	X	**X**
Processed Food Product											
Andersson et al. (1998)	Tomato Ketchup and bottle	/			X		**X**	X	X	X	X
Zufia & Arana (2008)	Industrial Cooked Dish	X		X	X		**X**	X	X	X	
Beverage											
Amienyo et al. (2013)	Soft drink	X		X	/		**X**	X			X
Point et al. (2012)	Bottled Wine	X	X	X	X		**X**	X	X	X	

Table 2.1: Identified food product studies addressing refrigeration, their scope, and inclusion of non-intrinsic factors as scenarios. Slashes indicate the category is partially addressed, and non-intrinsic factors are presented in bold

2.3 Intrinsic Factors

Intrinsic factors are inherent to the technology itself and include efficiency and functionality, spatial effects, infrastructure changes, and resource criticality (Miller and Keoleian, 2015). Efficiency and functionality factors play an important role in the energy consumption of refrigeration equipment and logistics of the food supply chain, as well as potential changes to food waste as the shelf life of food increases. The emergence of a cold chain also changes the spatial extent of the food system, enabling a shift from localized to global supply chains. A variety of infrastructure changes occur as a result of the cold chain, in the form of refrigerated transportation and storage and changes to retailing format. Each element of cold chain infrastructure is more energy-intensive than its non-refrigerated alternative, carrying potentially significant increases in energy and environmental burdens for the food system. In addition to using large amounts of energy, food production is associated with large quantities of water and has the potential to induce water stress. Global food waste is responsible for up to one quarter of total freshwater consumption (Hall et al., 2009). Depending on whether the cold chain increases or decreases food waste, there is a potential to either increase or decrease the energy consumption and water stress associated with the food system. There is very little empirical data associated with examining changes in energy, water stress, and other factors when refrigerated supply chains expand. Studies examining changes in systems emissions in the presence of the cold chain would provide critical data to informing both environmental and policy analyses relating to refrigeration.

Analyses of the intrinsic components of the cold chain are largely rooted in the engineering and supply chain management literatures, with a focus on optimizing the performance of refrigerated systems, decreasing food waste through spoilage, and improving supply chain efficiency. However, each of these factors connects with social aspects of the food system, as the operation and optimization of supply chains influences the availability of products in a market, and the ways in which these goods are supplied.

2.3.1 Energy Efficiency and Supply Chain Optimization

A substantial portion of the cold chain literature focuses on temperature monitoring and technical optimization of refrigerated systems (Garnett, 2013). The importance of efficiency should not be understated, as it has been estimated that potential energy savings of 20-50% in the existing cold chain are possible through technical improvements such as proper refrigerated equipment specification, use, and maintenance (Garnett, 2007).

An often-cited means of limiting the environmental impacts associated with cold chain expansion are through energy conservation efforts. The use phase is responsible for the largest amount of energy consumed throughout a refrigerator’s life cycle (Kim et al., 2006); therefore, energy efficiency is a logical target to reduce the environmental impact of refrigeration. There is a notable body of literature focusing on improving the efficiency of the cold chain with respect to energy consumption, with papers addressing potential savings and modifications for cold storage (Evans et al., 2014; S.A. Tassou et al., 2011), transportation stages of the cold chain (Tassou et al., 2009), wider system “inhibitors” to cold chain efficiency in the developing world (Joshi et al., 2009), as well as novel additions such as cold energy recovery from liquefied natural gas recovery (Messineo and Panno, 2011). At the household level, a life cycle assessment of the personal refrigerator was conducted as part of (Kim et al. 2006)’s study of optimal replacement policies, and a study including notes of technical and energy efficiency gains to be had from different types of refrigerator-freezers is conducted by (Bansal et al., 2011).

There are a number of studies which approach the optimization of moving goods through a refrigerated supply chain using econometric methods and Monte Carlo simulations (Aiello et al., 2012; Verbi, 2004; Flick et al., 2012), temperature sensors and RFID tracking and other wireless monitoring systems (Bo and Danyu, 2009; Fu et al., 2008; Tingman et al., 2010; Ruiz-Garcia et al., 2008), benchmarking (Shabani et al., 2012), and the application of traditional operations research approaches.

Minimizing refrigerant leaks in the cold chain is another area of inquiry that has received a good deal of well-warranted attention, given their relatively large global warming potential (Calm, 2006; Garnett, 2011; Johnson, 1998; McMullan, 2002; S. A. Tassou et al., 2011). (Garnett, 2007) authored a comprehensive report on the contribution to global greenhouse gas emissions from refrigeration, addressing both direct energy consumption for power and the role that refrigerants play, noting that refrigerants account for approximately 15% of the GHGs emitted from commercial systems. (Akkerman et al., 2010) specifically note that while some papers do examine energy consumption throughout the supply chain being studied, there is a notable lack of attention to sustainability in the relevant network planning literature.

2.3.1 Refrigerated Transportation

The link between refrigerated transportation and global commerce is addressed in the literature, with papers focusing on improving product value through more effective refrigerated transportation strategies (Reid and Jiang, 2005; Vigneault et al., 2009). (James et al. 2006) provide a comprehensive overview of the food transportation system, describing both the different processes for transporting products, but also addressing the modeling of factors like heat transfer and microbial growth. This analysis provides a striking picture of the complexity of the global food transportation system, and also reveals the immense importance of this technology in the effective transportation of perishable food products.

Refrigerated transportation consumes a substantial amount of energy. For example, for maritime individual shipping containers in New Zealand, it was found that 19% of the energy used during the shipping of food products was for refrigeration purposes (Fitzgerald et al., 2011). The energy-intensity of the shipping process depends on the product. For example, chilled goods are actually more energy-intensive to transport than frozen foods (Garnett, 2007).

It is frequently assumed that food traveling a longer distance to a market will carry a greater environmental impact than the same product provided through a local supply chain; however, the relationship between energy and the geographic supply chain for food is more complicated. An expanded cold chain can provide consumers access to products which would otherwise be unavailable, such as frozen foods and produce which is not locally in season. Some studies have found regional produce to be less environmentally intensive than those shipped from overseas (Blanke and Burdick, 2005). while others found imported products to be less energy-intensive due to cold storage to extend the seasonality of locally produced food (Saunders and Barber, 2008; Hospido et al., 2009). The energy tradeoffs between local food being held in cold storage for out-of-season months with imported seasonal food varies based on product and geographic area. (Edwards-Jones et al. 2008) conclude that food miles are a poor indicator of sustainability impacts. Therefore, a broad statement regarding the energy-efficiency of local versus non-local food products is not generalizable and highlights the need for better understanding of the circumstances when transportation over a greater spatial extent has greater or fewer environmental impacts than a more local supply chain.

When compared with the total life cycle GHG emission for a food product, the energy consumption from transportation can be relatively small, amounting to 11% of an average U.S. household's total footprint for food consumption (Weber and Matthews, 2008). However, due to the large volume of products being transported, and growing number those requiring refrigerated transportation, the emissions from this life cycle phase are still substantial, and in need of study.

2.3.3 Retailing Format

The modern supermarket would not be possible without refrigerator units or a temperature-controlled cold chain for product delivery. As such, supermarket retailing co-develops with the expansion of the cold chain. Many rural and poor areas of the developing world have relied on shorter food supply chains which have limited post-harvest infrastructure (Parfitt et al., 2010), a system which can be expected to radically change with the introduction of cold chain technologies. The use of refrigerated units in the supermarket retailing model will increase energy and environmental burdens due to the increased electricity required to operate refrigerated and freezer sections of the store. It is noted that the development of supermarkets often drives the replacement of smaller family-owned stores (Goldman et al., 2002), presenting a disruptive innovation whose effects will reverberate throughout the regional economy.

The rise of supermarkets can be observed in China, where it was estimated in 2004 that supermarket sales were growing 30-40% each year, a rate 2-3 times greater than that recorded for other parts of the developing world (Hu et al., 2004). The growth in household ownership of refrigerators facilitates the growth of supermarkets which have spread beyond their introductory niches in the neighborhoods of middle and higher income residents in large cities and are now spreading into other geographic areas, including markets consisting largely of lower-income consumers in urban areas (Hu et al., 2004). While the socio-economic effects of cold chain expansion are not typically considered in the more technically-focused literatures examining this technology, these are important effects and are important elements to be considered from a systems perspective.

2.3.4 Shelf-Life, Food Waste, and Packaging

Food waste presents a substantial energetic, economic, and environmental loss to our societies, with avoidable food waste in the United States comprising 2% of national GHG emissions and costing $198 billion on a life cycle basis (Venkat, 2011).

Approximately 35% of food waste at the household level is considered avoidable (Bernstad Saraiva Schott and Andersson, 2015), representing a substantial opportunity for reducing environmental and economic impacts. While developing countries are estimated to have similar levels of food loss (30-40%) (Godfray et al., 2012), many of these losses occur further upstream in the supply chain, rather than primarily at the household. This observation is confirmed by (Hiç et al. 2016), who note that while developed and developing nations have similar quantities of food loss, the developing world losses are more frequently due to infrastructure under-development. Defining food waste as the surplus between food availability and food requirements for a nation, this analysis looks at projected changes in food waste under different economic and sustainability scenarios at the national level, but does not address changes in the cold chain in any explicit way (Hiç et al., 2016).

The main purpose of refrigeration is to extend the shelf-life of food. Longer shelf-life is a desirable trait for actors throughout the supply chain since it reduces spoilage, allowing food to be stored in greater quantities, increased timeframe for distribution, and greater flexibility in eating choices for consumers. For farmers and food producers, refrigeration allows for the better management of “seasonal gluts” of products which cannot be sold or consumed all at once (Garnett, 2007). An increased shelf-life also presents clear health and safety benefits (Patsias et al., 2006). In an analysis of meat products, it was found that only 10% of bacteria initially present on meat are able to grow at refrigerated temperatures, with the fraction of bacteria which cause spoilage being even lower (Borch et al., 1996).

Decreased spoilage is also highly advantageous from a food security perspective, potentially facilitating decreased food waste (Garnett and Wilkes, 2014). There have been a number of studies which quantify the relationship between decreased food waste and increased shelf-life (Eriksson et al., 2016; Gruber et al., 2016; Montanari, 2008; Vanek and Sun, 2008). However, when quantified in terms of overall system energy, the relationship between shelf-life and food waste is complex and not uniformly beneficial. The introduction of the cold chain brings the use of packaging for food products with it, which may improve shelf-life and food safety, but introduces different environmental burdens within the food system. In the developing world, food may currently be sold at markets without any packaging, including animals either slaughtered or sold alive at wet markets directly to the consumer.

The potential role of packaging to reduce food waste is discussed and analyzed within the context of life cycle assessment by (Wikström et al. 2014), who examine six packaging scenarios and their impacts with respect to the functional unit of "eaten food," and (Calderón et al. 2010) recording different environmental performances for a ready-made meal with different packaging types. The energetic impacts of packaging choices can be substantial, with the energy required for the processing and packaging of food being often greater than the energy provided by the food product itself (Heller and Keoleian, 2003). Food packaging does, however, reduce potential losses for food in transit and storage (Marsh and Bugusu, 2007), providing some energetic savings along the food chain. In order to decrease food waste, sometimes packaging with greater environmental impacts must be selected, a choice which may be environmentally advantageous when attempting to preserve an energy-intensive product and easily spoiled product, such as cheese, with less energy-intensive packaging (Williams and Wikström, 2011). Packaging within the food sector of developing countries is likely to become increasingly important, as the cold chain allows for the greater sale and distribution of packaged, pre-prepared foods.

A more comprehensive examination of the emissions and energetic trade-offs associated with choosing between refrigerated storage and the importation of a product, and between efforts to lessen food spoilage such as increased packaging would add additional depth to the comparative LCA literature.

2.4 Indirect Factors

The environmental impacts of emerging technologies extend beyond the components which comprise it, but also as a result of changes to existing systems. The framework for analyzing transformative technologies characterizes four indirect factors that may influence the environmental impact of the emerging system: technology displacement, behavior change, rebound effects, and supply chain effects. Since the cold chain often displaces smaller, localized infrastructure with little associated energy use, technology displacement considerations are expected to be minor and not evaluated in this paper. Meanwhile, the cold chain may precipitate a range of behavioral changes, including changes in shopping behavior, dietary patterns, and demand for convenience foods. Potential for increased purchase of food due to greater system efficiencies and subsequent increases in food waste can be classified as a type of rebound effect. Finally, supply chain effects can also be significant, such as demand for reliable baseload power and changes in agricultural management practices.

The life cycle environmental burdens which result from these interactions can be in many cases either more or less impactful, with the direction and magnitude of these changes remaining variable or uncertain. These complicated systemic interactions further underscore the need for careful study and analysis of the larger effects of cold chain expansion on economy, society, and environment.

2.4.1 Effects in the Developing World

There is a body of literature characterizing and examining the effects of cold chain expansion on developing markets, and how its presence alters established supply chains and practices.

There have been studies examining the effectiveness and challenges to the cold chain system in India (Joshi et al., 2009;Mallik et al., 2011), a country which can be expected to experience substantial social changes and shifts in environmental burdens with access to a larger refrigerated supply chain. A number of studies have been devoted to analyzing shifts in food consumption behavior in China (Liu et al., 2013; Ma et al., 2006; Ovca and Jevšnik, 2009b; Wang and Zhang, 2008). It has been observed that with access to modern grocery stores and personal refrigerators, Chinese consumers are beginning to purchase goods in bulk during weekly shopping trips (Zhang and Pan, 2013) and shift their food consumption towards more environmentally-intensive foods including meat (Zhou et al., 2012) and frozen foods (Garnett and Wilkes, 2014) Additionally, it is noted that concerns over food safety by Chinese consumers are leading them to increasingly seek out organically certified foods and/or foods from global brands (Xu and Wu, 2010), preferences which further necessitate the presence of a global refrigerated supply chain.

Refrigeration requires consistent, undisrupted access to electricity. The cold chain has great potential to expand within areas of the world without reliable electrical service. The cold chain and electricity availability are likely to co-develop, with reliable and non-intermittent electricity provision a necessary condition for cold chain expansion. The substantial and regular quantity of electricity demanded by refrigerators has been noted in a number of studies (Holtedahl and Joutz, 2004; Jannuzzi and Schipper, 1991; Parkpoom et al., 2004; Stadler et al., 2009) with their frequent and regular power draw placing them as part of a household's baseload electricity demand (Nelson, 2008).

The environmental impacts made by the operation of new refrigerators and a refrigerated supply chain in a region will greatly differ depending on the base-load fuel source or grid mix used for power. The deployment of renewables, particularly with battery storage to mitigate intermittency challenges, have the potential to meet this demand without a substantial increase in emissions. However, this demand for reliable baseload energy may spur additional support for fossil fuel-based generation in the developing world. The precise connection between the development of electricity infrastructure and the expansion of refrigerated supply chains is an area in need of further examination.

2.4.2 Supply Chain Effects

With the cold chain providing better preservation and transportation of produce, the potential for near-global demand for certain fruits or vegetables, regardless of season, becomes possible. Farmers who produce these crops benefit from greater financial opportunities, but may be incentivized to adopt over-planting and/or over-harvesting practices. Attributing emissions and environmental effects of shifting farming practices specifically to the emergence of the cold chain is difficult; however, globalization of the food system is certainly linked to some of these patterns, which is not possible without access to refrigeration.

While the expansion of the cold chain does provide farmers with the opportunity to sell products into markets which would have otherwise been unavailable, supermarket purchasing patterns may also be disruptive to local growers who are now contracted to supply goods to the retailer, with some retailers requiring farmers to use their own purchased refrigerated trucks (Weatherspoon and Reardon, 2003). In addition to placing an economic burden on farmers, refrigerated transportation from the farmer to a retailer adds an extra dimension to the cold chain where the supplier has incentives to purchase the cheapest available refrigerated transportation vehicle, which may be inefficient and consume large amounts of energy.

There is a limited amount of literature related to the upstream effects associated with cold chain expansion, with the relevant literature largely scattered throughout different disciplines. A more comprehensive and focused examination of the effects of these changes in demand and retailing model on the larger agricultural system would provide a more informed picture of the upstream sustainability impacts of expanded refrigeration.

2.4.3 Behavior Change

Notable social and cultural changes can be expected to accompany to the introduction of the cold chain. While a substantial portion of sustainability-focused literature surrounding the cold chain looks primarily at the environmental impacts associated with refrigeration as a technology, the importance of behavioral patterns and culture cannot be discounted.

2.4.4 Dietary shifts

Refrigeration throughout distribution and at the household level both enables and is driven by shifts in dietary preferences. An unbroken temperature-controlled supply chain allows for the more effective retailing of meat, dairy, as well as chilled pre-packaged or frozen ready-made foods.

The connection between an unbroken refrigerated supply chain and the availability of meat and dairy is direct and evident. The historical co-development of refrigerated storage in the U.K. and meat retailing has been documented (Garnett, 2007), with meat and dairy recognized as requiring a refrigerated supply chain in analyses considering contemporary contexts (Likar and Jevšnik, 2006; James and James, 2010). Without the cold chain, meat and dairy would have to be produced, transported, and consumed within very strict spatial and temporal constraints. The refrigerated supply chain allows for increased demand for meat and dairy to be met, without these supply restrictions. Meat and dairy products have been documented as being greenhouse gas-intensive food products (Audsley et al., 2009; Garnett, 2013). A shift from the current UK diet to a vegetarian diet reduces GHG emissions by 22% and switching to a vegan diet represents a 26% reduction (Berners-Lee et al., 2012). As the cold chain expands, dietary shifts which include the greater consumption of meat and dairy are probable, and correspond to a significant increase in GHG emissions from these diets.

From the perspective of measuring environmental impacts, frozen and ready-made meals provide a challenge for LCA practitioners. (Zufia and Arana 2008) note that industrially-prepared food meals have one of the most complex agri-food chains, with environmental impacts resulting from a number of food products, packaging choices, storage and cooking facilities, and retail and end-of-life decisions. (Calderón et al. 2010) lay out an extensive framework for conducting life cycle assessment for ready-made foods. The management of frozen and chilled food products along the cold chain is examined through the lens of supply chain management by (Zanoni and Zavanella 2011), who model the economic and energy related outcomes associated with temperature control and food product preservation. The environmental impacts of ready-made foods when compared with freshly-prepared alternatives has not been examined by many studies. An analysis by (Rivera et al. 2014) comparing types of ready-made meals with home-prepared alternatives did find, however, that a frozen ready-made meal with frozen ingredients which is heated in an electric oven was the worst alternative for most of their measured environmental impacts.

The sale of frozen and pre-prepared foods is not possible without an integrated cold chain, reflecting the substantial role this technology has in changing the provision of goods into a society. Similarly, meat and dairy cannot be distributed at the same volume and effectiveness without a temperature-controlled supply chain. The extent to which refrigeration facilitates market transformations through the introduction of new products, and the way demand develops for these goods is a rich area for behavioral and economic study, and is one with notable societal and environmental relevance.

2.4.5 Shopping Patterns

Access to personal vehicles or public transportation in the developing world enables supermarket retailing (Reardon et al., 2004). When household refrigeration is available, some households may make one larger trip to a supermarket-styled store instead of making multiple trips within a similar period to purchase food. In terms of GHG emissions, the shift towards the use of a vehicle for potentially fewer trips presents an interesting case where it is difficult to determine whether household emissions and/or systems-level emissions will increase or decrease without empirical study and analysis. The direction in which overall emissions will shift is further complicated by the fact that vehicle adoption enables households to more easily travel to, and shop from, multiple retailers (Stassen et al., 1999), which may result in more trips to acquire food being taken. The impacts of transportation to and from a store can be dramatic, with (Coley et al. 2009) presenting the finding that a customer driving a round-trip distance of more than 6.7 kilometers to obtain organic vegetables releases emissions that are likely greater than those if the vegetables were subject to cold storage, packed, transported to a regional distribution center, and then delivered to the customer's doorstep.

For other households, particularly in the developing world, dietary shifts facilitated by refrigeration may prompt a move away from a subsistence-farming model: raising animals or cultivating food at the household-level and consuming the products there. In these cases, any trips to a store or market for food products will likely increase food-related transportation and could result in an increase in energy consumed per meal. The net environmental impacts associated with a shift towards a supermarket-retailing model of food sales and acquisition may vary significantly with respect to variables such as region, household vehicle types, and diets, presenting an academic area which is rich with opportunities for empirical studies.

2.4.5 Rebound Effects

The rebound effect refers to the phenomenon where actions that appear to decrease environmental burdens actually spur behavior changes resulting in larger environmental impacts.

Energy Efficiency

An often-expressed concern regarding the effects of higher efficiency standards for appliances is the extent to which the corresponding cost savings will result in an increase energy consumption by users. A study in South Korea attempted to estimate a rebound effect associated with refrigerators, but was unable to separate the pure rebound effect of increased electricity consumption from a detected income effect, where those who owned efficient refrigerators had increased electricity use but also higher incomes (Jin, 2007). The study did find, however, that while rebound effects associated with energy efficiency improvements were detected, there was no evidence in this study of any “backfire effect,” where gross energy consumption increased to be greater than before the energy efficiency intervention (Jin, 2007). Examining the extent to which there is a rebound effect for electricity consumption (and to what extent that varies from market to market) is an area of important inquiry, which can provide insightful data relating to the use of newly introduced technologies.

Food Waste

Refrigeration slows down the processes by which food spoils, which should decrease food waste during production, transportation, and storage. However, access to refrigeration affects consumer purchasing patterns in ways which facilitate over-buying, which can dramatically increase consumer-end food waste and is a type of rebound effect.

With the ability to purchase larger quantities of food and store them ahead of meal preparation, the consumer estimates the quantity of food that will be consumed prior to its likely expiration or spoilage, inevitably resulting in inaccurate estimates. Owning a household refrigerator has been linked to the over-buying of food (Ligon, 2014), something which (Garnett 2007) attributes to the storage acting as like a safety net where consumers overestimate the quantity of time they can store food in a refrigerator before it spoils.

Quantifying food waste is difficult, with (Parfitt et al. 2010) finding that data on food waste "varied widely," particularly for the developing world, where many of the data on post-harvest losses were collected over 30 years ago. Further, it is difficult to ascertain how introduction of household refrigeration will change food waste patterns, a phenomenon that is not currently well-studied. To facilitate meaningful and well-informed analyses studying food waste, particularly in developing regions, data collection and improvement appears to be a critical research need. Despite the presence of a fully-integrated cold chain in the developed world, one of the reasons food waste remains high is due to consumer attitudes towards food attributes and aesthetics (Garnett, 2007; Kahn and Wansink, 2004). Despite no evidence as to decreased safety of food, developed world consumers are likely to prematurely dispose of food products with blemishes or signs of oxidation or aging, due to visual or textural preferences for food.

It has been noted that in China, as consumers experience increases in income and more widespread access to modern food distribution networks, their consumption patterns are beginning to shift towards those more commonly seen in the western world (Garnett and Wilkes, 2014), indicating that this is a behavioral trend in consumption and food waste which may be expected to accompany cold chain expansion and its related factors into developing nations. The overall change in food waste and energy consumption within the larger food system is difficult to predict due to the interactions between a refrigerated supply chain and consumer behavior, depicted in Figure 2.2. The cold chain exerts two competing forces on food waste. On one hand, refrigeration extends shelf life and decreases overall spoilage. On the other hand, refrigeration enables consumption habits that lead to increased food waste.

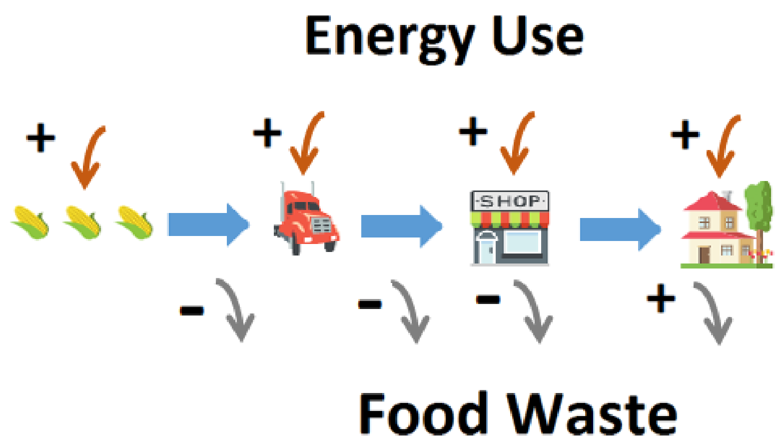

Figure 2.2: A simplified representation of the changes in direct energy use and food waste at different stages of the food supply chain with the introduction of refrigeration. While the refrigeration is anticipated to increase direct energy consumption at all stages of the process, overall changes food waste are unknown, with decreases in the supply chain competing with increased household waste.

To what extent the decrease in upstream food waste is offset by increased consumer-level food waste in situations of cold chain adoption is an open question, in need of study and of more robust data on baseline food waste and energy and water consumption in many areas of the world.

2.5 External Factors

The environmental performance of a transformative technology is also affected by factors which are primarily external to its deployment. The framework for analyzing transformative technologies classifies policy and regulatory effects and exogenous system effects as the two major factors that fall within this category. Exogenous system effects occur independently of the technology's adoption, but with the potential to influence its future environmental impacts.

2.5.1 Refrigerator Choice and Energy Efficiency

Despite facilitating reduced electricity consumption and promoting consumer savings, implementing energy standards for refrigeration technologies faces a number of challenges. One study which characterizes the various trade-offs faced in refrigerator selection identifies that despite consuming the least amount of electricity compared to other refrigerator types studied (thermoelectric and absorption refrigeration), vapor compression refrigerators were also the loudest and most costly (Bansal and Martin, 2000). In this case, purchasers are faced with a tradeoff between an inexpensive and quiet unit, or an alternative technology which consumes more energy. Depending on the context and consumer, the more readily-observable qualities of cost and noise may be weighed more highly in decision-making.

An additional challenge is the higher upfront costs associated with higher-efficiency technologies. This is a particular concern for refrigeration in developing countries such as Ghana, despite the potential for notable lifetime energy savings (Van Buskirk et al., 2007). However, despite initial barriers to adoption such as high capital/upfront investment costs, some developing nations have moved ahead with the process of implementing standards, with proposed measures in Malaysia (Mahlia et al., 2004) and national efficiency standards announced in China (Tao and Yu, 2011). Some motivation for moving ahead standards is that the costs of implementing energy efficiency standards have been recorded to often be less than estimates provided by manufacturers and agencies (Nadel, 2002), which suggests both hope for greater net economic savings than if often predicted, but also presents a very real difficulty in communicating about potential savings in the public or policy spheres.

Policies that affect the electricity grid will affect the environmental performance of refrigeration, even though they will occur independently. The environmental performance of refrigerators is dictated by the electricity generation portfolio of the grid. As smart grid and renewable energy technologies are increasingly implemented throughout the world, the environmental impact of electricity-intensive technologies will be reduced, irrespective of how refrigeration is deployed.

2.5.2 Regulation of refrigerants and refrigerators

The most prominent existing regulations related to the cold chain address the use and release of refrigerant chemicals. Expansion of the cold chain system will likely correspond in a growth in both energy consumed for refrigeration, and refrigerant chemicals emitted. These chemicals play a noted role in climate change, presenting a clear opportunity for sustainability improvements. The phase-out of harmful refrigerants has been a topic acted upon at an international level via the Montreal Protocol (D. Coulomb, 2008). A detailed discussion of regulated refrigerants and potential refrigerants for future use and production is provided by (Calm, 2008).

In a paper on options for refrigerator and refrigerant development, (Calm, 2002) writes that a lesson to be learned from ozone depletion and global climate change is that chemical emissions can accumulate in the atmosphere at damaging levels before the associated problems are noticed or proven. The successes seen in refrigerant regulation are substantial, and have the potential to be replicated in other contexts. Literature which analyses the factors contributing to successful regulations and agreements related to environmental emissions would undoubtedly benefit future efforts at emissions reduction regulations, allowing for these efforts to be informed by past successes.

2.5.3 Consumer Wealth

Consumers in the developing world are getting wealthier, which enables many of the transitions brought about by the cold chain. Increased wealth may be coupled with a desire for visually-pleasing products. If consumer expectations can be managed, substantial decreases in food waste compared to currently-developed nations can be obtained through a desire to accept food with blemishes or less-desirable textures (Garnett, 2007). The role of psychology and behavioral economics in examining consumer-level food waste cannot be overstated. Survey data on consumer perceptions of safe storage times for food and the extent to which future consumption is over or under estimated when purchasing food would be valuable to understanding the behavioral and economic decision-making related to food purchasing, consumption, and waste. Accompanying changes in consumer wealth, the role of decreasing trader barriers in the global economy is noted as playing a role in facilitating the greater importation and purchase of frozen and refrigerated food products (Hsu and Hung, 2003), a process further facilitated by cold chain expansion and the availability of supermarket and household refrigeration (Garnett, 2007). identifies a “snowballing effect” with respect to cold chain development and frozen food purchases, where the demand for frozen goods prompts the further development of the cold chain, and the development of the cold chain facilitates the further growth of the frozen foods market. Fewer trade barriers and an expanded cold chain provide the opportunity for diets which can now include out-of-season products, larger shares of meat, seafood, dairy, and other products requiring temperature-controlled storage, in addition to frozen and pre-prepared foods.

2.5.4 The Cold Chain and Climate Change

The cold chain amounts for approximately 1% of the world's total GHG emissions (James and James, 2010). While contributing to climate change, cold chain deployment is also affected by climate change. Increased ambient temperatures will require a greater quantity of energy to maintain a set temperature for refrigerated supply chains, corresponding with a greater quantity of GHG emissions (James and James, 2010). This finding identifies an important feedback loop for refrigeration and climate change.

Analyzing the feedback loop between refrigeration, global temperature, energy consumption, and GHG emissions will be a critical task in anticipating the environmental impacts of the cold chain. Only by understanding the relationship between these factors, and promoting interventions such as efficiency improvements or changes to lower-emitting energy sources, can the cold chain be expected to expand in a way which aligns with sustainability objectives.

2.6 Key Research Needs and Data Gaps

Refrigeration plays a major role in the global food system and interacts with a number of technical, environmental, and social factors. The environmental impacts accompanying cold chain expansion into developing countries will stem from the technology's intrinsic properties as well as the accompanying social and behavioral shifts.

While refrigerated supply chains have been robustly explored in the literature from a traditional, technical perspective, environmental effects due to overall infrastructure issues, indirect behavioral effects, and exogenous factors are not well studied. The inclusion of the social, non-technical elements which accompany cold chain expansion is critical to creating informed analyses which provide an accurate picture of the sustainability associated with the explored scenarios.

There is a great deal of feedback between the cold chain and larger global systems which is not typically considered in existing analyses. Refrigeration has a co-developing and co-dependent relationship with infrastructure within a market, corresponding with an area's socio-economic development. The role of behavior is also substantial, with the increased availability of frozen, chilled pre-prepared foods, and out-of-season produce cultivating demand for these products in new markets, which in turn increases the demand for widespread refrigeration in retailing and at home. The effects of changes in food demand are not just limited to the supply chain for goods and consumer behavior, however, as many of these newly-available food products may carry greater environmental burdens than the alternatives they are displacing. Coupling the behavioral and technical elements of this system, while refrigeration may decrease post-harvest food spoilage and losses, household refrigeration and altered buying patterns have the distinct potential to increase consumer-end food waste, leaving an ambiguous change in energy and resource use. Both the technical operation of the cold chain and behavior shifts connect with the larger issue of global climate change, where emissions from refrigeration are also engaged in a feedback loop with ambient temperatures and the global environment.

The cold chain is continually expanding and developing, but there is difficulty in the collection of accurate cold chain data, particularly in the developing world (Yahia, 2010). Given the limitations in available data, the evaluation of the cold chain, particularly studies directly addressing its interaction with dietary shifts, purchasing decisions, and food waste requires continued study and evaluation. Improved data quality and widespread availability is key to supporting useful and insightful studies related to the effects of refrigeration.

The cold chain's development is unlikely to wane, and as such, there is a need for studies which understand the relationships and effects of expanded refrigeration within the global food system.

Refrigeration must be viewed from a larger perspective which includes analysis of social and behavioral shifts, creating a more complete assessment of the system's sustainability impacts.

2.7 References

Aiello, G., La Scalia, G., Micale, R., 2012. Simulation analysis of cold chain performance based on time–temperature data. Prod. Plan. Control 23, 468–476. doi:10.1080/09537287.2011.564219

Akkerman, R., Farahani, P., Grunow, M., 2010. Quality, safety and sustainability in food distribution: A review of quantitative operations management approaches and challenges, OR Spectrum. doi:10.1007/s00291-010-0223-2

Amienyo, D., Gujba, H., Stichnothe, H., Azapagic, A., 2013. Life cycle environmental impacts of carbonated soft drinks. Int. J. Life Cycle Assess. 18, 77–92. doi:10.1007/s11367-012-0459-y

Andersson, K., Ohlsson, T., Olsson, P., 1998. Screening Life Cycle Assessment (LCA) of tomato ketchup: A case study. Doktorsavhandlingar vid Chalmers Tek. Hogsk. 6, 277–288. doi:10.1016/S0959-6526(98)00027-4

Audsley, E., Brander, M., Chatterton, J., Murphy-bokern, D., Webster, C., Williams, A., 2009. How low can we go ? An assessment of greenhouse gas emissions from the UK food system and the scope reduction by 2050, Report for the WWF and Food Climate Research Network; WWF-UK., 2009.

Bansal, P.., Martin, A., 2000. Comparative study of vapour compression, thermoelectric and absorption refrigerators. Int. J. Energy Res. 24, 93–107. doi:10.1016/S0140-6701(00)96814-0

Bansal, P., Vineyard, E., Abdelaziz, O., 2011. Advances in household appliances- A review. Appl. Therm. Eng. 31, 3748–3760. doi:10.1016/j.applthermaleng.2011.07.023

Beccali, M., Cellura, M., Iudicello, M., Mistretta, M., 2009. Resource Consumption and Environmental Impacts of the Agrofood Sector: Life Cycle Assessment of Italian Citrus-Based Products. Environ. Manage. 43, 707–724. doi:10.1007/s00267-008-9251-y

Berlin, J., 2002. Environmental life cycle assessment (LCA) of Swedish semi-hard cheese. Int. Dairy J. 12, 939–953. doi:10.1016/S0958-6946(02)00112-7

Berners-Lee, M., Hoolohan, C., Cammack, H., Hewitt, C.N., 2012. The relative greenhouse gas impacts of realistic dietary choices. Energy Policy 43, 184–190. doi:10.1016/j.enpol.2011.12.054

Bernstad Saraiva Schott, A., Andersson, T., 2015. Food waste minimization from a life-cycle perspective. J. Environ. Manage. 147, 219–226. doi:10.1016/j.jenvman.2014.07.048

Blanke, M.M., Burdick, B., 2005. Food (miles) for Thought: Energy Balance for Locally-Grown versus Imported Apple Fruit. Environ. Sci. Pollut. Res. 12, 125–127. doi:http://dx.doi.org/10.1065/espr2005.05.252

Blengini, G.A., Busto, M., 2009. The life cycle of rice: LCA of alternative agri-food chain management systems in Vercelli (Italy). J. Environ. Manage. 90, 1512–1522.

doi:10.1016/j.jenvman.2008.10.006
Bo, Y., Danyu, L., 2009. Application of RFID in Cold Chain Temperature Monitoring System, in: 2009 Second ISECS International Colloquium on Computing, Communication, Control, and Management. pp. 258–261. doi:10.1109/CCCM.2009.5270408
Bogataj, M., Bogataj, L., Vodopivec, R., 2005. Stability of perishable goods in cold logistic chains. Int. J. Prod. Econ. 93–94, 345–356. doi:10.1016/j.ijpe.2004.06.032
Borch, E., Kant-Muermans, M.L., Blixt, Y., 1996. Bacterial spoilage of meat and cured meat products. Int. J. Food Microbiol. 33, 103–120. doi:10.1016/0168-1605(96)01135-X
Calderón, L.A., Iglesias, L., Laca, A., Herrero, M., Díaz, M., 2010. The utility of Life Cycle Assessment in the ready meal food industry. Resour. Conserv. Recycl. 54, 1196–1207. doi:10.1016/j.resconrec.2010.03.015
Calm, J.M., 2008. The next generation of refrigerants - Historical review, considerations, and outlook. Int. J. Refrig. 31, 1123–1133. doi:10.1016/j.ijrefrig.2008.01.013
Calm, J.M., 2006. Comparative efficiencies and implications for greenhouse gas emissions of chiller refrigerants. Int. J. Refrig. 29, 833–841. doi:10.1016/j.ijrefrig.2005.08.017
Calm, J.M., 2002. Options and outlook for chiller refrigerants. Int. J. Refrig. 25, 705–715. doi:10.1016/S0140-7007(01)00068-8
Carlsson-Kanyama, A., Ekstrom, M.P., Shanahan, H., 2003. Food and life cycle energy inputs: Consequences of diet and ways to increase efficiency. Ecol. Econ. 44, 293–307. doi:10.1016/S0921-8009(02)00261-6
Coley, D., Howard, M., Winter, M., 2009. Local food, food miles and carbon emissions: A comparison of farm shop and mass distribution approaches. Food Policy 34, 150–155. doi:10.1016/j.foodpol.2008.11.001
Coulomb, D, 2008. Refrigeration and cold chain serving the global food industry and creating a better future: two key IIR challenges for improved health and environment. Trends Food Sci. Technol. 19, 413–417. doi:10.1016/j.tifs.2008.03.006
Coulomb, D., 2008. Refrigeration and cold chain serving the global food industry and creating a better future: two key IIR challenges for improved health and environment. Trends Food Sci. Technol. 19, 413–417. doi:10.1016/j.tifs.2008.03.006
Dreyer, L.C., Hauschild, M.Z., Schierbeck, J., 2006. A Framework for Social Life Cycle Impact Assessment. Int. J. Life Cycle Assess. 11, 88–97. doi:10.1065/lca2005.08.223
Edwards-Jones, G., Milà i Canals, L., Hounsome, N., Truninger, M., Koerber, G., Hounsome, B., Cross, P., York, E.H., Hospido, A., Plassmann, K., Harris, I.M., Edwards, R.T., Day, G.A.S., Tomos, A.D., Cowell, S.J., Jones, D.L., 2008. Testing the assertion that “local food is best”: the challenges of an evidence-based approach. Trends Food Sci. Technol. 19, 265–274. doi:10.1016/j.tifs.2008.01.008
Eide, M.H., 2002. Life cycle assessment (LCA) of industrial milk production. Int. J. Life Cycle Assess. 7, 115–126. doi:10.1007/BF02978855

Eriksson, M., Strid, I., Hansson, P.A., 2016. Food waste reduction in supermarkets - Net costs and benefits of reduced storage temperature. Resour. Conserv. Recycl. 107, 73–81. doi:10.1016/j.resconrec.2015.11.022

Evans, J.A., Hammond, E.C., Gigiel, A.J., Fostera, A.M., Reinholdt, L., Fikiin, K., Zilio, C., 2014. Assessment of methods to reduce the energy consumption of food cold stores. Appl. Therm. Eng. 62, 697–705. doi:http://dx.doi.org/10.1016/j.applthermaleng.2013.10.023

Fitzgerald, W.B., Howitt, O.J.. A., Smith, I.J., Hume, A., 2011. Energy use of integral refrigerated containers in maritime transportation. Energy Policy 39, 1885–1896. doi:10.1016/j.enpol.2010.12.015

Flick, D., Hoang, H.M., Alvarez, G., Laguerre, O., 2012. Combined deterministic and stochastic approaches for modeling the evolution of food products along the cold chain. Part I: Methodology. Int. J. Refrig. 35, 907–914. doi:10.1016/j.ijrefrig.2011.12.010

Fu, W., Chang, Y.S., Aung, M.M., Makatsoris, C., Oh, C.H., 2008. Wsn based intelligent cold chain management, in: The 6th International Conference on Manufacturing Research (ICMR08). pp. 353–360.

Garnett, T., 2013. Three perspectives on sustainable food security: efficiency, demand restraint, food system transformation. What role for life cycle assessment? J. Clean. Prod. 73, 10–18. doi:10.1016/j.jclepro.2013.07.045

Garnett, T., 2011. Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? Food Policy 36, S23–S32. doi:10.1016/j.foodpol.2010.10.010

Garnett, T., 2007. Food Refrigeration: What is the Contribution to Greenhouse Gas Emissions and How Might Emissions Be Reduced? Working Paper for the Good Climate Research Network; Food Climate Research Network, Environmental Change Institute, Universit of Oxford: Oxford, U.K., 2007

Garnett, T., Wilkes, A., 2014. Appetite for Change: Social , economic and environmental transformations in China’s food system, Food Climate Research Network. doi:10.1007/s13398-014-0173-7.2

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2012. The Challenge of Food Security. Science (80-.). 327, 812–818. doi:10.4337/9780857939388

Goldman, A., Ramaswami, S., Krider, R.E., 2002. Barriers to the advancement of modern food retail formats: Theory and measurement. J. Retail. 78, 281–295. doi:10.1016/S0022-4359(02)00098-2

González-García, S., Castanheira, É.G., Dias, A.C., Arroja, L., 2013. Environmental life cycle assessment of a dairy product: The yoghurt. Int. J. Life Cycle Assess. 18, 796–811. doi:10.1007/s11367-012-0522-8

Gruber, L.M., Brandstetter, C.P., Bos, U., Lindner, J.P., Albrecht, S., 2016. LCA study of

unconsumed food and the influence of consumer behavior. Int. J. Lif 21, 773–784. doi:10.1007/s11367-015-0933-4
Hall, K.D., Guo, J., Dore, M., Chow, C.C., 2009. The progressive increase of food waste in America and its environmental impact. PLoS One 4, 9–14. doi:10.1371/journal.pone.0007940
Heller, M.C., Keoleian, G. a., 2003a. Assessing the sustainability of the US food system: A life cycle perspective. Agric. Syst. 76, 1007–1041. doi:10.1016/S0308-521X(02)00027-6
Heller, M.C., Keoleian, G.A., 2011. Life Cycle Energy and Greenhouse Gas Analysis of a Large-Scale Vertically Integrated Organic Dairy in the United States. Environ. Sci. Technol. 45, 1903–1910. doi:10.1021/es102794m
Heller, M.C., Keoleian, G.A., 2003b. Assessing the sustainability of the US food system: A life cycle perspective. Agric. Syst. 76, 1007–1041. doi:10.1016/S0308-521X(02)00027-6
Hiç, C., Pradhan, P., Rybski, D., Kropp, J.P., 2016. Food Surplus and its Climate Burdens. Environ. Sci. Technol. under revi. doi:10.1021/acs.est.5b05088
Holtedahl, P., Joutz, F.L., 2004. Residential electricity demand in Taiwan. Energy Econ. 26, 201–224. doi:10.1016/j.eneco.2003.11.001
Hospido, A., Milà I Canals, L., McLaren, S., Truninger, M., Edwards-Jones, G., Clift, R., 2009. The role of seasonality in lettuce consumption: A case study of environmental and social aspects. Int. J. Life Cycle Assess. 14, 381–391. doi:10.1007/s11367-009-0091-7
Hsu, C.-I., Hung, S.-F., 2003. Vehicle Routing Problem for Distributing Refrigerated Food. J. East. Asia Soc. Transp. Stud. 5, 2261–2272.
Hu, D., Reardon, T., Rozelle, S., Timmer, P., Wang, H., 2004. The Emergence of Supermarkets with Chinese Characteristics: Challenges and Opportunities for China's Agricultural Development. Dev. Policy Rev. 22, 557–586. doi:10.1111/j.1467-7679.2004.00265.x
Ingwersen, W.W., 2012. Life cycle assessment of fresh pineapple from Costa Rica. J. Clean. Prod. 35, 152–163. doi:10.1016/j.jclepro.2012.05.035
Iribarren, D., Hospido, A., Moreira, M.T., Feijoo, G., 2010. Carbon footprint of canned mussels from a business-to-consumer approach. A starting point for mussel processors and policy makers. Environ. Sci. Policy 13, 509–521. doi:10.1016/j.envsci.2010.05.003
James, S.J., James, C., 2010. The food cold-chain and climate change. Food Res. Int. 43, 1944–1956. doi:10.1016/j.foodres.2010.02.001
James, S.J., James, C., Evans, J. a., 2006. Modelling of food transportation systems – a review. Int. J. Refrig. 29, 947–957. doi:10.1016/j.ijrefrig.2006.03.017
Jannuzzi, G.D.M., Schipper, L., 1991. The structure of electricity demand in the Brazilian household sector. Energy Policy 19, 879–891. doi:10.1016/0301-4215(91)90013-E
Jin, S.-H., 2007. The effectiveness of energy efficiency improvement in a developing country: Rebound effect of residential electricity use in South Korea. Energy Policy 35, 5622–5629. doi:10.1016/j.enpol.2007.05.028

Johnson, E., 1998. Global warming from HFC. Environ. Impact Assess. Rev. 18, 485–492. doi:10.1016/S0195-9255(98)00020-1
Jørgensen, A., 2013. Social LCA - A way ahead? Int. J. Life Cycle Assess. 18, 296–299. doi:10.1007/s11367-012-0517-5
Joshi, R., Banwet, D.K., Shankar, R., 2009. Indian cold chain: modeling the inhibitors. Br. Food J. 111, 1260–1283. doi:10.1108/00070700911001077
Jul, M., 1985. Refrigeration and world food requirements. Rev. Int. du Froid 8, 6–12.
Kahn, B.E., Wansink, B., 2004. The Influence of Assortment Structure on Perceived Variety and Consumption Quantities. J. Consum. Res. 30, 519–533. doi:10.1086/380286
Kim, H.C., Keoleian, G.A., Horie, Y.A., 2006. Optimal household refrigerator replacement policy for life cycle energy, greenhouse gas emissions, and cost. Energy Policy 34, 2310–2323. doi:10.1016/j.enpol.2005.04.004
Ligon, V.K., 2014. Shop More, Buy Less: A Qualitative Investigation into Consumer Decisions that Lead to Food Waste in U.S. Households. The University of Arizona.
Likar, K., Jevšnik, M., 2006. Cold chain maintaining in food trade. Food Control 17, 108–113. doi:10.1016/j.foodcont.2004.09.009
Liu, J., Lundqvist, J., Weinberg, J., Gustafsson, J., 2013. Food losses and waste in china and their implication for water and land. Environ. Sci. Technol. 47, 10137–10144. doi:10.1021/es401426b
Ma, H., Huang, J., Fuller, F., Rozelle, S., 2006. Getting Rich and Eating Out: Consumption of Food Away from Home in Urban China. Can. J. Agric. Econ. Can. d'agroeconomie 54, 101–119. doi:10.1111/j.1744
Mahlia, T.M.I., Masjuki, H.H., Saidur, R., Amalina, M.A., 2004. Cost–benefit analysis of implementing minimum energy efficiency standards for household refrigerator-freezers in Malaysia. Energy Policy 32, 1819–1824. doi:10.1016/S0301-4215(03)00169-1
Mallik, S., Mandal, P.K., Chatterjee, C., Ghosh, P., Manna, N., Chakrabarty, D., Bagchi, S.N., Dasgupta, S., 2011. Assessing cold chain status in a metro city of India: an intervention study. Afr. Health Sci. 11, 128–133.
Markets and Markets, 2015. Cold Chain Market worth 234.49 Billion USD by 2020 [WWW Document]. URL http://www.marketsandmarkets.com/PressReleases/cold-chain.asp
Marsh, K., Bugusu, B., 2007. Food Packaging - Roles, Materials, and Environmental Issues. J. Food Sci. 72. doi:10.1111/j.1750-3841.2007.00301.x
McMullan, J.T., 2002. Refrigeration and the environment - issues and strategies for the future. Int. J. Refrig. 25, 89–99. doi:10.1016/S0140-7007(01)00007-X
Messineo, A., Panno, G., 2011. LNG cold energy use in agro-food industry: A case study in Sicily. J. Nat. Gas Sci. Eng. 3, 356–363. doi:10.1016/j.jngse.2011.02.002
Miettinen, P., Hamalainen, R.P., 1997. How to benefit from decision analysis in environmental life cycle assessment (LCA). Eur. J. Oper. Res. 102, 279–294.

Miller, S.A., Keoleian, G.A., 2015. Framework for Analyzing Transformative Technologies in Life Cycle Assessment. Environ. Sci. Technol. 49, 3067–3075. doi:10.1021/es505217a

Mogensen, L., Hermansen, J.E., Halberg, N., Dalgaard, R., 2009. Life Cycle Assessment across the Food Supply Chain, in: Baldwin, C.J. (Ed.), Sustainability in the Food Industry. Wiley-Blackwell, pp. 115–144. doi:10.1002/9781118467589.ch5

Montanari, R., 2008. Cold chain tracking: a managerial perspective. Trends Food Sci. Technol. 19, 425–431. doi:10.1016/j.tifs.2008.03.009

Nadel, S., 2002. Applicance and Equipment Efficiency Standards. Annu. Rev. Energy Environ. 27, 159–192. doi:10.1146/annurev.energy.27.122001.083452

Nelson, D.J., 2008. Residential Baseload Energy Use: Concept and Potential for AMI Customers, in: Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings. pp. 233–245.

Ovca, A., Jevšnik, M., 2009a. Maintaining a cold chain from purchase to the home and at home: Consumer opinions. Food Control 20, 167–172. doi:10.1016/j.foodcont.2008.03.010

Ovca, A., Jevšnik, M., 2009b. Maintaining a cold chain from purchase to the home and at home: Consumer opinions. Food Control 20, 167–172. doi:10.1016/j.foodcont.2008.03.010

Parfitt, J., Barthel, M., Macnaughton, S., 2010. Food waste within food supply chains: quantification and potential for change to 2050. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 365, 3065–81. doi:10.1098/rstb.2010.0126

Parkpoom, S., Harrison, G.P., Bialek, J.W., 2004. Climate change impacts on electricity demand. 39th Int. Univ. Power Eng. Conf. 2004. UPEC 2004. 3, 1342–1346. doi:10.1109/UPEC.2004.192393

Patsias, A., Chouliara, I., Badeka, A., Savvaidis, I.N., Kontominas, M.G., 2006. Shelf-life of a chilled precooked chicken product stored in air and under modified atmospheres: Microbiological, chemical, sensory attributes. Food Microbiol. 23, 423–429. doi:10.1016/j.fm.2005.08.004

Peters, G.M., Rowley, H. V., Wiedemann, S., Tucker, R., Short, M.D., Schulz, M., 2010. Red Meat Production in Australia: Life Cycle Assessment and Comparison with Overseas Studies. Environ. Sci. Technol. 44, 1327–1332. doi:10.1021/es901131e

Point, E., Tyedmers, P., Naugler, C., 2012. Life cycle environmental impacts of wine production and consumption in Nova Scotia, Canada. J. Clean. Prod. 27, 11–20. doi:10.1016/j.jclepro.2011.12.035

Reardon, T., Timmer, P., Berdegue, J., 2004. The Rapid Rise of Supermarkets in Developing Countries: Induced Organizational, Institutional, and Technological Change in Agrifood Systems. Electron. J. Agric. Dev. Econ. 1, 168–183.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S., Weidema, B.P., Pennington, D.W., 2004. Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications. Environ. Int. 30, 701–720.

doi:http://dx.doi.org/10.1016/j.envint.2003.11.005
Reid, M.S., Jiang, C.Z., 2005. New strategies in transportation for floricultural crops, in: 5th International Postharvest Symposium. pp. 1667–1674.
Rivera, X.C.S., Orias, N.E., Azapagic, A., 2014. Life cycle environmental impacts of convenience food : Comparison of ready and home-made meals. J. Clean. Prod. 73, 294–309. doi:10.1016/j.jclepro.2014.01.008
Roy, P., Nei, D., Okadome, H., Nakamura, N., Orikasa, T., Shiina, T., 2008. Life cycle inventory analysis of fresh tomato distribution systems in Japan considering the quality aspect. J. Food Eng. 86, 225–233. doi:10.1016/j.jfoodeng.2007.09.033
Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N., Shiina, T., 2009. A review of life cycle assessment (LCA) on some food products. J. Food Eng. 90, 1–10. doi:10.1016/j.jfoodeng.2008.06.016
Ruiz-Garcia, L., Barreiro, P., Robla, J.I., 2008. Performance of ZigBee-Based wireless sensor nodes for real-time monitoring of fruit logistics. J. Food Eng. 87, 405–415. doi:10.1016/j.jfoodeng.2007.12.033
Salin, V., Nayga Jr., R.M., 2003. A cold chain network for food exports to developing countries. Int. J. Phys. Distrib. Logist. Manag. 33, 918–933. doi:10.1108/09600030310508717
Saunders, C., Barber, a., 2008. Carbon Footprints, Life Cycle Analysis, Food Miles: Global Trade Trends and Market Issues. Polit. Sci. 60, 73–88. doi:10.1177/003231870806000107
Schau, E.M., Fet, A.M., 2008. LCA studies of food products as background for environmental product declarations. Int. J. Life Cycle Assess. 13, 255–264. doi:10.1065/lca2007.12.372
Schmidt, J.H., 2008. System delimitation in agricultural consequential LCA: Outline of methodology and illustrative case study of wheat in Denmark. Int. J. Life Cycle Assess. 13, 350–364. doi:10.1007/s11367-008-0016-x
Shabani, A., Saen, R.F., Torabipour, S.M.R., 2012. A new benchmarking approach in Cold Chain. Appl. Math. Model. 36, 212–224. doi:10.1016/j.apm.2011.05.051
Stadler, M., Krause, W., Sonnenschein, M., Vogel, U., 2009. Modelling and evaluation of control schemes for enhancing load shift of electricity demand for cooling devices. Environ. Model. Softw. 24, 285–295. doi:10.1016/j.envsoft.2008.07.003
Stassen, R.E., Mittelstaedt, J.D., Mittelstaedt, R. a., 1999. Assortment Overlap: Its Effect on Shopping Patterns in a Retail Market When the Distributions of Prices and Goods are Known. J. Retail. 75, 371–386. doi:10.1016/S0022-4359(99)00013-5
Tao, J., Yu, S., 2011. Implementation of energy efficiency standards of household refrigerator/freezer in China: Potential environmental and economic impacts. Appl. Energy 88, 1890–1905. doi:10.1016/j.apenergy.2010.11.015
Tassou, S.A., De-Lille, G., Ge, Y.T., 2009. Food transport refrigeration – Approaches to reduce energy consumption and environmental impacts of road transport. Appl. Therm. Eng. 29, 1467–1477. doi:10.1016/j.applthermaleng.2008.06.027

Tassou, S.A., Ge, Y., Hadawey, A., Marriott, D., 2011. Energy consumption and conservation in food retailing. Appl. Therm. Eng. 31, 147–156. doi:10.1016/j.applthermaleng.2010.08.023

Tassou, S. A., Ge, Y., Hadawey, A., Marriott, D., 2011. Energy Consumption And Conservation In Food Retailing. Appl. Therm. Eng. 31, 147–156. doi:10.1016/j.applthermaleng.2010.08.023

Thoma, G., Popp, J., Nutter, D., Shonnard, D., Ulrich, R., Matlock, M., Kim, D.S., Neiderman, Z., Kemper, N., East, C., Adom, F., 2013. Greenhouse gas emissions from milk production and consumption in the United States: A cradle-to-grave life cycle assessment circa 2008. Int. Dairy J. 31, S3–S14. doi:10.1016/j.idairyj.2012.08.013

Tillman, A.M., 2000. Significance of decision-making for LCA methodology. Environ. Impact Assess. Rev. 20, 113–123. doi:10.1016/S0195-9255(99)00035-9

Tingman, W., Jian, Z., Xiaoshuan, Z., 2010. Fish product quality evaluation based on temperature monitoring in cold chain. African J. Biotechnol. 9, 6146–6151. doi:10.5897/AJB09.1344

Van Buskirk, R., Hagan, E. Ben, Ahenkorah, A.O., McNeil, M.A., 2007. Refrigerator efficiency in Ghana: Tailoring an appliance market transformation program design for Africa. Energy Policy 35, 2401–2411. doi:10.1016/j.enpol.2006.08.017

Vanek, F., Sun, Y., 2008. Transportation versus perishability in life cycle energy consumption: A case study of the temperature-controlled food product supply chain. Transp. Res. Part D Transp. Environ. 13, 383–391. doi:10.1016/j.trd.2008.07.001

Venkat, K., 2011. The Climate Change and Economic Impacts of Food Waste in the United States. Int. J. Food Syst. Dyn. 2, 431–446.

Verbi, M., 2004. Econometric Estimation of Parameters of Preservation of Perishable Goods in Cold Logistic CHains.

Vigneault, C., Thompson, J., Wu, S., Hui, K.P.C., Leblanc, D.I., 2009. Transportation of fresh horticultural produce. Postharvest Technol. Hortic. Crop. 2, 1–24.

Wang, L., Zhang, Z.Y., 2008. A Research on Related Questions of Chinese Food Cold Chain Development, in: International Conference on Management of E-Commerce and e-Government. pp. 18–21. doi:10.1109/ICMECG.2008.76

Weatherspoon, D.D., Reardon, T., 2003. The Rise of Supermarkets in Africa: Implications for Agrifood Systems and the Rural Poor. Dev. Policy Rev. 21, 1–17. doi:10.1111/1467-7679.00214

Weber, C.L., Matthews, H.S., 2008. Food-Miles and the Relative Climate Impacts of Food Choices in the United States. Environ. Sci. Technol. 42, 3508–3513. doi:10.1021/es702969f

Weidema, B.P., 2005. ISO 14044 also Applies to Social LCA. Int. J. Life Cycle Assess. 10, 381–381. doi:10.1065/lca2005.11.002

Wikström, F., Williams, H., Verghese, K., Clune, S., 2014. The influence of packaging attributes on consumer behaviour in food-packaging life cycle assessment studies - a neglected topic.

J. Clean. Prod. 73, 100–108. doi:10.1016/j.jclepro.2013.10.042
Williams, H., Wikström, F., 2011. Environmental impact of packaging and food losses in a life cycle perspective: A comparative analysis of five food items. J. Clean. Prod. 19, 43–48. doi:10.1016/j.jclepro.2010.08.008
Xu, L., Wu, L., 2010. Food safety and consumer willingness to pay for certified traceable food in China. J. Sci. Food Agric. 90, 1368–1373. doi:10.1002/jsfa.3985
Yahia, E.M., 2010. Cold Chain Development and Challenges in the Developing World, in: Erkan, M., Aksoy, U. (Eds.), 6th International Postharvest Symposium. pp. 127–132.
Zanoni, S., Zavanella, L., 2012. Chilled or frozen? Decision strategies for sustainable food supply chains. Int. J. Prod. Econ. 140, 731–736. doi:10.1016/j.ijpe.2011.04.028
Zhang, Q.F., Pan, Z., 2013. The Transformation of Urban Vegetable Retail in China: Wet Markets, Supermarkets and Informal Markets in Shanghai. J. Contemp. Asia 43, 497–518. doi:10.1080/00472336.2013.782224
Zhou, G., Zhang, W., Xu, X., 2012. China's meat industry revolution: Challenges and opportunities for the future. Meat Sci. 92, 188–196. doi:10.1016/j.meatsci.2012.04.016
Zhu, X., van Ierland, E.C., n.d. Protein Chains and Environmental Pressures: A Comparison of Pork and Novel Protein Foods. Environ. Sci. 1, 254–276. doi:10.1080/15693430412331291652
Ziegler, F., Nilsson, P., Mattsson, B., Walther, Y., 2003. Life Cycle Assessment of Frozen Cod Fillets Including Fishery-Specific Environmental Impacts. Int. J. Life Cycle Assess. 8, 39–47. doi:10.1007/BF02978747
Zufia, J., Arana, L., 2008. Life cycle assessment to eco-design food products: industrial cooked dish case study. J. Clean. Prod. 16, 1915–1921. doi:10.1016/j.jclepro.2008.01.010

Chapter 3

Potential Changes in Greenhouse Gas Emissions from Refrigerated Supply Chain Introduction in a Developing Food System

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Abstract

Refrigeration transforms developing food systems, changing the dynamics of production and consumption. This study models the introduction of an integrated refrigerated supply chain, or "cold chain," into Sub-Saharan Africa and estimates changes in pre-retail greenhouse gas (GHG) emissions if the cold chain develops similarly to North America or Europe. Refrigeration presents an important and understudied trade-off: the ability to reduce food losses and their associated environmental impacts, but increasing energy use and creating GHG emissions. It is

estimated that postharvest emissions added from cold chain operation are larger than food loss emissions avoided, by 10% in the North American scenario and 2% in the European scenario.

The cold chain also enables changes in agricultural production and diets. Connected agricultural production changes decrease emissions, while dietary shifts facilitated by refrigeration may increase emissions. These system-wide changes brought about by the cold chain may increase the embodied emissions of food supplied to retail by 10% or decrease them by 15%, depending on the scenario.

3. 1 Cold Chain Introduction and the Food Supply Chain

This study explores the inherent trade-off of reducing food losses and their associated embodied greenhouse gas (GHG) emissions by deploying refrigeration, a technology that increases GHG emissions through energy consumption and refrigerant emissions. This analysis first examines only the direct postharvest trade-offs between increased energy and refrigerant emissions compared to the GHG savings of reduced food loss. This study then takes a broader systems-level examination of the potential impacts of introduced refrigeration, including anticipated impacts on agricultural production with development and dietary shifts brought about by improved access to perishable foods.

An integrated refrigerated supply chain, or “cold chain,” can provide benefits for community health, nutrition, and food security (Aung and Chang, 2014; Sahin et al., 2007). Refrigeration increases access to perishable foods, extends the shelf-life of food, and has the potential to reduce food losses.(Garnett, 2007; Kitinoja, 2013) Access to refrigeration is associated with improved health outcomes, including reduced risk of foodborne illness (Garnett, 2007) and improved capacity to store antibiotics and vaccines (Zhang et al., 2012). The cold chain has critical connections to the Sustainable Development Goals, with target 12.3 seeking a reduction in food loss and waste along the food supply chain (Food and Agriculture Organization of the United Nations, 2016), and Goal 2 seeking to improve food security and nutrition (United Nations, 2015). The global cold chain market was valued at $203.14 billion USD in 2018 and is expected to grow 7.6% per year, driven by increased demand in emerging markets (Markets and Markets, 2015).

Despite these benefits, refrigeration is energy-intensive and often uses refrigerants with high global warming potentials (Heard and Miller, 2016). When accounting only for direct energy use and refrigerant leakage, refrigeration is responsible for approximately 1% of the world's total carbon dioxide emissions (S.J. James and James, 2010), and can represent 3-3.5% of GHG emissions in developed economies such as the UK (Garnett, 2007). In addition to energy use and emissions, refrigeration facilitates increased consumption of more-perishable foods, which tend to be more environmentally-intensive (Garnett, 2007). Consumer demand for food determines the agricultural production systems required to provide the types and quantities of food demanded. Agricultural industrialization may not initially seem to be a result of the cold chain;

however, particularly for perishable goods, cold storage enables more industrialized systems since it expands distribution capacity, facilitating larger production.

Food loss and waste is an environmental, economic, and social loss (Food and Agriculture Organization of the United Nations, 2017, 2013; Papargyropoulou et al., 2014; World Resources Institute, 2016). Additionally, food losses that occur further along the supply chain are more carbon-intense due to additional embodied energy (Food and Agriculture Organization of the United Nations, 2011). Approximately one-third of all food produced for human consumption is lost or wasted (Gustavsson et al., 2011), and reducing food losses and waste has been identified as a key goal in improving food security (Food and Agriculture Organization of the United Nations, 2013; Hiç et al., 2016; Papargyropoulou et al., 2014; Porter et al., 2016; United States Agency for International Development, 2016; World Resources Institute, 2016). The cold chain has been identified as a key means for reducing food loss and waste, providing savings in embodied GHG emissions (Carrier Transicold, 2016; Food and Agriculture Organization of the United Nations, 2017; Global Food Cold Chain Council and BIO Intelligence Service, 2015; Kitinoja, 2013). Therefore, it becomes crucial to first develop a better understanding of whether the emissions savings from reduced food loss are offset by increased emissions from the cold chain and determine potential improvements to reduce cold chain impacts while maintaining these societal benefits.

The cold chain is a transformative technology which influences, co-develops, and interacts with a number of food system properties ranging from consumer behavior to upstream production methods (Heard and Miller, 2016). The cold chain fundamentally changes markets and supply chains, necessitating consideration of not only direct, but also indirect and external factors associated with this technology when modeling its environmental impacts (Heard and Miller, 2016; Miller and Keoleian, 2015). Parfitt et al. characterize the level of postharvest infrastructure and supply chain technology as it directly relates to the overall development of a country, explicitly noting the presence of the cold chain as a hallmark of industrialized countries with advanced food system infrastructure (Parfitt et al., 2010). Garnett describes cold chain technologies as ubiquitous for a modern food system, embedded in every stage of a product's life cycle (Garnett, 2007). It has also been noted that supply chains for several goods are now based on the ability to supply chilled or frozen products (Zanoni and Zavanella, 2012). As such, cold chain introduction is fundamental to food system development.

3.2 Study Overview

This study examines the extent to which the cold chain may increase or decrease net GHG emissions when introduced into a developing food system.

Academic study of the cold chain has been limited and fragmented, with few connections between the technical research on refrigeration technologies and the broader food systems literature, presenting notable research gaps (Heard and Miller, 2016). (S. J. James and James, 2010) present a valuable analysis of the cold chain's relationship to climate change, detailing mechanisms through which these emissions could be reduced, but warning of potential emissions increases should a rise in ambient temperatures from climate change occur. Garnett discusses refrigeration from a food systems perspective in a comprehensive working paper, summarizing the literature on the environmental impacts of refrigeration systems, and also discussing how refrigeration may prompt dietary shifts and consumer behavior changes (Garnett, 2007).

This study first examines a fundamental trade-off of refrigeration: the ability to reduce food losses which carry embodied emissions, but increasing energy use and GHG emissions to do so. The study assesses whether the cold chain adds more emissions per food type supplied to retail than it saves through avoided losses with its introduction. Once the direct trade-offs are evaluated, a broader system view is taken, first estimating changes in emissions required to supply each food type to retail due to improved efficiencies in agricultural production occurring with development, then estimating potential emissions changes from dietary shifts enabled by refrigeration.

Greenhouse gas emissions (in CO_2e) are estimated for one kg of food supplied to retail for seven food categories: cereals, roots and tubers, fruits, vegetables, meat, fish and seafood, and milk. Additional important impacts associated with agriculture, including blue water consumption, land use change, nutrient runoff, and biodiversity effects are not included due to a lack of data. The food supply chain (FSC) is defined as a linear model of mass flow with five stages in accordance with (Gustavsson et al., 2011) three of which occur upstream (prior to retail). This analysis defines food loss as edible food at one stage of the FSC that is not supplied to the next stage of the FSC, corresponding with common use in the literature (Gustavsson et al., 2011; Parfitt et al., 2010). The boundary of this study is the upstream, pre-retail portion of the FSC. Therefore, total food loss reported throughout this analysis is edible food not successfully supplied to retail. The functional unit considered is 1 kg of food reflecting a representative diet comprised of the seven food types studied. A visual depiction of food mass in the model FSC is displayed in Figure 3.1.

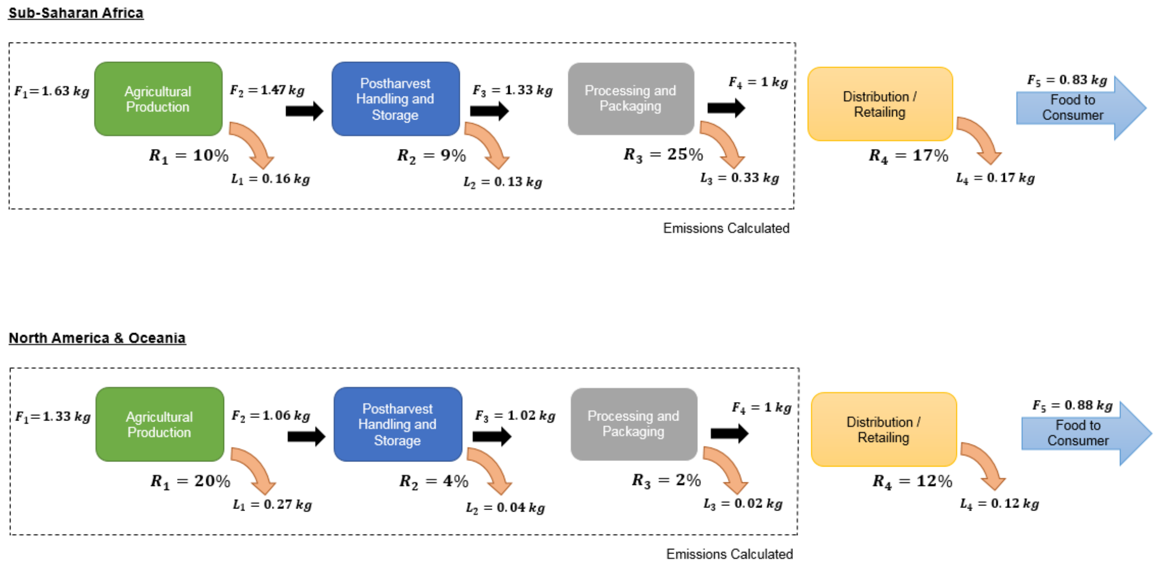


Figure 3.1: Visual representations of mass flows for food (F), loss rates (R), and losses (L) in the upstream food supply chain to supply 1 kg of food to retail. R values are loss rates in each FSC stage for fruits and vegetables for Sub-Saharan Africa (top) and North America & Oceania (bottom) from Gustavsson et al.(Gustavsson et al., 2011) Each food type has unique food loss rates at each stage; the values for fruits and vegetables are shown here as an example. Emissions in this study are calculated for the pre-retail portion of the FSC due to data constraints and the role of consumer behavior and retailing heterogeneity in the downstream FSC. Further description of the study boundary and these terms available in Methods.

The Sub-Saharan African (SSA) food system is the baseline for this model. Sub-Saharan Africa is an ideal case to examine potential cold chain deployment as it has some of the highest upstream loss rates for food (Gustavsson et al., 2011), and is characterized by a lack of current cold chain infrastructure. The United States was estimated to have 0.37 cubic meters of refrigerated storage per capita in 2014, compared to estimates of 0.015 cubic meters per capita in urban areas of South Africa in 2008, and estimates of 0.002 cubic meters per capita in urban areas of Ethiopia and the United Republic of Tanzania, and 0.0051 cubic meters per capita in urban areas of Namibia in 2012 (AGRO Merchants Group, 2018; Food and Agriculture Organization of the United Nations; International Institute of Refrigeration, 2016) (see Appendix A.1).

Two scenarios of cold chain introduction and food system development are considered: one that substitutes North American (NA) parameters into the model, and one that substitutes European (Eur.) parameters. Modeling a transition from the Sub-Saharan African food system to one with North American or European properties is the closest to a total ("zero-to-one") introduction of the cold chain as can be examined with available data. The results of this modeling provide insights into the direct and indirect emissions effects associated with the cold chain as have currently been realized in development.

As seen in the comparison of fruit and vegetable loss rates between Sub-Saharan Africa and North America & Oceania in Figure 3.1, a greater quantity of food needs to be produced in Sub-Saharan Africa to supply a similar amount of food to retail, attributable to more-developed food supply chains. Agricultural losses tend to be higher in North America & Oceania due to increased grading from higher quality standards set by retailers (Gustavsson et al., 2011). These changes in grading standards are an example of how FSC development may influence consumer and retailer preferences, affecting the efficiency and environmental impacts of food supply chains. In Sub-Saharan Africa, the larger share of losses occurring after agricultural production are attributed to crop deterioration from climate exposure as well as crop gluts from the seasonality of production (Gustavsson et al., 2011).

Four parameters are integral to modeling the FSC for each system: loss rates (% of food loss at FSC stages), demand (kg type consumed per capita), agricultural emissions factors (kg CO_2e/kg food), and cold chain emissions factors (kg CO_2e/kg food). The relationship between these parameters and specific calculations conducted are detailed in the Methods section. Due to the fairly-sparse and non-standardized nature of data on food and its environmental impacts, data sources were harmonized to the extent possible. Harmonization choices are detailed in Appendix A.2.

3.3 Methods

The changes in food supplied and the emissions associated with cold chain introduction are determined by adjusting loss rates (R_1, R_2, R_3, R_4), demand (F_5), agricultural emissions factors (E_A), and cold chain emissions factors (E_c). $F_{1\text{-}4}$ are determined by the mass balance equations below. Emissions factors characterize food (and food losses) which enter a stage and are subject to its emissions-contributing processes. Emissions are calculated for the pre-retail portion of the FSC, though demand is defined at the consumer level due to data constraints, and back-calculated using loss rates for the entire FSC. These parameters are drawn from the Monte Carlo distribution types described, with specific parameter described in Appendix A.3. Parameter distributions are assumed to be independent and 10,000 Monte Carlo simulations are run to produce this study's results. Sensitivity analysis for these parameters is detailed in Appendix A.4.

There are five stages of the food supply chain corresponding to Gustavsson et al.(Gustavsson et al., 2011): 1. Agricultural Production, 2. Postharvest Handling and Storage, 3. Processing and Packaging, 4. Distribution/Retail, and 5. Consumption, where stages 1-3 are considered to be "upstream" and 4-5 are "downstream." This analysis only examines emissions for the upstream supply chain. Values of variables which correspond to one of these stages are indicated with numerical subscripts (e.g. a subscript of "2" for a Postharvest Handling and Storage value).

Every parameter is defined for each of the seven food types studied: Cereals, Roots and Tubers, Fruits, Vegetables, Meat, Fish and Seafood, and Milk. Therefore, each model parameter has a value associated with the seven food types (*x*) and three study regions (*y*). For example, $R_{1,v,SSA}$ denotes the loss rate of vegetables between Agricultural Production and Postharvest Handling and Storage in SSA.

As depicted in Figure 1, the food present at each section of the supply chain can be represented by:

$$F = \{F_{1,x,y}, F_{2,x,y}, F_{3,x,y}, F_{4x,y}. F_{5,x,y}\}$$

Where F_n represents mass (kg) of each food type at each stage of the region's FSC, *x* denotes the food type, and *y* denotes the study region. F_5 is defined from a truncated normal distribution (lower bound of zero) defined with "food" values for each region and type from the 2013 FAOSTAT Food Balance Sheets,(Food and Agriculture Organization of the United Nations, n.d.) capturing the food available for human consumption in each region within a given year.

Between each stage of the FSC is a loss rate:

$$R = \{R_{1,x,y}, R_{2,x,y}, R_{3,x,y}, R_{4,x,y}\}$$

Where R_n represents the percentage of food lost (% of kg) between FSC_n and FSC_{n+1} for each of the seven food types (*x*) in each region (*y*). Loss rates calculated by Gustavsson et al.(Gustavsson et al., 2011) are used to define triangular Monte Carlo distributions for this parameter for each food type and region, with specific values provided in Appendix A.3.

The food loss for each type and region in each stage is defined as $L_{n,x,y}$ (kg food) and can be calculated as:

Eqn. 1

$$L_{n,x,y} = F_{n,x,y} * R_{n,x,y}$$

The mass balance of the system can be represented as:

Eqn 2.

$$F_{5,x,y} = [\{[F_{1,x,y} * (1 - R_{1,x,y})] * (1 - R_{2,x,y})\} * (1 - R_{3,x,y})] * (1 - R_{4,x,y})$$

Beginning with values obtained from FAOSTAT and using mass balance, the food available at each upstream FSC stage can be computed by:

Eqn. 3

$$F_{n-1,x,y} = \frac{F_{n,x,y}}{(1 - R_{n-1,x,y})}$$

Direct Trade-Off between Food Savings and Cold Chain Emissions

This analysis first evaluates the direct trade-off of additional cold chain emissions with potential savings in food loss throughout the upstream food supply chain. The direct trade-off calculation does not take into account any indirect behavioral or system-wide changes. As such, it calculates the potential differences in the system before and after cold chain introduction by holding all elements of the baseline SSA model constant, with the exception of the portions of the FSC where the cold chain is introduced and induces changes in the food loss rates (R_2, R_3) and cold chain emissions factors (E_c), as detailed in Equations 4-6. The cold chain co-develops and is integrated with related post-harvest storage, processing, transportation, and spoilage-reducing supply chain properties.(Garnett, 2007b; Heard and Miller, 2016; Parfitt et al., 2010; Yahia, 2010) As a result, some GHG emissions and changes in loss rates attributed to the cold chain are not directly due to refrigeration, but cannot be distinguished or separated from those which are in the data.

Eqn. 4 computes GHG emissions added through cold chain operation when changed to the North American parameters. A similar equation is used to calculate the European scenario.

Eqn. 4

$$E_{\Delta C} = E_{C,x,NA}\left(\frac{F_{4,x,NA} + L_{2,x,NA} + L_{3,x,NA}}{F_{4,x,NA}}\right) - E_{C,x,SSA}\left(\frac{F_{4,x,SSA} + L_{2,x,SSA} + L_{3,x,SSA}}{F_{4,x,SSA}}\right)$$

Where $E_{\Delta C}$ is the change in GHG emissions (kg CO_2e/kg food) added to the upstream FSC from cold chain operation. Since the baseline models a food system with negligible cold chain infrastructure, $E_{c,SSA}$ is assumed to be zero.

L_1 is not included in Eqn 4 since it pertains to losses from agriculture and is not exposed to the cold chain. Cold chain emissions (kg CO_2e/kg food) by food type are drawn from lognormal distributions, with parameters compiled from averages by food type using studies from Porter et al.'s meta-analysis(Porter et al., 2016) which contained sufficient post-farm gate data on emissions from the cold chain.

Eqn. 5 calculates the difference in postharvest food loss emissions from cold chain introduction for the North America scenario, with a similar calculation performed for the European scenario.

Eqn. 5

$$\mathrm{E}_{\Delta \mathrm{L,x}} = E_{A,x,SSA}\left[\left(\frac{F_{4,x,SSA} + L_{2,x,SSA} + L_{3,x,SSA}}{F_{4x,SSA}}\right) - \left(\frac{F_{4,x,NA} + L_{2,x,NA} + L_{3,x,NA}}{F_{4x,NA}}\right)\right]$$

Where $E_{\Delta L,x}$ is the change in GHG emissions (kg CO_2e/kg) from changes in food loss emissions associated with cold chain introduction. Because the analysis only includes food loss emissions directly resulting from cold chain introduction, which occurs after agricultural production losses occur, the values associated with R_1 (and subsequent calculation of L_1) do not change.

The $E_{A,x}$ values used in the analysis are weighted averages of agricultural production emissions (kg CO_2e/kg food) by food type with a cradle-to-farm gate boundary. Values are drawn from lognormal distributions with parameters defined from a meta-analysis of life cycle assessments by Porter et al.(Porter et al., 2016) These values include any environmental burdens prior to food leaving its place of agricultural production.

The net emissions change comparing cold chain emissions and food loss emissions is shown as Eqn. 6.

Eqn. 6

$$E_D = \mathrm{E}_{\Delta C} - \mathrm{E}_{\Delta L}$$

Induced System-Wide Changes

Once the direct cold chain trade-off is calculated, this analysis estimates potential system-wide shifts associated with cold chain introduction, including changes to agricultural production and shifts in dietary patterns.

Introduction of the cold chain has the potential to change system logistics and expand agricultural distribution, making the parameters governing the SSA baseline case more similar to agricultural systems in either North America or Europe. To model this, R_1, L_1 and E_A, which were held constant when estimating direct trade-offs, are now assumed to change in addition to the direct trade-offs calculated in Eqns 4-6.

Changes in diet are considered as part of the system-wide changes induced from the cold chain. Food supplied to retail is normalized to one kilogram of a representative diet, where each fraction corresponds to the fraction of each food type in the diet examined.

Per-capita demand is calculated for each region as:

Eqn. 7

$$C_{x,y} = \frac{F_{5,x,y}}{P_y}$$

Where $C_{x,y}$ is the per-capita food consumption of a food type *x* in region *y*

And P_y is the population for the region.

The shift toward diets similar to Europe and North America is then calculated as shown in Eqn 8.

Eqn. 8

$$F_{5,x,y} = F_{5,x,SSA} * \frac{C_{x,y}}{C_{x,SSA}}$$

Food supply emissions are calculated in Equation 9, both when diet has been held constant and when it has been shifted.

Eqn. 9

$$\mathrm{E_P} = E_{A,x,y}\left[\left(\frac{F_{2,x,y} + L_{1,x,y}}{\sum_{x=1}^{7} F_{4,x,y}}\right) + E_{C,x,y}\left(\frac{F_{4,x,y} + L_{2,x,y} + L_{3,x,y}}{\sum_{x=1}^{7} F_{4,x,y}}\right)\right]$$

3.4 Results

3.4.1 Trade-Off Between Added Emissions and Avoided Food Losses in the Cold Chain

A fundamental question for refrigerated supply chain sustainability is whether the increased emissions from cold chain operation will eclipse the avoided emissions from reduced food spoilage. Equations 4-6 are used to calculate this trade-off and the results are depicted in Figures 3.2 and 3.3.

In total, the cold chain is found to add more emissions than it saves through avoided food losses. Without taking into account any other changes to the system, introducing refrigeration to Sub-Saharan Africa would increase net food-related GHG emissions by 10% from the baseline in the North American scenario and 2% in the European scenario, despite reducing postharvest food loss quantities by 23% in both scenarios. The difference in these emissions increases is due to the recorded North American cold chain emissions being larger than those for Europe for 5 out of 7 food types, while avoided food loss emissions are similar for both scenarios.

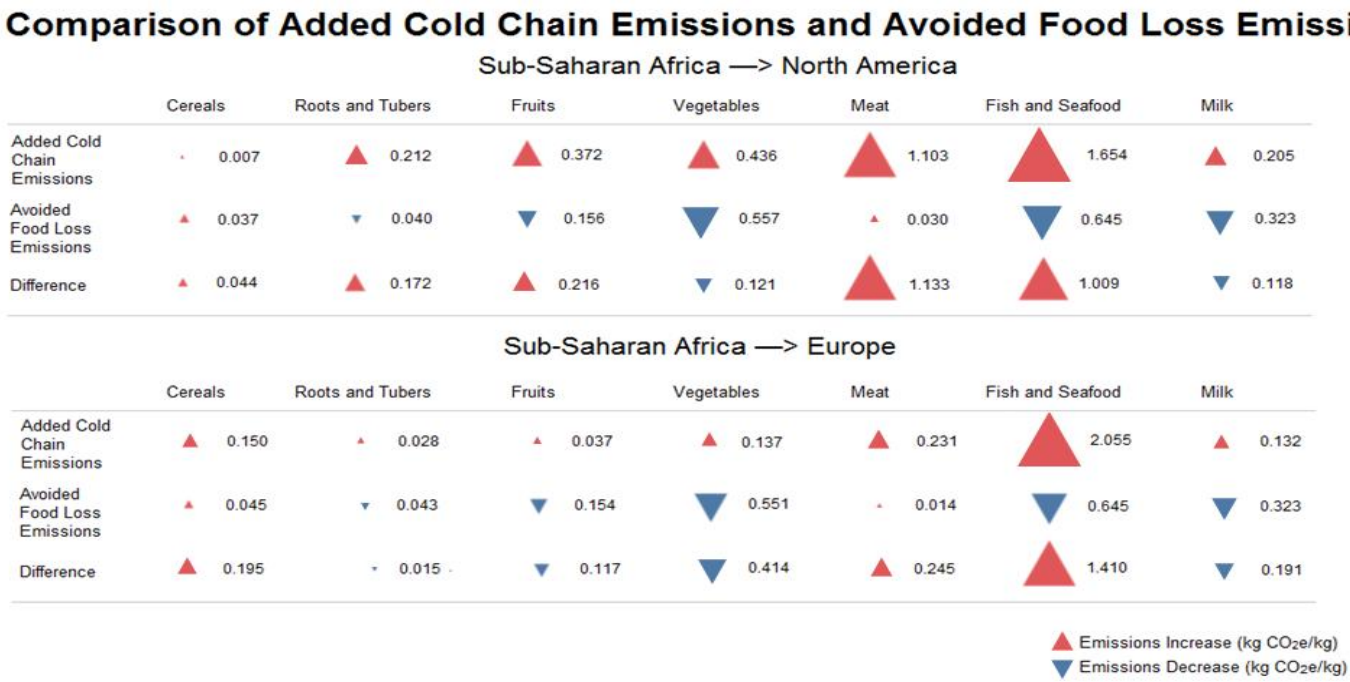


Figure 3.2: Comparison of median emissions added from cold chain introduction and emissions associated with avoided food losses. The calculated values pertain to emissions occurring during the postharvest and pre-retail supply chain (i.e. L_2, and L_3 in Figure 3.1). The calculated difference indicates the direct trade-off between introduced cold chain emissions and avoided food loss emissions for each food type

While total emissions added are larger than loss emissions avoided, the difference between these vary by food type and scenario. Figure 3.2 shows the cold chain adding more emissions than it avoids on a per kg basis for 5 of 7 food categories if North American values are used, and for 3 of 7 food categories if European values are used. The largest cold chain emissions are associated with fish and seafood, meat, and vegetables in the North American scenario, and with fish and seafood, meat, and cereals in the European scenario. The food types that have the greatest reductions in food loss are fish and seafood, vegetables, and milk in both scenarios. This study finds mixed results for fruit depending on development scenario, though an evaluation of kinnow spoilage in India found GHG reductions of 16% from cold chain presence (Carrier & United Technologies, 2016).

For both scenarios, emissions associated with food loss actually increase for cereals and meat. For cereals, the increase in food losses result from the addition of a specific "packaging" loss rate in the North American and European processing and packaging stage (R_3), which is not present for Sub-Saharan Africa in (Gustavsson et al., 2011). Meat losses increase by 0.3% in North American postharvest handling and storage (R_2), affecting the MCA distributions for North America and Europe (see Appendix A.3). The cause for an increased postharvest meat loss rate in North America is not discussed by (Gustavsson et al., 2011), but may be from meat supply practices present in North America but not as common in Sub-Saharan Africa (such as the transportation, slaughter, and portioning of meat prior to retail rather than slaughtering animals for meat at market (Grace and Roesel, 2015) or for immediate consumption). Both food loss-related emissions increases are modest in size, but highlight the need to consider cold chain introduction as inseparable from interconnected changes in the food supply chain (Heard and Miller, 2016).

The distribution of differences between added cold chain emissions and avoided loss emissions by food type and in total dietary emissions are displayed in Figure 3.3. With the exceptions of meat and fish and seafood, the median difference between these values is close to zero, indicating either negligible changes to food types that are not typically refrigerated or that any increase in cold chain emissions are offset by a similar amount of embodied emissions within food savings. Meat and fish and seafood both show larger emissions increases, and also possess larger variances. This indicates that the amount of food savings is insufficient to offset increases in emissions introduced by the cold chain.

The histograms in Figure 3.3c and 3.3d show the expected change in GHG emissions due to cold chain introduction, using the weighted averages of each food type in the average Sub-Saharan diet. A larger share of total emissions differences are greater than zero for the North American scenario than for the European scenario. The North American scenario added more cold chain emissions than loss emissions avoided in 99.9% of runs, and the European scenario resulted in more emissions added than were saved in 89% of runs.

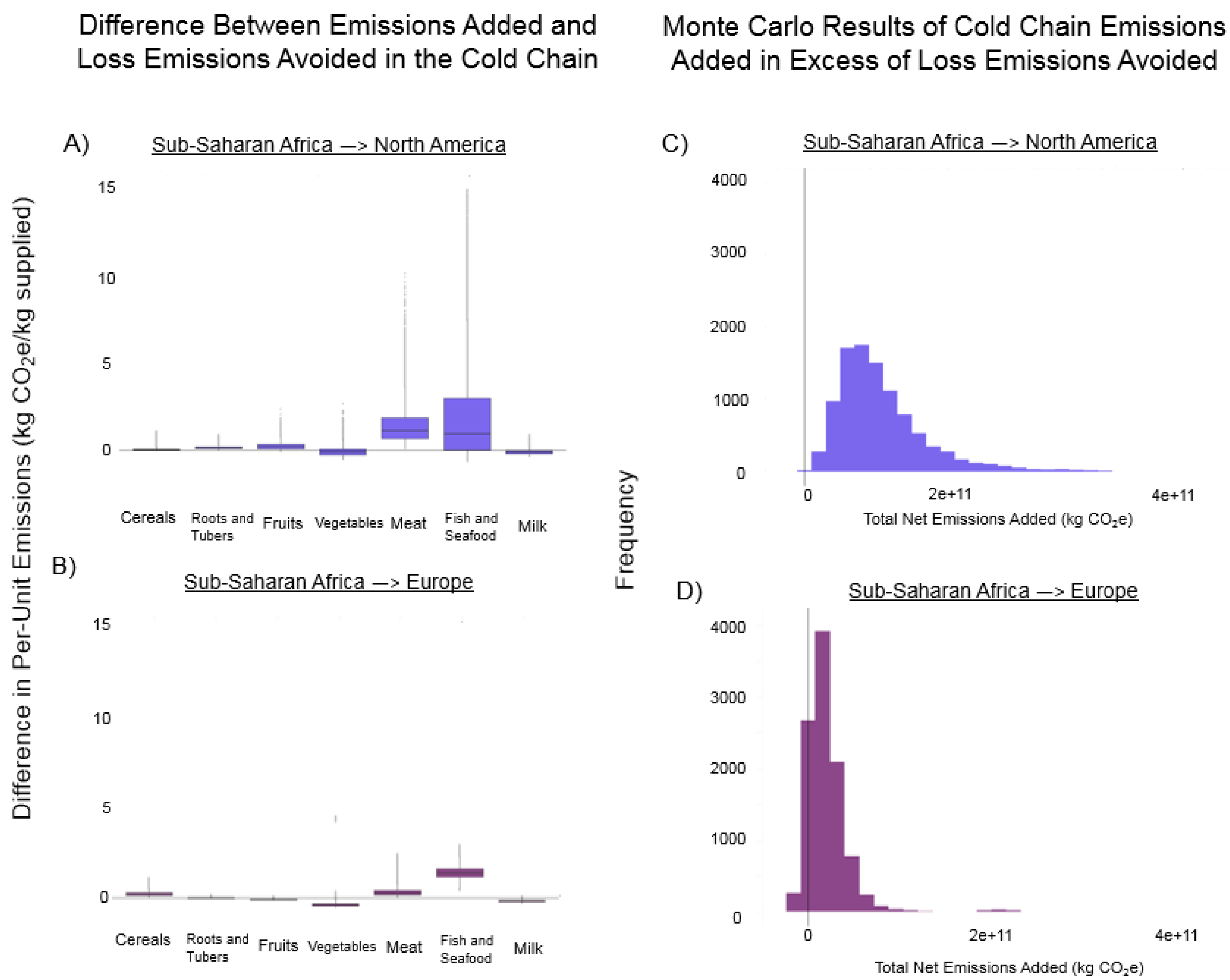


Figure 3.3: Boxplots and histograms of the difference between added cold chain emissions and avoided loss emissions in the postharvest cold chain for both introduction scenarios. Panel A) is a boxplot of the emissions difference per kg of each food type food delivered to retail for the North American scenario, with Panel C) reflecting these emissions for the European scenario. Boxes show the range of values between the 25th and 75th percentiles generated from Monte Carlo Analysis, with the box's line indicating the median. The grey tails are data points generated which fall outside of this interquartile range. Panel B) shows the histogram of total net emissions for the North American scenario's model runs based on a weighted average of food types, with Panel D) showing these results for the European scenario.

3.4.2 Indirect Effects of Cold Chain Introduction on Upstream Food Supply Emissions

The influence of cold chain introduction on upstream FSC emissions is now examined from a broader, systems perspective, incorporating changes to agricultural production and demand.

Refrigeration enables structural changes in food production systems. For example, cold storage allows for agriculture system industrialization, since farms can supply a greater quantity of perishable crops due to lower spoilage rates (Reddy et al., 2010). The indirect effect of cold chain introduction on agricultural emissions is modeled by changing the parameters for agricultural emissions (EA) and agricultural production loss rates (R_1) from their SSA values to the North American and European values. These changes are made in addition to the post-agriculture loss rates and cold chain emission changes reflected in Figures 3.2 and 3.3.

Access to refrigeration changes food demand. The cold chain allows for the supply and consumption of perishable food products in a way not possible without robust refrigerated supply chains (Heard and Miller, 2016), and has been linked with shifts in diet as nations develop (Garnett, 2016, 2007). The effects of demand changes reflecting a North American or European diet facilitated by the cold chain are examined. The food demand parameter (F_5) is adjusted from its baseline value in addition to the values for agricultural production emissions, loss rates, and cold chain emissions. Figure 3.4 shows changes in the emissions required to supply a representative kilogram of food to retail, based on a weighted average of each food type using median MCA values for each parameter. Changes are displayed first with cold chain introduction and changes in agricultural production emissions but with the baseline diet, then with demand changes from dietary shifts.

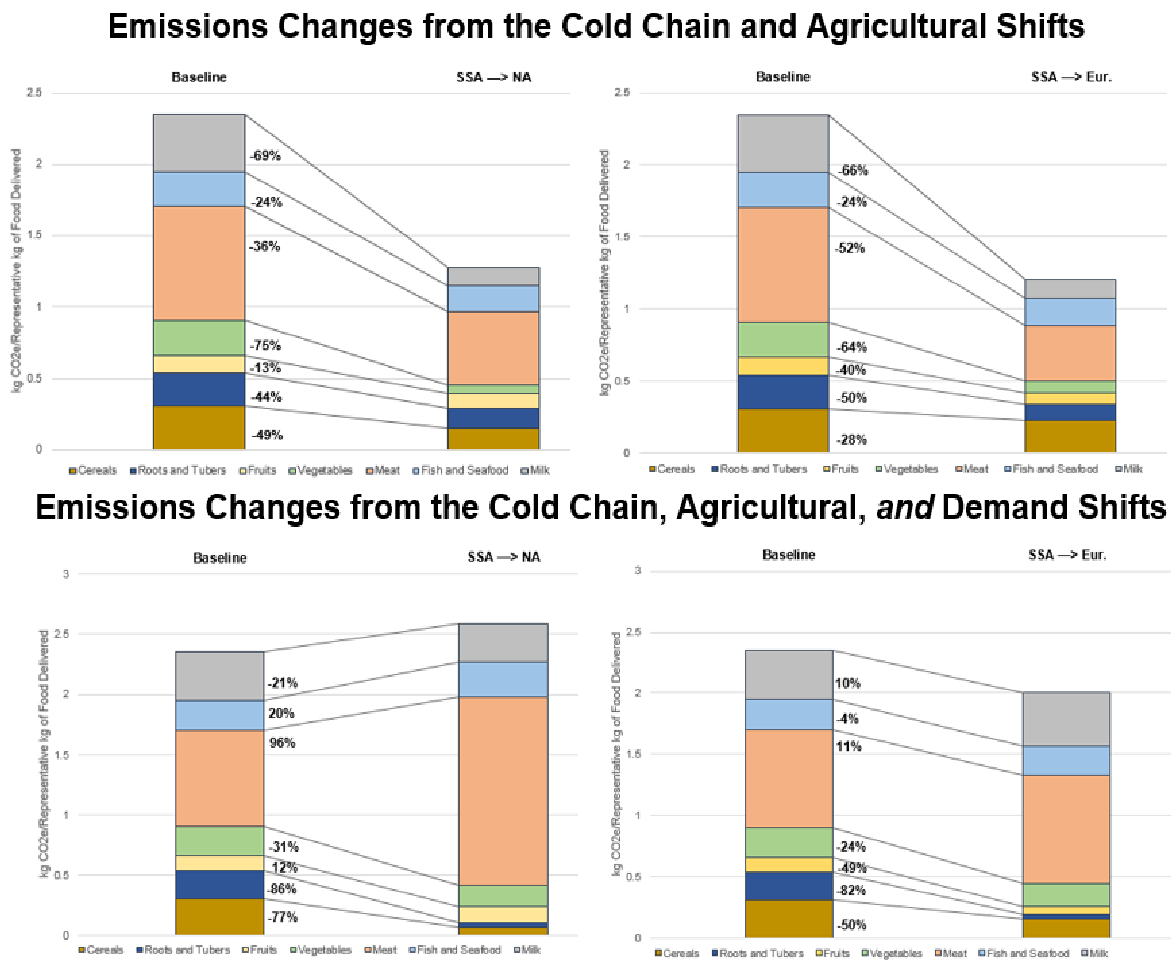


Figure 3.4: Changes in upstream food supply emissions (kg CO_2e) required to deliver one kg of a representative diet, based on a weighted average of each food type within a typical diet. Percentage differences in emissions are displayed by corresponding food type in the graph.

When examining the indirect effects of the cold chain on agricultural production in addition to its direct effects, emissions decrease in both development scenarios: by 46% for the North American scenario and 49% in the European scenario. Emissions decreases are largest for vegetables, milk, and cereals in the North American scenario, and for milk, vegetables, and meat in the European scenario. These results align with a prior study indicating a decrease in food loss GHGs of 38% is possible from supply chain improvements including cold chain introduction (Food and Agriculture Organization of the United Nations, 2011).

Changes in agricultural production emission factors, which decrease with development, put a downward pressure on emissions. It must be noted that there are trade-offs associated with industrialized agricultural systems which may decrease the emissions per kg of food produced, but may increase other environmental consequences including water pollution, soil depletion, biodiversity loss, and also geographically concentrate these effects (Horrigan et al., 2002)
The agricultural production loss rate for roots and tubers increases in both development scenarios due to increased grading standards for produced food (see Appendix A.3) (Gustavsson et al., 2011). Fruits and vegetables see similar increases in their agricultural production loss rate due to grading, but experience decreases in loss rates in the later upstream stages which result in a net decrease in overall upstream loss rates. Increased grading standards may be considered as a way in which consumer demand influences FSC parameters, with the visual appearance of food being a key determinant of food acceptance and perceived quality by consumers (Aschemann-Witzel et al., 2015; Wadhera and Capaldi-Phillips, 2014). However, since fruit and vegetable exposure to refrigeration is typical in their developed supply chains (Paull, 1999), these losses are recouped through decreased postharvest spoilage with supply chain development. Roots and tubers, on the other hand, experience losses due to grading and are not always subject to refrigeration in developed supply chains, and in some large storehouses may be cooled with ventilation from outdoor air (Gottschalk, 1996). Reductions in agricultural loss rates put a downward pressure on emissions for all other food types.

Upstream emissions do not uniformly change when incorporating demand changes. Food supply emissions increase by 10% for the North American scenario but decrease by 15% for the

European scenario. The difference between these outcomes is primarily due to the level of meat consumption in the North American diet, where the per-capita meat consumption is 37% greater than in the European scenario, corresponding to a meat emissions increase of 96% over the baseline. The North American scenario also sees emissions increases from fruits and fish and seafood when incorporating demand shifts. The European scenario sees increases in meat and milk emissions with dietary change, but still experiences a total decrease in upstream emissions. The demand shifts modeled capture both substitutions between food types within a diet, but also increases in total quantities consumed. In this context of Sub-Saharan Africa, increases in calorie consumption would improve health outcomes for many individuals (Abrahams et al., 2011), an effect not measured in this model. Pradhan et al. characterize diet types by calorie composition, and find low-calorie diets to be decreasing worldwide, with general shifts towards higher-calorie observed with development (Pradhan et al., 2013). Increased availability of refrigeration has been connected to increased consumption of perishable food items (Garnett, 2007), which may also improve nutritional outcomes (International Organization for the Development of Refrigeration, 2009). (Pradhan et al., 2013) find low calorie diets observed in the developing world to have similar GHG emissions as higher-calorie diets in the developed world, attributable to differences in food production efficiency. The connection between the cold chain and economic development related to shifts in food demand, supply, and trade should be examined as the subject of future research, as there are notable aspects of well-being and health that are not taken into account in this study.

The demand shifts modeled illustrate scenarios of dietary convergence. In an analysis of the GHG implications of dietary convergence, Ritchie et al. find modeled diets for the U.S., Australia, Canada, and Germany exceeding average per capita emissions budgets for 1.5°C of global warming by 2050 (Ritchie et al., 2018), That being said, the dietary shifts examined in this study are not pre-ordained, merely reflecting two plausible diets in a developed food system. Culture and development individual to any given area will be a critical determinant of diet. If diets develop to correspond with South Africa's nationally recommended diet as modeled by (Behrens et al., 2017), emissions increase 7% or decrease 4% from the baseline, depending on whether North American or European values are used for the other model parameters. This finding illustrates how emissions decreases (or more-modest increases) could accompany health improvements if diets develop in line with a regional nationally recommended diet. Additional details regarding this diet are in Appendix A.5.

These results indicate the importance of incorporating a technology's influence on consumer preferences into an assessment of its environmental outcomes. Despite decreased agriculture emissions associated with the cold chain, refrigeration may prompt shifts towards more emissions-intense foods, creating a scenario of increased environmental impacts.

3.5 Discussion

In contextualizing the results of this analysis, it should be noted that this study focuses only on GHG emissions, and does not take into account societal benefits of the cold chain, which include food security, health outcomes, nutrition, and economic development. The purpose of the study is to highlight the GHG trade-offs of the technology in order to identify potential areas for improvement as the cold chain continues to expand globally.

We find that the emissions from cold chain operation will likely exceed the emissions saved from reductions in food losses, if the cold chain is implemented in a way which resembles its presence in North America or Europe. While the results for individual food types vary, these net emissions increases are larger and more statistically certain to occur in the North American development scenario than the European scenario. This difference is due to the magnitude of cold chain emissions recorded for each region.

This study presents findings relevant to a number of stakeholders. Manufacturers of refrigeration equipment can mitigate emissions increases by employing efficiency improvements, the substitution of refrigerants with low Global Warming Potentials, and/or working with firms along the FSC to increase efficiency. The Postharvest Education Foundation has produced a valuable white paper on considerations for the use of the cold chain in developing areas (Kitinoja, 2013). Potential emissions increases from shifts to high-GHG diets could be mitigated through reducing food losses and the consumption of particularly emissions-intensive foods such as beef (Heller and Keoleian, 2014). Shifting diets is a complex topic, which intersects with elements of culture, equity, and nutrition. Garnett provides a discussion of the best opportunities for mitigating food system GHGs, highlighting key opportunities and challenges (Garnett, 2011). The Kigali Amendment to the Montreal Protocol will have African nations freeze the use of hydrofluorocarbon (HFC) refrigerants in 2024 (United Nations Environment Programme, 2016a). These refrigerants carry high global warming potential values (United Nations Environment Programme, 2016,) with HFC leakage from stationary refrigeration estimated to release 1740,000 tonnes of CO_2e in 2005 (AEA Technology Environment, 2004), and use in the mobile portion of the cold chain comprising 7% of global HFC consumption (Global Food Cold

Chain Council and BIO Intelligence Service, 2015). This amendment presents the opportunity to reduce direct environmental impacts from refrigeration. The Montreal Protocol has been a remarkably successful example of international environmental governance (DeSombre, 2000), with past adherence by signatories and industry cooperation indicating future successes for the Kigali Amendment. Refrigerators and cold chain technology will also likely experience increases in efficiency over time, which could decrease direct emissions. (Dahmus, 2014) notes that energy efficiency improvements in U.S. residential refrigerators since the 1960s has been enough to mitigate resource consumption increases driven by increased refrigerator ownership and size. These improvements are attributed to efficiency mandates, further highlighting the role of governance and regulation in mitigating potential emissions increases from technology.

As noted by (Porter et al., 2016), multiple entries in the literature find that production/pre-farm gate emissions comprise the majority (ranging from 50%-90%) of emissions associated with a food product. However, post-farm processes including refrigeration make both direct and indirect emissions contributions. When incorporating indirect emissions impacts (such as dietary shifts), the total emissions from post-farm processes are larger than just their direct emissions. The cold chain is an integral element of an industrialized food system, with introduction enabling highly integrated systems connecting agricultural producers and the postharvest food supply chain (Parfitt et al., 2010). These feedbacks necessitate a systems view of the FSC in order to capture the full influence and environmental impacts associated with the cold chain.

When incorporating the cold chain's indirect effects, decreases in agricultural production emissions and upstream food losses decrease total upstream emissions in supplying food to retail. However, incorporating shifts in diet leads to an increase in total emissions in the North American scenario and a decrease in the European scenario. This difference is attributable to higher meat consumption in the North American diet. The outsized role of meat-intense diets in comprising food system emissions has been quantified for the United States' diet (Heller et al., 2018). It is possible that dietary shifts enabled by increased access to perishable foods could eclipse GHG additions from the cold chain, but this depends largely on consumer choices. Promoting reduced-meat diets requires engaging with sociocultural norms as well as psychological perceptions, and may require different strategies to be effective for different groups of people (Uta and Schmidt, 2016).

The influence of behavioral choices and diet on food system emissions has been noted in the literature (Garnett, 2011; Heller and Keoleian, 2014). While anticipated shifts in diets are modeled and addressed in the sustainability literature, they are infrequently integrated with more-technically oriented models of the FSC. Similarly, differences in food production systems are often not accounted for in studies of sustainable diets (Garnett, 2016). Without including behavioral and production system differences in modeling the FSC, important influences on environmental outcomes may not be captured.

Data on food losses and waste are limited and uncertain (Parfitt et al., 2010; Reutter et al., 2017; Xue et al., 2017), presenting distinct challenges in creating informed models. There is similarly-limited data on the cold chain, particularly in the developing world (Yahia, 2010). These data quality issues affect this study, which draws on limited and uncertain data for all major model parameters. While there have been means proposed to better-optimize data collection from food life cycle assessments (studying the environmental impacts of a product throughout its lifespan) (Pernollet et al., 2017), different reporting formats, functional units, and system boundaries pose challenges in data collection and standardization. Improving the quantity and quality of estimates for food loss and waste rates, and the environmental impacts from food production and supply are critical research needs.

Sub-Saharan Africa is not a uniform region, and contains notable heterogeneity and differences within it. The aggregation of this region as a baseline case is a limitation of this study which can be improved upon by future work. In addition to differences in cold chain penetration, diet, and agricultural production, Sub-Saharan Africa differs from North America and Europe in local ambient temperature. This will affect elements of the food system ranging from agricultural production (Rosenzweig et al., 2014) to the efficiency and emissions of cold chain operation.(S. J. James and James, 2010).

Development does not occur smoothly, and is often asymmetric in ways which are difficult to capture in a model. Assumptions including the matching of food demand with supply and reliable provision of energy from the electricity grid may differ from an observed development process. This analysis assumes no improvements in cold chain technology upon introduction: however, James and James suggest that the cold chain can be extended without an increase in global CO_2, or possibly even with a decrease, if the most energy efficient refrigeration technologies are used (James and James, 2013). The deployment of renewable and alternative energy technologies such de-centralized solar power in areas of Africa (Szabó et al., 2011; Ulsrud et al., 2015) could also provide important emissions reductions within the food system studied, and have been identified as a key means of reducing post-farm food system emissions (Garnett, 2011).

Refrigerated supply chains transform food systems. Examining the introduction of the cold chain requires modeling more than the technology itself: incorporating the behavioral and broader systemic changes which accompany it. This systems view allows for greater insights into environmental trade-offs and changes in food system sustainability.

3.6 References

Abrahams, Z., McHiza, Z., Steyn, N.P., 2011. Diet and mortality rates in Sub-Saharan Africa: Stages in the nutrition transition. BMC Public Health 11, 801. doi:10.1186/1471-2458-11-801

AEA Technology Environment, 2004. Emissions and Projections of HFCs, PFCs and SF6 for the UK and Constituent Countries.

AGRO Merchants Group, 2018. Worldwide Cold Storage Capacity estimated at 552 Mi Cubic Meters.

Aschemann-Witzel, J., de Hooge, I., Amani, P., Bech-Larsen, T., Oostindjer, M., 2015. Consumer-Related Food Waste: Causes and Potential for Action. Sustainability 7, 6457–6477. doi:10.3390/su7066457

Aung, M.M., Chang, Y.S., 2014. Temperature management for the quality assurance of a perishable food supply chain. Food Control 40, 198–207.

Behrens, P., Kiefte-de Jong, J.C., Bosker, T., Rodrigues, J.F.D., de Koning, A., Tukker, A., 2017. Evaluating the environmental impacts of dietary recommendations. Proc. Natl. Acad. Sci. 114, 13412–13417. doi:10.1073/pnas.1711889114

Carrier & United Technologies, 2016. Cold Chain Development for Fruits & Vegetables in India: Knnow Cold Chain Study.

Carrier Transicold, 2016. India Pilot Study Shows How the Cold Chain Can Help Reduce Food Loss and Carbon Emissions [WWW Document]. URL https://www.carrier.com/carrier/en/us/news/news-article/india_pilot_study_shows_how_the_cold_chain_can_help_reduce_food_loss_and_carbon_emissions.aspx

Dahmus, J.B., 2014. Can Efficiency Improvements Reduce Resource Consumption? J. Ind. Ecol. 18, 883–897. doi:10.1111/jiec.12110

DeSombre, E.R., 2000. The Experience of the Montreal Protocol: Particularly Remarkable and Remarkably Particular. UCLA J. Environ. Law Policy 19, 49–81.

Food and Agriculture Organization of the United Nations; International Institute of Refrigeration, 2016. Developing the cold chain in the agrifood sector in sub-Saharan Africa.

Food and Agriculture Organization of the United Nations, 2017. Save Food for a Better Climate: Converting the Food Loss and Waste Challenge into Climate Action. Rome.

Food and Agriculture Organization of the United Nations, 2016. SDG Target 12.3 on Food Loss and Waste: 2016 Progress Report.

Food and Agriculture Organization of the United Nations, 2013. Food Wastage Footprint: Impacts on natural resources, Food wastage footprint: Impacts on natural resources. doi:ISBN 978-92-5-107752-8

Food and Agriculture Organization of the United Nations, 2011. Food Wastage Footprint & Climate Change.

Food and Agriculture Organization of the United Nations, n.d. FAOSTAT [WWW Document].

Garnett, T., 2016. Plating up solutions. Science (80-.). 353, 1202–1204.

Garnett, T., 2011. Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? Food Policy 36, S23–S32. doi:10.1016/j.foodpol.2010.10.010

Garnett, T., 2007a. Food Refrigeration: What is the Contribution to Greenhouse Gas Emissions and How Might Emissions Be Reduced? (No. April 2007), FCRN Working Paper.

Garnett, T., 2007b. Food Refrigeration: What is the Contribution to Greenhouse Gas Emissions and How Might Emissions Be Reduced?
Global Food Cold Chain Council, BIO Intelligence Service, 2015. Assessing the potential of the cold chain sector to reduce GHG emissions through food loss and waste reduction.
Gottschalk, K., 1996. Mathematical Modelling Of The Thermal Behaviour Of Stored Potatoes & Developing Of Fuzzy Control Algorithms To Optimise The Climate In Storehouses. Acta Hortic. 406, 331–340. doi:10.17660/ActaHortic.1996.406.34
Grace, D., Roesel, K., 2015. What's eating sub-Saharan Africa? Al Jazeera 1–5.
Gustavsson, J., Cederberg, C., Sonesson, U., 2011. Global Food Losses and Food Waste: Extent, Causes, and Prevention.
Heard, B.R., Miller, S.A., 2016. Critical Research Needed to Examine the Environmental Impacts of Expanded Refrigeration on the Food System. Environ. Sci. Technol. 50, 12050–12071. doi:10.1021/acs.est.6b02740
Heller, M.C., Keoleian, G.A., 2014. Greenhouse Gas Emission Estimates of U.S. Dietary Choices and Food Loss. J. Ind. Ecol. 19, 391–401. doi:10.1111/jiec.12174
Heller, M.C., Willits-Smith, A., Meyer, R., Keoleian, G.A., Rose, D., 2018. Greenhouse gas emissions and energy use associated with production of individual self-selected US diets. Environ. Res. Lett. 13. doi:10.1088/1748-9326/aab0ac
Hiç, C., Pradhan, P., Rybski, D., Kropp, J.P., 2016. Food Surplus and Its Climate Burdens. Environ. Sci. Technol. 50, 4269–4277. doi:10.1021/acs.est.5b05088
Horrigan, L., Lawrence, R.S., Walker, P., 2002. How sustainable agriculture can address the environmental and human health harms of industrial agriculture. Environ. Health Perspect. 110, 445–456. doi:10.1289/ehp.02110445
International Organization for the Development of Refrigeration, 2009. 5th Informatory Note on Refrigeration and Food: The role of refrigeration in worldwide nutrition. Paris.
James, S.J., James, C., 2013. Sustainable Cold Chain, in: Tiwari Brijesh K., Norton, T., Holden, N.M. (Eds.), Sustainable Food Processing. John Wiley & Sons, Ltd, pp. 463–496. doi:10.1002/9781118634301.ch19
James, S.J., James, C., 2010. The food cold-chain and climate change. Food Res. Int. 43, 1944–1956. doi:10.1016/j.foodres.2010.02.001
James, S. J., James, C., 2010. The food cold-chain and climate change. Food Res. Int. 43, 1944–1956. doi:10.1016/j.foodres.2010.02.001
Kitinoja, L., 2013. Use of cold chains for reducing food losses in developing countries (No. 13–03), PEF White Paper.
Markets and Markets, 2015. Cold Chain Market worth 234.49 Billion USD by 2020 [WWW Document]. URL http://www.marketsandmarkets.com/PressReleases/cold-chain.asp
Miller, S.A., Keoleian, G.A., 2015. Framework for Analyzing Transformative Technologies in Life Cycle Assessment. Environ. Sci. Technol. 49, 3067–3075. doi:10.1021/es505217a
Papargyropoulou, E., Lozano, R., K. Steinberger, J., Wright, N., Ujang, Z. Bin, 2014. The food waste hierarchy as a framework for the management of food surplus and food waste. J. Clean. Prod. 76, 106–115. doi:10.1016/j.jclepro.2014.04.020
Parfitt, J., Barthel, M., Macnaughton, S., 2010. Food waste within food supply chains: quantification and potential for change to 2050. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 365, 3065–81. doi:10.1098/rstb.2010.0126
Paull, R.E., 1999. Effect of temperature and relative humidity on fresh commodity quality. Postharvest Biol. Technol. 15, 263–277.

Pernollet, F., Coelho, C.R. V, van der Werf, H.M.G., 2017. Methods to simplify diet and food life cycle inventories: Accuracy versus data-collection resources. J. Clean. Prod. 140, 410–420. doi:10.1016/j.jclepro.2016.06.111

Porter, S.D., Reay, D.S., Higgins, P., Bomberg, E., 2016. A half-century of production-phase greenhouse gas emissions from food loss & waste in the global food supply chain. Sci. Total Environ. 571, 721–729. doi:10.1016/j.scitotenv.2016.07.041

Pradhan, P., Reusser, D.E., Kropp, J.P., 2013. Embodied Greenhouse Gas Emissions in Diets. PLoS One 8, 1–8. doi:10.1371/journal.pone.0062228

Reddy, G.P., Murthy, M.R.K., Meena, P.C., 2010. Value Chains and Retailing of Fresh Vegetables and Fruits, Andhra Pradesh. Agric. Econ. Res. Rev. 23, 455–460.

Reutter, B., Lant, P.A., Lane, J.L., 2017. The challenge of characterising food waste at a national level—An Australian example. Environ. Sci. Policy 78, 157–166. doi:10.1016/j.envsci.2017.09.014

Ritchie, H., Reay, D.S., Higgins, P., 2018. The impact of global dietary guidelines on climate change. Glob. Environ. Chang. 49, 46–55. doi:10.1016/j.gloenvcha.2018.02.005

Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., Boote, K.J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T.A.M., Schmid, E., Stehfest, E., Yang, H., Jones, J.W., 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proc. Natl. Acad. Sci. 111, 3268–3273. doi:10.1073/pnas.1222463110

Sahin, E., Zied Babaï, M., Dallery, Y., Vaillant, R., 2007. Ensuring supply chain safety through time temperature integrators. Int. J. Logist. Manag. 18, 102–124.

Szabó, S., Bó dis, K., Huld, T., Moner-Girona, M., 2011. Energy solutions in rural Africa: mapping electrification costs of distributed solar and diesel generation versus grid extension. Environ. Res. Lett. 6, 1–9. doi:10.1088/1748-9326/6/3/034002

Ulsrud, K., Winther, T., Palit, D., Rohracher, H., 2015. Village-level solar power in Africa: Accelerating access to electricity services through a socio-technical design in Kenya. Energy Res. Soc. Sci. 5, 34–44.

United Nations, 2015. UN Resolution 2020 Agenda for Sustainable Development, in: Seventieth Session Agenda Items 15 and 116. doi:10.1007/s13398-014-0173-7.2

United Nations Environment Programme, 2016a. The Kigali Amendment to the Montreal protocol: another global commitment to stop climate change [WWW Document]. UN Environ. URL https://www.unenvironment.org/news-and-stories/news/kigali-amendment-montreal-protocol-another-global-commitment-stop-climate

United Nations Environment Programme, 2016b. The Kigali Amendment to the Montreal Protocol: HFC Phase-down, 28th Meeting of the Parties to the Montreal Protocol, 10-14 October, 2016, Kigali, Rwanda.

United States Agency for International Development, 2016. U.S. Government Global Food Security Strategy.

Uta, S.S., Schmidt, J., 2016. Reducing meat consumption in developed and transition countries to counter climate change and biodiversity loss : a review of influence factors. Reg. Environ. Chang. doi:10.1007/s10113-016-1057-5

Wadhera, D., Capaldi-Phillips, E.D., 2014. A review of visual cues associated with food on food acceptance and consumption. Eat. Behav. 15, 132–143. doi:10.1016/j.eatbeh.2013.11.003

World Resources Institute, 2016. Food Loss and Waste Accounting and Reporting Standard.

Xue, L., Liu, G., Parfitt, J., Liu, X., Van Herpen, E., Stenmarck, A., O'Connor, C., Östergren, K., Cheng, S., 2017. Missing food, missing data? A critical review of global food losses and food waste data. Environ. Sci. Technol. 51, 6618–6633. doi:10.1021/acs.est.7b00401
Yahia, E.M., 2010. Cold Chain Development and Challenges in the Developing World, in: Erkan, M., Aksoy, U. (Eds.), 6th International Postharvest Symposium. pp. 127–132.
Zanoni, S., Zavanella, L., 2012. Chilled or frozen? Decision strategies for sustainable food supply chains. Int. J. Prod. Econ. 140, 731–736. doi:10.1016/j.ijpe.2011.04.028
Zhang, J., Pritchard, E., Hu, X., Valentin, T., Panilaitis, B., Omenetto, F.G., Kaplan, D.L., 2012. Stabilization of vaccines and antibiotics in silk and eliminating the cold chain. Proc. Natl. Acad. Sci. 109, 11981–11986. doi:10.1073/pnas.1206210109

Chapter 4

The Influence of Household Refrigerator Ownership on Diets in Vietnam

Chapter 4: Heard BR, Thi HT, Burra DD, Heller MC, Miller SA, Duong TT, Jones AD. "The Influence of Household Refrigerator Ownership on Diets in Vietnam." *Economics & Human Biology* (Under Review).

Abstract

Refrigerator ownership accompanies socio-economic development, having a transformative effect on human diets. Household refrigerator ownership in Vietnam has increased from 13% to 59% between 2004-2014. This study estimates changes in food consumption associated with household refrigerator ownership in Vietnam, controlling for socioeconomic control variables, using a GAMLSS regression model on Vietnam Household Living Standards Survey (2004-2014) data. Our study finds refrigerator ownership to be associated with a 135 kcal/day/adult-equivalent decrease in starchy staple foods consumption, a 3 kcal/day/adult-equivalent decrease in nuts and seeds, a 0.15 kcal/day/adult-equivalent decrease in pulses, a 12 kcal/day/adult-equivalent increase in flesh foods (meat and fish), and a 3 kcal/day/adult-equivalent increase in dairy for the average household at a statistically significant level ($p < 0.001$). No significant relationship is found for egg, fruit, and vegetables consumption. The implications of these

coefficients for nutrition and those for socioeconomic covariates for sustainable development are discussed.

4.1 Introduction

Vietnam has experienced tremendous economic growth over the past thirty years as a result of the government's Đổi Mới policy promoting market liberalization. GDP growth has averaged 6.42% between the beginning of this program in 1986 and 2017, with annual per capita GDP growth averaging 5.04% (The World Bank, 2018). This growth has been attained in part through infrastructure development throughout the country. For example, household electrification has increased from less than 50% in 1993 to including nearly all households in 2014 (World Wildlife Fund, 2016).

As a country develops, dietary shifts towards lower amounts of starchy staple foods and greater quantities of protein-rich and higher-fat foods have been demonstrated (Thang and Popkin, 2004). While this linkage is well-established, the specific mechanisms enabling these shifts are understudied, including the presence of refrigeration. This study assesses the relationship between household refrigerator ownership and the consumption of food types in Vietnam, filling part of this research gap.

Refrigeration plays a transformative role in food system development, and is interconnected with changes in what foods are consumed and can be supplied (Heard and Miller, 2016). The presence of refrigeration is connected with diets containing more perishable food items (Garnett, 2007), with a connection to increased meat consumption explicitly noted in China's development (6). Perishable foods have the potential to improve health outcomes in developing countries (International Organization for the Development of Refrigeration, 2009), but the availability of refrigeration in conjunction with income increases may also promote diets which increase obesity and related health burdens (Popkin, 2001). The relationship between refrigeration, diet, and development has been addressed in the academic literature either largely qualitatively (Garnett, 2011, 2007; Parfitt et al., 2010) or modeled more-abstractly, carrying an assumption of dietary convergence reflecting diets in developed Western countries (Heard and Miller, 2019). Refrigerator ownership is tied to wealth, with sufficiently high household wealth being a necessary precursor for purchasing a refrigerator. Wealth increases have been empirically connected with decreased starchy staple food consumption and increases in fruit, vegetable, meat, dairy, and refined grain consumption; with the degree of these shifts dependent on the relative cost of these food types (Godfray et al., 2018). Due to the technological and logistical requirements of supplying perishable foods, shifts towards their consumption is in part enabled by refrigeration as a technology, and in part enabled by wealth used to purchase these products and a refrigerator. The extent to which diet shifts with development are attributable to refrigeration, wealth, and/or the interaction between these factors is relatively unassessed in the academic literature (Heard and Miller, 2016).

The unbroken refrigerated supply chain, or "cold chain," provides the capacity to robustly supply perishable foods, and its presence is a characteristic of a developed, industrialized food system (Parfitt et al., 2010). Cold chain services have developed in Vietnam in recent years due to an increase in international investment and an increase in the presence of supermarkets, with sales from modern grocery retailers growing from 30.9 trillion VND in 2011 to 69.2 trillion VND in 2015 (Euromonitor, 2017). The cold chain also plays a key role in agricultural development and in the transition towards Vietnam becoming an agricultural product exporter (Arita and Dyck, 2014). Despite these changes, cold chain development in Vietnam still faces several challenges including the need for improved training at the professional and farmer levels, a lack of supporting information technology, and high costs of installation and operation (Gligor et al., 2018). The introduction of refrigerators into the household connects the cold chain to the consumer; with this analysis assessing the influence of household refrigerator ownership on diet. Household refrigerator ownership is hypothesized to have a positive and statistically significant relationship with the consumption of the more-perishable food types assessed: flesh foods (meat and fish), eggs, vegetables, fruits, and dairy. Refrigeration in hypothesized to have a negative and statistically significant decrease in consumption of the less-perishable foods studied: starchy staple foods, nuts and seeds, and pulses.

Refrigerator ownership is likely not the only variable influencing a household's consumption of different food types. Socio-economic variables including income, household location, education level, and household size (among others) can be expected to affect food consumption. Multiple regression analysis allows the researcher to 'control' for the effects of other variables in the dataset on the outcome variable of interest. Variable choice and regression model specification are critical for best-disaggregating the influence of each variable on food consumption. The following section details our approach to informing this study's regression model.

4.2 Methods

4.2.1 Data

This study uses the Vietnam Household Living Standards Survey (VHLSS) from the Living Standard Measurement Survey (LSMS) conducted by the General Statistics Office of Vietnam (GSO). This multi-purpose survey has been conducted in approximately 9,000 Vietnamese households every two years since 2002. The survey records ownership of nearly 40 durable goods for households, including refrigerator ownership. Our analysis uses the most recent VHLSS dataset: 2004 to 2014. To measure income, we use household per capita expenditure (PCE), which has been widely used as an appropriate proxy (Baulch and Masset, 2003; Minot et al., 2006; Trinh Thi et al., 2018). Per capita expenditure serves as a useful income proxy as it avoids the issues of underreported income (Deaton, 1997) and income volatility (Bhalotra and Attfield, 1998). An overall income measure is studied in this analysis as it affects a household's ability to purchase both food and durable goods such as a refrigerator. This study normalizes PCE to 2014 US dollars.

The VHLSS survey collects recall responses on household food consumption, which are used to calculate individual-level food consumption for household members. Between 2004-2008 the dietary recall period is the last 12 months, and between 2010-2014 the recall period is the last 30 days. Food consumption quantity is normalized into daily intake values and converted into calories by using a calorie conversion table constructed by Vietnam National Institute of Nutrition (National Institute of Nutrition, 2013). Food consumption is measured the VHLSS survey by food expenditure, and has been transformed into calories through the Vietnamese National Institute of Nutrition's conversion table, as employed by (Trinh Thi et al., 2018). The authors refer the reader to (Zezza et al., 2017) for a useful discussion of the relative advantages and disadvantages of household expenditure surveys for measuring food consumption.
Cereals and roots and tubers have been aggregated into a single category as "starchy staple foods," in addition to an aggregation of meat and fish types into "flesh foods", and dairy products (as "dairy") as is recommended for validated indicators of dietary diversity (Food and

Agriculture Organization of the United Nations, 2016; World Health Organization, 2008). A full table of the food types aggregated into the categories is available in Appendix B.1.

4.2.2 Statistical Analysis

The influence of refrigerator ownership on dietary outcomes for households in the VHLSS data is examined through multiple regression analysis using Generalized Additive Models for Location Scale and Shape (GAMLSS) models (25) in the statistical software R. The distribution of GAMLSS model dependent variables are not limited to the exponential family, making this model family more general than General Linear Models (GLM) and Generalized Additive Models (GAM).

The regression equation estimated is described in Eqn. 1:

$$Y = \alpha + \alpha_1 X_{RO} + \sum_j \beta_j X_j \ + \epsilon \qquad (1)$$

The response variable Y is daily energy intake per adult equivalent (kcal/day-adult equivalent) of the studied food types, X_{RO} is a binary refrigerator ownership indicator variable (equal to 1 if the household owns a refrigerator, and 0 if not), and X_j are other covariates for each household observation. Covariates included in each regression model are observation year, PCE, urban area indicator variable, number of people in the household, geographic area of the country, education level, ethnic minority indicator variable, and a clean water for cooking indicator variable. Summaries of observations and categories for these variables are available in Appendix B.2.

Three distributions were tested for modeling the dependent variables: the Zero-Adjusted Gamma distribution (ZAGA), the Zero adjusted Inverse Gaussian distribution (ZAIG) and the Zero

Adjusted Logarithmic (ZALG) families. All three distributions are potential matches to the properties of the data examined: continuous distributions defined to include zero values (CRAN 2018, Rigby & Stasinopoulos, 2009). ZAGA was selected for this analysis based on a comparison of Akaike information criterion (AIC) statistics for all regression models analyzed.

The Zero-Adjusted Gamma distribution exists on $[0,\infty)$ where the dependent variable equaling zero has probability ν, and non-zero values are estimated using a gamma distribution with at a probability of $(1-\nu)$ with non-zero mean μ and dispersion σ. The μ link function is log, and the ν link function is logit. Zero-adjusted distributions present a modeling advantage as it allows for an analysis of the characteristics associated with zero consumption of a given food group. The authors refer the reader to (Rigby and Stasinopoulos, 2009) for more detail.

Explanatory variables selected for the regression model include household refrigerator ownership (X_{RO}, the key variable of interest), as well as socio-economic variables identified as potentially having an impact on household food consumption in the literature (Trinh Thi et al., 2018). A regression model was defined using stepwise regression in both directions with the step-generalized AIC (GAIC) function, regressing dependent dietary variables on X_{RO} in the null model, and on all identified relevant socio-economic variables in the full model. Generalized variance-inflation factors indicate no issues of multicollinearity for the regression models when examined.

GAMLSS link functions correspond to those of generalized linear models (GLMs) (Stasinopoulos and Rigby, 2007). GLM coefficients should be interpreted multiplicatively with respect to the mean of the expected value of the outcomes variable considered (Barber and Thompson, 2004). All μ coefficient interpretations should be interpreted as estimating the direction and magnitude of relationships between variables and food consumption, conditioning on there being positive consumption of that food type (a non-zero outcome variable) (Tong et al., 2013). ν coefficients should be interpreted as odds ratio of zero consumption of food types.

4.3 Results

4.3.1 Increasing Refrigerator Ownership in Vietnam

Trends of Vietnamese refrigerator ownership and its relationship to average per capita expenditure over the study period are displayed in Figure 4.1.

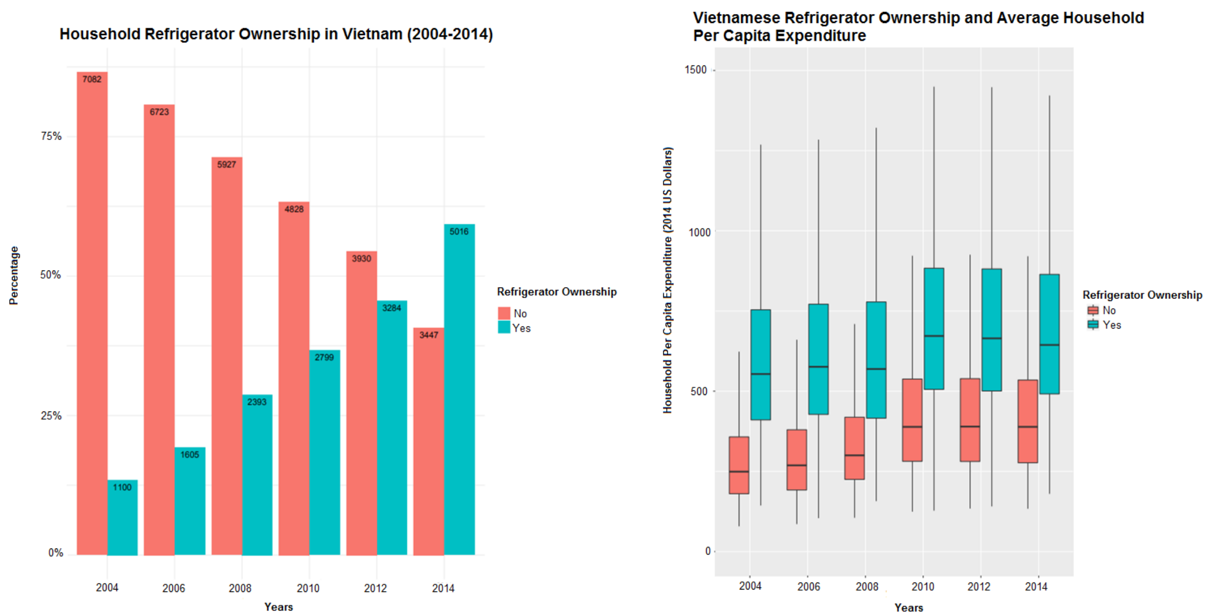


Figure 4.1: Vietnamese refrigerator ownership and average household per capita expenditure (PCE) over 2004-2014 as recorded by the Vietnam Household Living Standards Survey. The right plot boxes encompass the 25th and 75th percentile values of PCE per year, with the black lines extending to the extreme high and low values recorded. The horizontal black lines in the boxes indicate the median PCE value for each group per year.

The prevalence of household refrigeration has increased notably during the time period observed, with 2014 being the first year when more surveyed households owned refrigerators than did not. Average household PCE is higher among refrigerator-owning households than those households that do not own a refrigerator. However, PCE increases 83% among both categories of households over the study period of 2004-2014.

Refrigerator ownership over the study period by province is displayed in Figure 4.2.

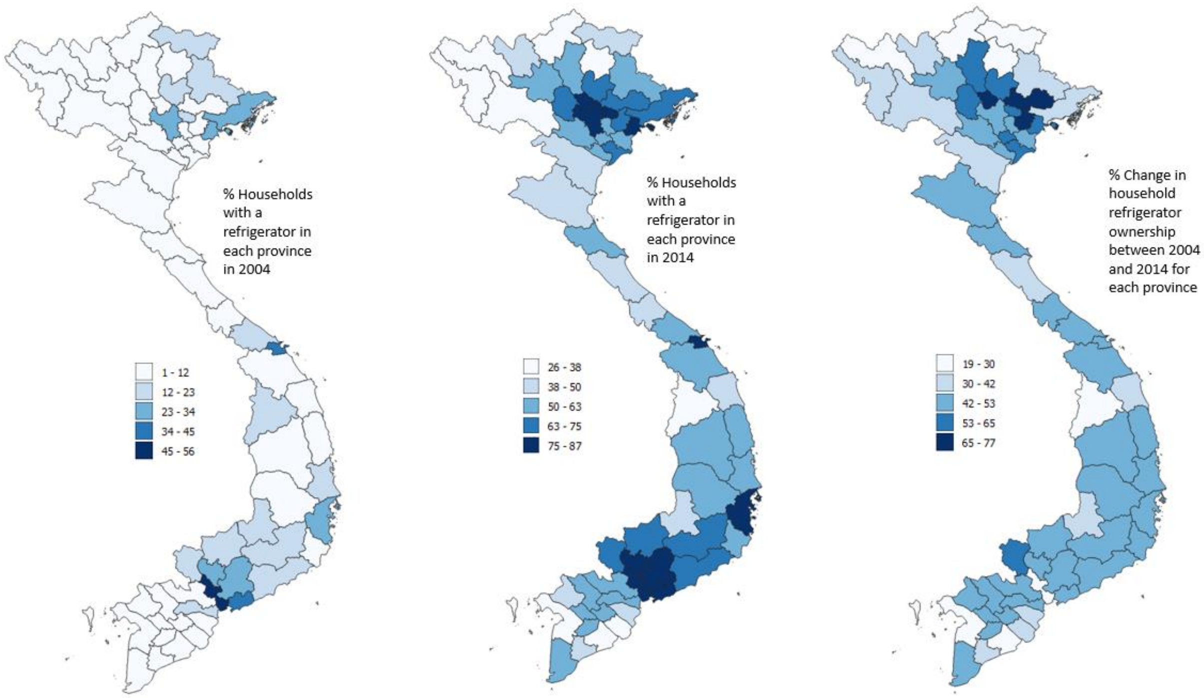


Figure 4.2: Percentage of households reporting ownership of a refrigerator in the Vietnam Household Living Standards Survey. Data from the 2004 survey wave is displayed in the left-most map, 2014 data in the middle, and the percentage change between these survey waves on the right

The largest growth (65-77%, depicted in Figure 2) in household refrigerator ownership between 2004-2014 is seen in the provinces surrounding Hanoi, with moderate growth experienced elsewhere in the country. Data on household refrigerator ownership in developing nations is sparse. However, for comparison, Vietnamese refrigerator ownership percentages in both 2010 and 2014 were lower than those recorded for China in both rural and urban regions (97% urban and 45% rural ownership in China compared with 60% and 28% for Vietnam in 2010; 92% urban and 78% rural Chinese ownership in 2014 compared with 80% and 51% for Vietnam) (National Bureau of Statistics of China, 2019). Additionally, using data from (USDA Economic Research Service, n.d.), Vietnamese household refrigerator ownership is recorded as larger than that for India in 2002, 2006, and 2008, and below that for Indonesia for 2002 and 2006, but exceeding Indonesian ownership rates in 2008.

5.3.2 Vietnamese Dietary Change

Changes in food consumption by Vietnamese households over the study period is displayed in Figure 4.3.

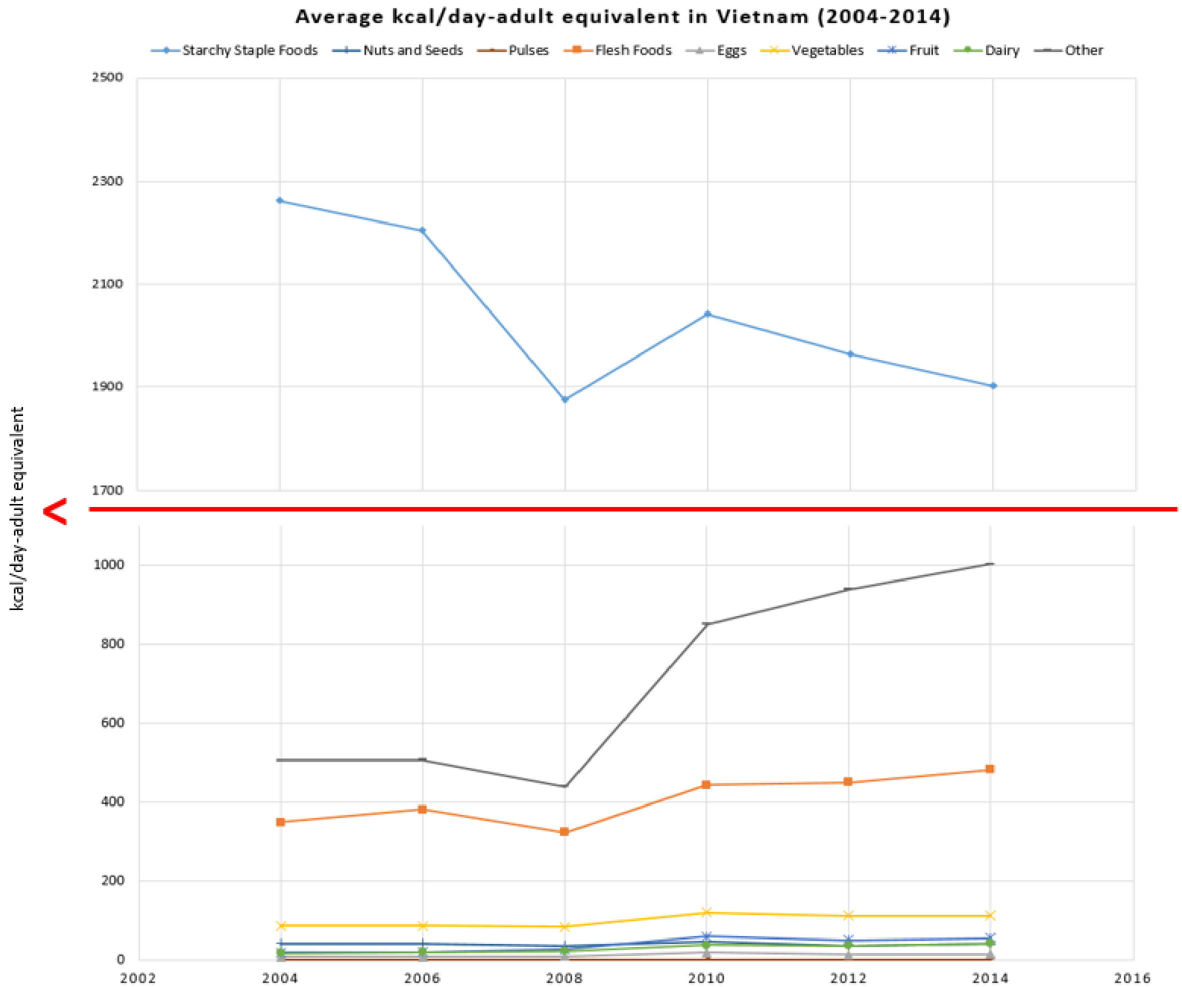


Figure 4.3: Average household kcal/day per adult equivalent of food types examined as measured by the VHLSS between 2004 and 2014. A y-axis break is defined between 1100 and 1700 kcal/Per Adult Equivalent to better-display the changes in consumption of Starchy Staple Foods in conjunction with other food categories.

Starchy staple food consumption decreases 16% over the time period observed, while flesh food consumption rises 38%. Calories from "other" sources rise 98% between 2004-2014, capturing changes in calories from non-major food sources including sugars, alcohol, lard, cooking oil, among others. These food groups have the largest average consumption in kcal, with averages for the other foods examined (nuts and seeds, pulses, eggs, vegetables, fruit, and dairy) remaining below 125 kcal/day over the observation period.

5.3.3 The Influence of Household Refrigerator Ownership on Diet

The statistical association between refrigerator ownership, per capita expenditure, and socio-economic covariates with the consumption of food types is discussed. Regression coefficients for household refrigerator ownership and per capita expenditure results are reported in Table 4.1 and depicted visually in Figure 4.4. The μ link function (for the continuous portion of the distribution) is log, and displayed in Table 1 as the first coefficient for each type and bolded. The ν link function is logit and displayed as the second set of coefficients. Values in parentheses are standard errors.

GAMLSS Regression	Starchy Staple Foods		Nuts and Seeds		Pulses		Flesh Foods		Eggs		Vegetables		Fruit		Dairy	
	Dependent variable:															
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
Refrigerator Ownership	**-6.45e-02*** (3.59e-03)**	-1.86*** (0.43)	-7.71e-02*** (1.11e-02)	-0.22*** (0.04)	-8.66e-02*** (1.66e-02)	-1.15e-01*** (2.87e-02)	**3.18e-02*** (5.22e-03)**	-2.16e+00*** (4.86e-01)	**1.35e-02 (8.39e-03)**	-1.88e-01*** (4.03e-02)	**1.49e-01*** (1.47e-02)**	-5.00e-01*** (2.67e-02)	**-1.22e-02 (1.29e-02)**	-2.87e-01*** (3.50e-02)	**1.49e-01*** (1.47e-02)**	-5.00e-01*** (2.67e-02)
Per Capita Expenditure	**-2.45e-05*** (2.67e-06)**	6.41e-04*** (1.80e-04)	1.98e-04*** (1.74e-06)	0.00*** (0.00)	1.66e-04*** (2.69e-06)	-4.1e-04*** (2.55e-05)	**3.13e-04*** (3.92e-06)**	7.08e-04*** (1.71e-04)	**1.96e-04*** (1.54e-06)**	-5.82e-04*** (4.44e-0)	**3.02e-04*** (2.28e-06)**	-5.62e-04*** (2.59e-05)	**8.65e-06*** (1.71e-06)**	-7.23e-04*** (3.41e-05)	**3.02e-04*** (2.28e-06)**	-5.62e-04*** (2.59e-05)

Note: *p<0.1; **p<0.05; ***p<0.01

Table 4.1: GAMLSS Zero Adjusted Gamma model coefficients for refrigerator ownership and per capita expenditure, predicting on the consumption of food types. The first regression coefficients (1) by food type are for the strictly positive portion of the distribution (μ, log-linked) and the second (2) are for the log odds of zero consumption of each food type (ν, logit link). Control variable coefficients not listed for brevity, but full regression outputs are included in Appendix B.3.

The log-linked regression coefficients can be interpreted (through exponentiation) as percentage changes from the average diet, with the corresponding changes are described as follows, and presented in Figure 4.4. Average consumption of each food category per year is summarized in Appendix B.3.

Refrigerator ownership is associated with a notable decrease in starchy staple foods consumption: 127.7 kcal/day-adult eq. (a 6.25% decrease from the mean) at a statistically significant level (p <0.001). Refrigerator ownership is also associated with a drop in nuts and seeds and pulses consumption at the same level of statistical significance, with decreases of 3.03 kcal (7.42%) and 0.15 kcal (8.30%), respectively. Household refrigerator ownership is associated with increases in flesh foods (13 kcal, 3.23%) and dairy (4.80 kcal, 16.09%) at the same level of statistical significance. Refrigerator ownership is not statistically significantly related to changes in the consumption of eggs, vegetables, or fruit.

Per capita expenditure is statistically significantly ($p < 0.001$) associated with changes in the consumption of all food types, but at differing magnitudes. The mean price of a refrigerator in the VHLSS data used is 200 USD, with Figure 4 displaying the changes in diet associated with a household refrigerator and changes from the amount of wealth required to purchase a refrigerator, as a means of assessing the influence of refrigerator and wealth effects of a similar magnitude.

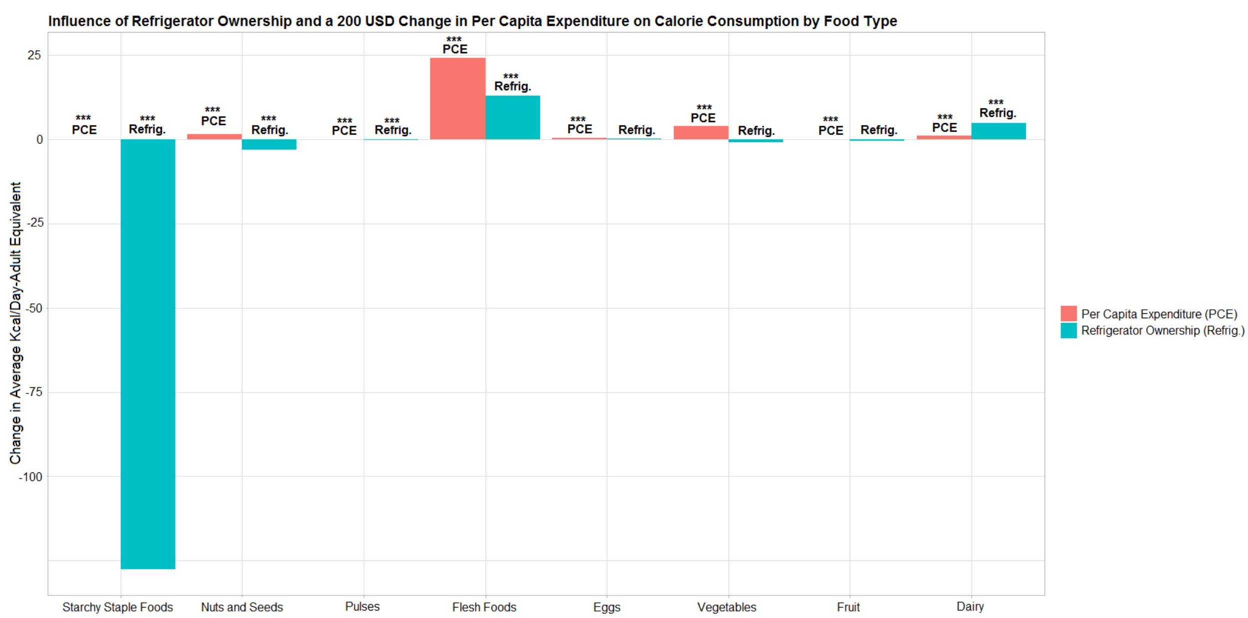


Figure 4.4: Estimated changes in consumption of each food type corresponding with refrigertor ownership or a 200 USD increase in per capita expenditure. Esimates are from GAMLSS ZAGA μ coefficients for each food type, reflecting changes in average kcal/day per adult equivalent consumption of each food group. Statistical significance is labeled at the levels: '***' 0.001, '**' 0.01, and '*' 0.05

A 200 USD increase in PCE is associated with a 24.22 Kcal/day-adult eq. (0.03%) increase in flesh foods consumption, a 1.19 kcal (0.03%) increase in dairy, a 1.63 kcal (0.02%) increase in nuts and seeds, a 0.07 (0.02%) kcal increase in pulses, a 0.49 kcal (0.02%) increase in eggs consumption, and a 4 kcal (0.03%) increase in vegetables consumption. The magnitude of these changes in terms of a percentage change from mean consumption are very similar across these food types. There is an approximately 0% change associated between PCE and changes in starchy staple foods and fruit consumption.

Changes in diet may be driven both by wealth and the technology of refrigeration. However, in order for households to purchase a refrigerator, they must attain the level of wealth necessary to buy this technology. The relative influence of refrigerator ownership on the consumption of food types and the influence of the typical amount of money required for a Vietnamese household to purchase a refrigerator are assessed and compared.

As seen in Figure 4.4, refrigeration is associated with the largest estimated decrease (starchy staple food consumption) and PCE is associated with the largest estimated increase (flesh foods). Refrigeration and a 200 USD change in PCE are associated with statistically significant increases of both flesh foods and dairy consumption, with the PCE change associated with a larger increase. Refrigerator ownership is statistically significantly associated with a decrease in starchy staple foods, and the PCE increase is associated with no change in this food group. Refrigerator ownership and a PCE increase are statistically significantly associated with opposite effects for nuts and seeds and pulses (associated with a decrease and increase in consumption, respectively). PCE is statistically significantly associated with changes in eggs, fruit, and vegetable consumption, while refrigeration is not.

4.3.4 The Influence of Socio-Economic Variables on Diet

Coefficients estimated for some of the socio-economic control variables provide additional insights into the influence of development on diet. The urban indicator variable is negatively associated with starchy staple foods and nuts and seeds consumption, but positively associated with the consumption of all other food types excluding pulses (with coefficient sizes ranging from 0.18 for dairy to 0.05 for flesh foods) at statistically significant levels, reflecting the same pattern seen with per capita expenditure.

Coefficients for the education level variable indicate an “inverted U” relationship for flesh foods: with a positive association between consumption and attaining a secondary/high school education level, but a decreasing association with attaining a university-level education. These both occur at statistically significant levels and similar magnitudes (a coefficient of 0.04 for secondary/high school, and -0.03 for university). Dairy has a linear and statistically significant association with education: increasing with a coefficient of 0.03 for a secondary education, and 0.17 for university educational attainment.

Increasing household size is positively and statistically significantly associated with increases in starchy staple food consumption, and statistically significant decreases in nuts and seeds, pulses, egg, vegetable, fruit, and dairy consumption. Flesh foods display the only association with variation, with statistically significant increases associated in consumption associated with house size until reaching its largest category (> 6), which is negatively associated with flesh foods consumption.

4.3.5 Non-Consumption of Food Types

Households reporting zero consumption of food types are assessed, corresponding to the ν coefficient (log odds of non-consumption) estimated in the regression models estimated. Table 4.2 displays percentages of non-consumption of each food type by year and refrigerator ownership status. The implications of these statistics and results for non-consumption from regression modeling are then discussed as follows.

Percent of Households Not Consuming Food Groups	2004		2006		2008		2010		2012		2014	
	Non-Refrigerator Owning	Refrigerator Owning	Non-Refrigerator Owning	Refrigerator Owning	Non-Refrigerator Owning	Refrigerator Owning	Non-Refrigerator Owning	Refrigerator Owning	Non-Refrigerator Owning	Refrigerator Owning	Non-Refrigerator Owning	Refrigerator Owning
Starchy Staple Foods	0.02%	0%	0.02%	0.01%	0.02%	0.01%	0.20%	0.01%	0.10%	0.04%	0.11%	0.02%
Nuts and Seeds	11.19%	0.68%	10.9%	1.46%	8.34%	1.85%	14.2%	4.76%	14.4%	6.86%	10.8%	7.70%
Pulses	40.3%	5.02%	42.9%	8.15%	35.5%	11%	51.7%	26.6%	48%	36.2%	36.2%	48.3%
Flesh Foods	0.05%	0.01%	0.05%	0.01%	0.02%	0.02%	0.3%	0.03%	0.08%	0%	0.09%	0%
Eggs	10.2%	0.79%	11.7%	1.33%	7.57%	1.11%	12.3%	3.23%	11%	4.2%	8.63%	6.43%
Vegetables	0.18%	0.05%	0.17%	0.02%	0.14%	0.02%	0.41%	0.03%	0.36%	0.07%	0.7%	0.24%
Fruit	14.5%	0.72%	14.8%	1.34%	10.4%	1.57%	23.9%	7.22%	24%	10.9%	17.6%	12.5%
Dairy	46.6%	2.77%	43.3%	4.21%	32.2%	6.62%	38%	12.7%	32.6%	14.8%	23.6%	19.1%

Table 4.2: Percentage of Households in each VHLSS response year which report consuming no quantity of each food type (kcal/day-adult equivalent) and either do or do not own a refrigerator

Non-consumption (zero consumption of a food category reported) is observed to be very low for dietary staples, notably starchy staple foods, flesh foods, and vegetables, independent of refrigerator ownership. Flesh foods consumption is observed to increase significantly in connection with refrigerator ownership, though the low values of non-consumption (all less than 1%) indicate that nearly all households are consuming at least some quantity of flesh foods. Rates of fruit and dairy non-consumption are larger among households without refrigerators than those with, though the difference between these groups decreased over time (with non-consumption of fruit and dairy being 13.8% and 43.9% greater, respectively, for households without refrigerators in 2004, compared with 5.1 and 4.5% in 2014). Nuts and seeds non-consumption is higher for households without refrigerators than for those with and decreases over the observation period, while non-consumption is lower for households with refrigerators but is increasing over time. Rates of pulses non-consumption are fairly high across years, and increases notably for households with refrigerators over the time period observed (from 5.02% compared with 40.30% for non-owning households in 2004 to 48.30% for refrigerator-owning households compared with 36.22% for non-owning households in 2014).

It should be noted that the ν coefficients apply to an extreme low end of the distributions of food consumption, which applies far more frequently to dairy, fruit, and eggs (with 19,663, 9,802, and 5,927 households not recording expenditure on each respective food) than foods such as starchy staple foods or flesh foods (with 44 and 52 households recording no expenditure on each, respectively). Refrigerator ownership is negatively and statistically significantly associated with odds of non-consumption for all food types. PCE is found to be negatively associated with odds of non-consumption for dairy, fruit, pulses, and eggs; positively associated with odds of non-consumption of flesh foods and starchy staple foods, and associated with a zero change in nuts and seeds consumption, all at a statistically significant level ($p < 0.001$).

4.3.6 Consumption of Self-Produced or Purchased Foods

Households which do not own a refrigerator consume a higher share food from their own production than households who do own a refrigerator, as illustrated in Figure 4.5.

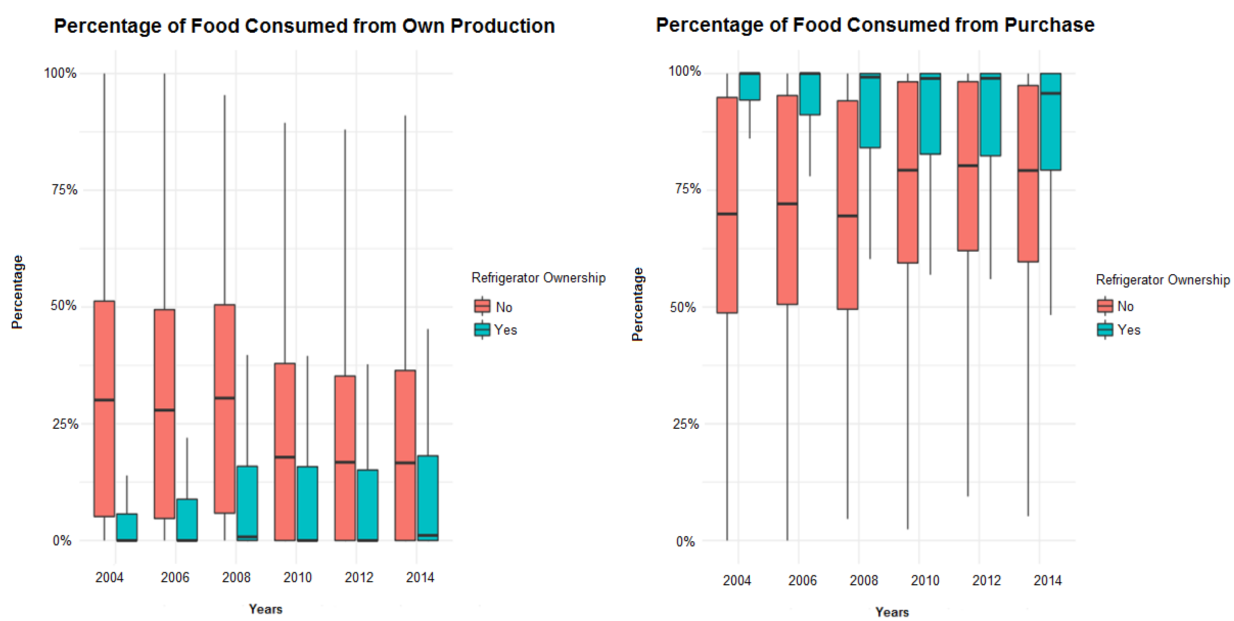


Figure 4.5: Boxplots of proportions of food consumed from a household's own production (left) or purchased external to the home (right). Proportions are of the food when characterized into monetary values, and displayed for households with or without refrigerators.

This trend coincides with a similar division by income: the average household in the highest income quintile purchases 92% of their food over the years observed, compared with 58% for households in the lowest quintile. An average lowest quintile household produces 42% of their food consumed over the observed years, compared with 7% for an average household in the highest income quintile.

4.3.7 Dietary Diversity

Acquired Dietary Diversity Score (aDDS) measures the quantity of different food groups acquired by a household through food purchases, own production, and food received. A higher aDDS score reflects a diet consisting of a greater variety of foods. For a total of nine food groups, aDDS scores range from 1 to 9, reflecting a simple count of whether there is reported consumption of foods within each food group by the household (see Appendidx B.2 for food types per group). Dietary diversity measures positively correlate with nutrient adequacy for individuals in both developing and developed countries (Ruel, 2003), however, the relationship between dietary diversity and food system development remains a research gap. Dietary Diversity as it relates to refrigerator ownership over the time period observed in displayed in Figure 4.6.

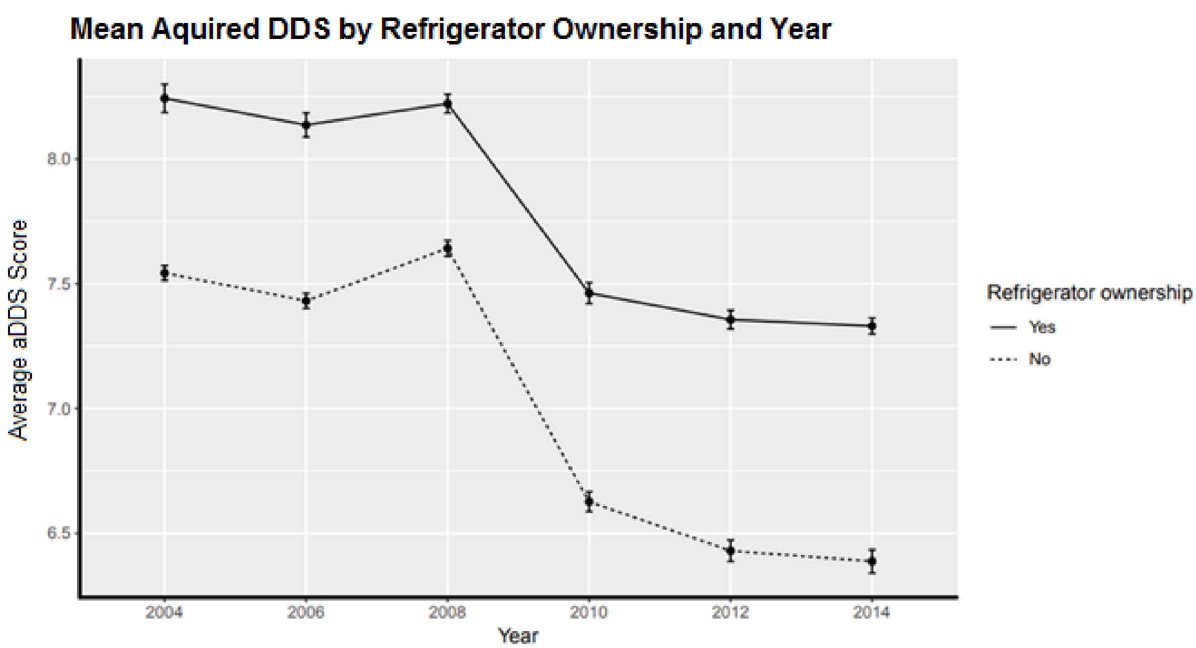


Figure 4.6: Acquired Dietary Diversity Scores (out of a maximum of 9) by year and refrigerator ownership status in VHLSS data (2004-2014). Error bars represent 95% confidence intervals.

aDDS is higher for refrigerator-owning households in all observations periods as compared to households that do not own refrigerators (by an average of 0.78), with this gap widening in recent years. Refrigerator-owning households experience an aDDS decrease of 11% over the observation period, compared with a decrease of 15% for non-owning households. However, mean aDDS is lower among both groups in 2010, 2012 and 2014 as compared to earlier survey years. Reasons for the aDDS decline may include increases in the consumption of the "other" food group over the observation period, as well as the VHLSS food categories remaining fixed over the years, despite new foods being increasingly introduced in Vietnam through import or general increases in availability. When running the regression model with aDDS as the outcome variable, refrigerator ownership is found to be positively and statistically-significantly associated with aDDS (with a coefficient of 0.03), as is per capita expenditure, though with a near-zero coefficient.

5.4 Discussion

At a basic level, the purpose of a refrigerator is to increase the capacity to store perishable foods. This study finds that when controlling for socio-economic variables, refrigerator ownership is statistically significantly associated with decreases in the consumption of less-perishable food types (starchy staple foods, nuts and seeds, pulses), significantly associated with increases in the consumption of some perishable food types (flesh foods, dairy) but not all (with no statistically significant association with fruit, vegetable, or egg consumption).

The magnitudes of the changes in the caloric contribution of flesh foods and dairy in the diet associated with refrigerator ownership are quite small. For example, a single serving of pork (approx. 85 g) may contribute 150-200 kcal depending on its preparation, while a single serving of whole milk (approx. 250 mL) may contribute approximately 150 kcal. Compared to the 12 and 3 kcal/day/adult equivalent changes in flesh foods and dairy, respectively, that were observed to be associated with refrigerator ownership, the impacts on cumulative nutrient intakes of these changes might be expected to be quite small. In contrast, a 135 kcal/day/adult equivalent decline in starchy staple foods may be more impactful, representing approximately 1 serving of cooked white rice (100 g of cooked white rice contains approximately 150 kcal). Given the low overall consumption of pulses in Vietnam (i.e., 1.9 kcal/day per adult equivalent on average across all survey years), even large percentage changes in consumption of pulses would likely have minimal effect on overall dietary intake. Therefore, the estimated 8.3% decline in consumption of pulses associated with refrigerator ownership is likely not nutritionally meaningful. Though consumption of nuts and seeds is somewhat higher in the country (40.8 kcal/day per adult equivalent), the 7.4% decrease in consumption of nuts and seeds associated with refrigerator ownership represents a decrease of approximately 3 kcal/day per adult equivalent— just a small fraction of the recommended daily caloric contribution of nuts and/or seeds (i.e., the average recommended daily intake of nuts and seeds is approximately 42 grams (1.5 oz) which equates to approximately 250 kcal/day from cashews or sunflower seeds, for example). While many changes observed are small in calorific terms, if the consumption of food types increases within Vietnam, then changes associated with refrigerator ownership and wealth (estimated as percentage changes from mean consumption) may be more meaningful in absolute terms.

One limitation of this study is that each regression estimated only considers the consumption of one food type. Households very typically consume food from more than one food group, however, regression models including the variables for more than one food type became too multicollinear for interpretation when tested.

Refrigerator ownership in Vietnam increases over the time period studied, as does mean per capita expenditure and other developmental indicators. Wealth is connected to both the ability to own a refrigerator and with dietary shifts, and a refrigerator is a technological pre-condition to support diets which have higher quantities of perishable foods. While associations between refrigerator ownership and diet shifts have been identified when controlling for income effects, refrigerator ownership is unlikely to occur wholly independently of wealth increases. As such, refrigerator ownership has diet-shifting effects, but is concurrently a necessary enabler for wealth effects.

Refrigerator ownership and income growth are occurring within the context of grocery retail development in Vietnam. The growth in supermarket retailing in Asia has been associated with refrigerator ownership in addition to income growth, urbanization, and other elements of development (Shepherd, 2005). Retail development typically results in more centralized food provision, realized in its fullest form as groceries of all types sold in a supermarket or hypermarket. This process of “de-fragmentation” in retail is characterized as occurring first for dry goods, then later for fresher foods (Reardon et al., 2003). Vietnamese retail sales through “modern” grocery retailers grew by 11% in 2017, though the quantity of these stores are still vastly outnumbered by traditional retailers (Vo and Francic, 2017) and with 77%–99% of food expenditures by urban consumers still occurring at traditional outlets (The Centre for Global Food and Resources, 2018a). Supermarket shopping in Vietnam is stratified by income, with lower-income consumers found to be purchasing less from supermarkets, and more from a diversity of outlets (both formal and informal), considering factors including accessibility, the ability to purchase on credit, and prices (Figuié and Moustier, 2009). Supermarket purchasing has been found to be highly income-elastic, with income's effect playing a stronger role in influencing fruit and vegetables purchases at a supermarket than price or supermarket penetration in Vietnam (Mergenthaler et al., 2009). Findings from this study showing smaller and often non-significant changes in fruit and vegetable consumption suggest a continuation of purchasing produce from more-traditional, local vendors. Lower prices, the proximity of these venues, as well as traditional shopping habits have been noted as maintaining this practice (Maruyama and Trung, 2007).

These findings align with the literature examining socio-economic variables and dietary outcomes in Vietnam. Those with higher incomes, education levels, and residing in urban areas have been positively associated with the consumption of more-diverse foods, with the variety measure increasing faster with an income increase for less-educated groups than higher-educated groups, indicating some non-linearity in dietary and socio-economic relationships (Chul Ahn et al., 2006). Non-linearity has also been modeled for per-capita expenditure and per capita calorie consumption in Vietnam (Trinh Thi et al., 2018). In an assessment of energy intake by food type, rural households are found to consume larger total quantities of food and have higher energy intake than urban households, but consume fewer animal products, fruits, and vegetables, with most energy derived from starches (Dien et al., 2004).

In health outcomes, a trend towards higher body mass index values for children connected with increased household food expenditures at supermarkets may be emerging (The Centre for Global Food and Resources, 2018b), which in the context of Vietnam may lead to a situation where parts of the population are overweight, with other portions of the population undernourished (Khan and Ha, 2008).

Meat accounts for the largest share of monthly food expenditures among Vietnamese households, with pork accounting for an average of 32% to 40% of meat expenditures (The Centre for Global Food and Resources, 2018c). Vietnam has also experienced a growth in beef consumption in recent years. While still 5.2 times smaller than pork supply, there has been an almost 180% increase in beef supply between 2001-2011, making beef the largest greenhouse gas emissions-contributor in the Vietnamese meat supply (Heller et al., 2019). This increase in beef consumption has been characterized as part of the "meatification" of the Vietnamese food system (Hansen, 2018): encompassing the intensification of production systems, addition of more meat to traditional meals, changes in consumption patterns for food, as well as the role of meat as a socio-economic status symbol.

The availability of refrigerators has implications for nutrition and sustainability outcomes. Concurrent and pressing challenges from malnutrition and health burdens, climate change and environmental pressures, in addition to socio-economic and cultural inequities motivate a broader consideration of diet in the context of sustainability. The interdependencies between these considerations motivate the concept of a sustainable diet (Johnston et al., 2014). Analyses of these interconnected relationships in Vietnam is an essential task for future research. Integrated metrics assessing these dimensions of dietary transitions provides an opportunity to assess the multi-faceted elements of sustainable diets (Jones et al., 2016).

There are particular research gaps related to refrigeration's effects on nutrition and food system development (Heard and Miller, 2016). Topics explored in this analysis but still in need of further study include both the effects of refrigeration and wealth in isolation, but also their interactions and interdependencies. Research addressing the relationship between refrigeration and infrastructure such as the electricity grid and transportation networks is also needed. Finally, culture and tradition must not be overlooked when assessing diet shifts, development, and the use of technology. This study finds that the practice of shopping for fruits and vegetables on a regular basis from informal vendors (Maruyama and Trung, 2007; The Centre for Global Food and Resources, 2018a) may explain the lack of association between refrigeration and fruits and vegetables, and PCE's statistically significant near-zero relationship with fruit. This study's findings provide some insights into refrigerator ownership's connection with diet, but this topic remains in need of continuing research.

4.5 References

Arita, S., Dyck, J., 2014. Vietnam's Agri-food Sector and the Trans-Pacific Partnership.

Barber, J., Thompson, S., 2004. Multiple regression of cost data : use of generalised linear models. J Heal. Serv Res Policy 9, 197–204.

Baulch, B., Masset, E., 2003. Do monetary and nonmonetary indicators tell the same story about chronic poverty? A study of Vietnam in the 1990s. World Dev. 31, 441–453. doi:10.1016/S0305-750X(02)00215-2

Bhalotra, S., Attfield, C., 1998. Intrahousehold Resource Allocation in Rural Pakistan : A Semiparametric Analysis. J. Appl. Econom. 13, 463–480.

Chul Ahn, B., Engelhardt, K., Joung, H., 2006. Diet variety is associated with socio-economic factors. Ecol. Food Nutr. 45, 417–430. doi:10.1080/03670240600985183

CRAN, 2018. gamlss.family: Family Objects for fitting a GAMLSS model [WWW Document]. gamlss.dist. URL https://rdrr.io/cran/gamlss.dist/man/gamlss.family.html

Deaton, A., 1997. The analysis of household surveys: A microeconometric approach to development policy. Johns Hopkins University Press. doi:doi:10.1596/0-8018-5254-4

Dien, L.N., Thang, N.M., Bentley, M.E., 2004. Food consumption patterns in the economic transition in Vietnam. Asia Pac. J. Clin. Nutr. 13, 40–47.

Euromonitor, 2017. Grocery Retailers in Vietnam.

Figuié, M., Moustier, P., 2009. Market appeal in an emerging economy: Supermarkets and poor consumers in Vietnam. Food Policy 34, 210–217. doi:10.1016/j.foodpol.2008.10.012

Food and Agriculture Organization of the United Nations, 2016. Minimum Dietary Diversity for Women: A Guide for Measurement. Rome.

Garnett, T., 2011. Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? Food Policy 36, S23–S32. doi:10.1016/j.foodpol.2012.04.006

Garnett, T., 2007. Food Refrigeration: What is the Contribution to Greenhouse Gas Emissions and How Might Emissions Be Reduced?

Garnett, T., Wilkes, A., 2014. Appetite for Change: Social , economic and environmental transformations in China's food system, Food Climate Research Network. doi:10.1007/s13398-014-0173-7.2

Gligor, D., Tan, A., Nguyen, T.N.T., 2018. The obstacles to cold chain implementation in developing countries: insights from Vietnam. Int. J. Logist. Manag. 29, 942–958. doi:10.1108/IJLM-02-2017-0026

Godfray, H.C., Aveyard, P., Garnett, T., Hall, J.W., Key, T.J., Lorimer, J., Pierrehumbert, R.T., Scarborough, P., Springmann, M., Jebb, S.A., 2018. Meat consumption, health, and the environment. Science (80-.). 361. doi:10.1126/science.aam5324

Hansen, A., 2018. Meat consumption and capitalist development : The meatification of food provision and practice in Vietnam. Geoforum 93, 57–68. doi:10.1016/j.geoforum.2018.05.008

Heard, B.R., Miller, S.A., 2019. Potential Changes in Greenhouse Gas Emissions from Refrigerated Supply Chain Introduction in a Developing Food System. Environ. Sci. Technol. 53, 251–260. doi:10.1021/acs.est.8b05322

Heard, B.R., Miller, S.A., 2016. Critical research neeeded to examine the environmental impacts of expanded refrigeration on the food system. Environ. Sci. Technol. 50, 12050–12071. doi:10.1021/acs.est.6b02740

Heller, M.C., Walchale, A., Heard, B.R., Hoey, L., Khoury, C.K., Haan, S. De, Burra, D.D., Duong, T.T., Osiemo, J., Trinh, T.H., Jones, A.D., 2019. Environmental analyses to inform transitions to sustainable diets in developing countries : case studies for Vietnam and Kenya. Int. J. Life Cycle Assess. 1–14. doi:https://doi.org/10.1007/s11367-019-01656-0

International Organization for the Development of Refrigeration, 2009. 5th Informatory Note on Refrigeration and Food: The role of refrigeration in worldwide nutrition. Paris.

Johnston, J.L., Fanzo, J.C., Cogill, B., 2014. Understanding Sustainable Diets: A Descriptive Analysis of the Determinants and Processes That Influence Diets and Their Impact on Health, Food Security, and Environmental Sustainability. Adv. Nutr. An Int. Rev. J. 5, 418–429. doi:10.3945/an.113.005553

Jones, A.D., Hoey, L., Blesh, J., Miller, L., Green, A., Shapiro, L.F., 2016. A Systematic Review of the Measurement of Sustainable Diets. Adv. Nutr. An Int. Rev. J. 7, 641–664. doi:10.3945/an.115.011015

Khan, N.C., Ha, H.K., 2008. Double burden of malnutrition: The Vietnamese perspective. Asia Pac. J. Clin. Nutr. 17, 116–118. doi:10.1016/j.epsl.2017.12.039

Maruyama, M., Trung, L.V., 2007. Supermarkets in Vietnam: Opportunities and obstacles. Asian Econ. J. 21, 19–46. doi:10.1111/j.1467-8381.2007.00245.x

Mergenthaler, M., Weinberger, K., Qaim, M., 2009. The food system transformation in developing countries: A disaggregate demand analysis for fruits and vegetables in Vietnam. Food Policy 34, 426–436. doi:10.1016/j.foodpol.2009.03.009

Minot, N., Baulch, B., Epprecht, M., 2006. Poverty and inequality in Vietnam: spatial patterns and geographic determinants. doi:10.2499/0896291510

National Bureau of Statistics of China, 2019. Number of refrigerators per 100 rural and urban households in China from 1990 to 2017 [WWW Document]. Stat. - Stat. Portal. URL https://www.statista.com/statistics/278747/number-of-refrigerators-per-100-households-in-china/ (accessed 3.4.19).

National Institute of Nutrition, 2013. Vietnamese food composition table. Medical Publishing House, Hanoi, Vietnam.

Parfitt, J., Barthel, M., Macnaughton, S., 2010. Food waste within food supply chains: quantification and potential for change to 2050. Philos. Trans. R. Soc. Lond. B. Biol. Sci. 365, 3065–81. doi:10.1098/rstb.2010.0126

Popkin, B.M., 2001. The Nutrition Transition and Obesity in the Developing World, in: Caballero, B., Mokhtar, N. (Eds.), Symposium: Obesity in Developing Countries: Biological and Ecological Factors. American Society for Nutritional Sciences, San Diego, CA, pp. 871–873.

Reardon, T., Timmer, C.P., Barrett, C.B., Berdegué, J., 2003. The rise of supermarkets in Africa, Asia, and Latin America. Am. J. Agric. Econ. 85, 1140–1146. doi:10.1111/j.0092-5853.2003.00520.x

Rigby, B., Stasinopoulos, M., 2009. A flexible regression approach using GAMLSS in R.

Ruel, M.T., 2003. Operationalizing Dietary Diversity: A Review of Measurement Issues, in: Demment, M., Allen, L. (Eds.), Animal Source Foods to Improve Micronutrient Nutrition and Human Function in Developing Countries. Washington, DC, pp. 3911S-3926S.

Shepherd, A.W., 2005. The implications of supermarket development for horticultural farmers and traditional marketing systems in Asia. Rome.

Stasinopoulos, M. (London M.U., Rigby, R.A. (London metropolitan U., 2007. Generalized Additive Models for Location Scale and Shape (GAMLSS) in R. J. Stat. Softw. 223, 1–46. doi:10.1111/j.1467-9876.2005.00510.x

Thang, N.M., Popkin, B.M., 2004. Patterns of food consumption in Vietnam : effects on socioeconomic groups during an era of economic growth. Eur. J. Clin. Nutr. 58, 145–153. doi:10.1038/sj.ejcn.1601761

The Centre for Global Food and Resources, 2018a. The Vietnam Urban Food Consumption and Expenditure Study Factsheet 4: Where do consumers shop? Wet markets still dominate! The.

The Centre for Global Food and Resources, 2018b. The Vietnam Urban Food Consumption and Expenditure Study Factsheet 12: Are there relationships between food shopping behaviour and diet- related health outcomes for urban Vietnamese consumers?

The Centre for Global Food and Resources, 2018c. The Vietnam Urban Food Consumption and Expenditure Study Factsheet 11: What meat products do consumers purchase and does meat consumption change with increased income?

The World Bank, 2018. Vietnam [WWW Document]. World Bank Data. URL https://data.worldbank.org/country/vietnam

Tong, E.N.C., Mues, C., Thomas, L., 2013. A zero-adjusted gamma model for mortgage loan loss given default. Int. J. Forecast. 29, 548–562. doi:10.1016/j.ijforecast.2013.03.003

Trinh Thi, H., Simioni, M., Thomas-Agnan, C., 2018. Assessing the nonlinearity of the calorie-income relationship: An estimation strategy – With new insights on nutritional transition in Vietnam. World Dev. 110, 192–204. doi:10.1016/j.worlddev.2018.05.030

USDA Economic Research Service, n.d. Ownership of household amenities among selected countries [WWW Document]. URL https://www.ers.usda.gov/media/9393/householdamenities.xls

Vo, K., Francic, M., 2017. Vietnam Retail Foods - Sector Report 2018.

World Health Organization, 2008. Indicators for assessing infant and young child feeding practices: Part 1 Definitions.

World Wildlife Fund, 2016. Power Sector Vision: Towards 100% Renewable Energy by 2050 In Greater Mekong Region - Vietnam Report.

Zezza, A., Carletto, C., Fiedler, J.L., Gennari, P., Jolliffe, D., 2017. Food counts. Measuring food consumption and expenditures in household consumption and expenditure surveys (HCES). Introduction to the special issue. Food Policy 72, 1–6. doi:10.1016/j.foodpol.2017.08.007

Chapter 5

Greening the Cold Chain

Heard BR, Miller SA. "Greening the Cold Chain." In preparation for *Environmental Science & Technology*.

Abstract

Refrigerated supply chains are expanding worldwide, changing the greenhouse gas (GHG) emission profile for the food system by altering food waste patterns, increasing energy use, and increasing the use and potential release of refrigerants. Interventions for decreasing the emissions burden from refrigeration and food supply are essential elements of meaningful climate change mitigation. This study models 28 potential cold chain interventions to assess potential changes in life cycle GHG emissions (kg CO_2e/kg) for 1 kg each of fresh broccoli, frozen broccoli, fresh chicken, frozen chicken, apples, fresh fish, frozen fish, and milk. The largest absolute emissions reduction recorded is 1.20 kg CO_2e/kg frozen fish supplied, from using decarbonized electricity, representing 39% of GHG emissions from frozen fish. The largest percentage reduction is 64% (1.06 kg CO_2e/kg) from ambient retailing of fresh broccoli. Across food types, the largest absolute reductions were obtained from zero-emissions electricity, improved supermarket refrigeration systems, zero hours in retail, or a complete reductions in pre-consumer food losses. When combining interventions, reductions of up to 1.61 kg CO2e/kg frozen fish can be obtained, when combining zero-emissions electricity with a CO_2NH_3 supermarket refrigeration system. The foods most responsive to cold chain interventions were broccoli, apples, and fish, given the relatively higher supply chain emissions burden added post-agricultural production. Adopting

effective and practical refrigerated supply chain improvements can provide meaningful GHG reductions in the food supply chain.

5.1 Introduction

Refrigerated food supply chains are the backbone of modern food distribution. An integrated refrigerated supply chain, or "cold chain," is ubiquitous in developed food systems, but is also connected with notable greenhouse gas (GHG) emissions associated with energy consumption and unintended releases of refrigerants. This analysis assesses potential interventions for reducing GHG emissions from supplying food through the cold chain.

Refrigeration is a technology that transforms food supply chains, but is largely understudied in the sustainability literature (Heard and Miller, 2016). It is critical to better-understand the full scope of the role that refrigeration plays in our food system and environment, as cold chain technology is embedded in every stage of a modern, developed food supply chain (Garnett, 2011a). In a review of opportunities for climate change mitigation in the food supply chain, (Niles et al., 2018) identify the adoption of high-efficiency processing and refrigeration systems as important means for reducing emissions. In contrast to the current literature on cooling and refrigeration's potential for climate change mitigation which largely summarizes existing statistics, this paper develops a refrigerated supply chain model, establishes baseline GHG emissions for supplying foods, then models potential cold chain interventions to determine their relative effectiveness at reducing emissions to supply these food types.

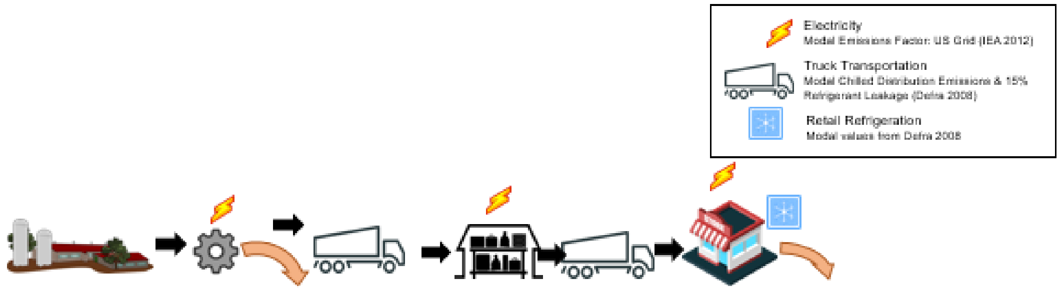
The environmental impacts of refrigeration come from two main sources: refrigerants and electricity. The climate change impacts from refrigerant leakage is a topic of great concern, given their often-high global warming potential values (Calm, 2008). Motivated by the benefits from eliminating high-GWP refrigerants, the Kigali Amendment to the Montreal Protocol phases-down hydrofluorocarbon refrigerants as a means for climate change mitigation (United Nations Environment Programme, 2016). In addition, energy efficiency and the impacts of electricity consumption for refrigeration has been identified as having key importance to improving the sustainability of the cold chain (James and James, 2013). Refrigeration is estimated to account for 17% of electricity use worldwide (Coulomb et al., 2015) and the cold chain is estimated to contribute 1% of total global CO_2 emissions (James and James, 2010). It is also important to remember that the cold chain encompasses more than refrigerated storage. Environmental burdens from an integrated refrigerated supply chain also include the transportation and logistics connecting refrigerated storage, with mitigation opportunities present for these cold chain elements as well (Halldórsson and Kovács, 2010).

The cold chain is expanding rapidly into areas of the developing world (Salin, 2018), making identifying effective means of decreasing the environmental burdens from refrigerated supply chains critical. When modeling the introduction of the cold chain in a developing food system, (Heard and Miller, 2019) find that the cold chain will likely add more emissions through its operation that it will save through pre-retail food loss reductions if cold chain development is not accompanied by simultaneous improvements in logistics and efficiency. (Hu et al., 2019) find that a cold chain expansion could result in a net emissions decrease through food loss reductions for meat, milk and aquatic products and (James and James, 2010) posit that if adequate energy efficiency improvements are attained, the cold chain can expand into developing food systems without an increase in emissions.

This study establishes a model of a typical pre-consumer refrigerated food supply chain as exists in a developed, industrialized food system, recording the GHG emissions required to supply 1 kg of food through the supermarket retailing process. 25 interventions are developed and applied to this cold chain, examining the effects of commonly-recommended methods for reducing refrigerated supply chain GHG emissions. The changes in emissions required to supply food to retail are then recorded and assessed.

5.2 Methods

This study models the life cycle greenhouse gas emissions from agricultural production through grocery retail for 1 kg of food (kg CO_2e/kg). Interventions to reduce GHG emissions associated with cold chain improvements are then modeled in this supply chain structure. The foods assessed are fresh broccoli, frozen broccoli, fresh chicken, frozen chicken, apples, fresh fish, frozen fish, and milk. These foods were selected because they cover a variety of typically-consumed food types (vegetables, meat, fruit, seafood, dairy) in both fresh and frozen varieties. These particular items were selected because there were detailed life cycle assessment studies available providing granular information about their production processes and packaging quantities. Data on the emissions for producing each food comes from the ecoinvent 3.4 database and characterized by the IPCC GWP 100 factor. The packaging required per kg of food, and processing energy burdens are obtained from the LCA studies for broccoli (Canals et al., 2008), chicken (González-García et al., 2014), apples (Blanke and Burdick, 2005), fish (Svanes et al., 2011), and milk (Hospido et al., 2003). These data are then harmonized with the energy and emissions for post-processing food supply chains reported in (Defra, 2008), covering regional distribution storage, truck transportation, and grocery retailing. A depiction of the food supply chain modeled and the corresponding data sources are shown in Figure 5.1.



	Agricultural & Packaging Production	Processing	Processing Food Losses (Modal Loss Rate, Gustavsson et al. 2011)	Regional Distribution Center Storage	Grocery Store Retailing	Retail Food Losses (Modal Loss Rate, Buzby et al. 2014)
Fresh Broccoli	Ecoinvent 3.4	Processing electricity from Canals et al. 2008	2%	Storage emissions from Canals et al. 2008	Refrigerated display cabinet (Defra 2008)	10%
Frozen Broccoli	Ecoinvent 3.4	Processing electricity, natural gas, & diesel from Canals et al. 2008	2%	Storage emissions from Canals et al. 2008	Display Cabinet & Walk-In Storage (Defra 2008)	6%
Fresh Chicken	Ecoinvent 3.4	Processing electricity & diesel from González-García et al., 2014	5%	Storage emissions from Defra 2008	Display Cabinet & Walk-In Storage (Defra 2008)	4%
Frozen Chicken	Ecoinvent 3.4	Processing electricity & diesel from González-García et al., 2014	5%	Storage emissions from Defra 2008	Display Cabinet & Walk-In Storage (Defra 2008)	4%
Apples	Ecoinvent 3.4	Initial cooling: Blanke and Burdick, 2005	2%	Storage emissions from Defra 2008	Refrigerated display cabinet (Defra 2008)	12%
Fresh Fish	Ecoinvent 3.4	Processing electricity from Svanes et al., 2011	6%	Storage emissions from Svanes et al., 2011	Display Cabinet & Walk-In Storage (Defra 2008)	8%
Frozen Fish	Ecoinvent 3.4	Processing electricity from Svanes et al., 2011	6%	Storage emissions from Svanes et al., 2011	Display Cabinet & Walk-In Storage (Defra 2008)	8%
Milk	Ecoinvent 3.4	Processing electricity from Hospido et al., 2003	1.2%	N/A (zero hours storage; Defra 2008)	Display Cabinet & Walk-In Storage (Defra 2008)	2%

Figure 5.1: Depictions of the food supply chain processes for each food type modeled, with key parameters described. A detailed list of all model parameters is included in Appendix C.

Because the study focuses specifically on interventions within the commercial cold chain, emissions associated with transportation to households, household refrigeration, food preparation, and disposal are outside the boundaries of this analysis. The hours food is retailed in display cabinet and stored in walk-in coolers or freezers is taken from (Defra, 2008). Values in

(Defra, 2008) for fresh strawberries are used for fresh broccoli, and frozen peas for frozen broccoli, due to data limitations. No retail walk-in refrigeration is applied to fresh produce (Defra, 2008), but this emissions burden is applied to meat, dairy, and frozen foods, reflecting typical retailer practices. Additionally, milk is not subject to regional distribution center storage as per (Defra, 2008), instead trucked directly to grocery retailing from processing. The burdens from capital equipment manufacturing are excluded from this study, as is the production of refrigerated equipment used in the cold chain and its end-of-life disposal impacts. Monte Carlo distributions are defined for all supply chain parameters, and the model is run 10,000 times. Multipliers reflecting interventions (e.g. a 25% less-emitting electricity grid) are applied to the results of the Monte Carlo draws.

Food (of each food type studied, F) which must be supplied to the store to yield 1 kg of food entering retail (Q_{R_F}) is:

$$Q_{R_F} = \frac{Q_{C_F}}{(1 - R_{R_F})}$$

Where Q_{C_F} is the 1 kg of food F available to the consumer (kg) and R_{R_F} is the retail food loss rate (%) for each particular food type.

Similarly, the food which must be created at the beginning of the supply chain (before processing losses) (kg) is:

$$Q_{X_F} = \frac{Q_{R_F}}{(1 - R_{X_F})}$$

GHG emissions (kg CO_2e) from agricultural production are:

$$E_F = Q_{X_F} * C_F$$

Where C_F is the emissions factor (kg CO_2e/kg) for producing food type F. Packaging emissions burdens E_{P_F} (kg CO_2e) per kg of food are calculated similarly:

$$E_{P_F} = P_F * C_{P_F}$$

Where P_F is the quantity of packaging (kg) required to supply 1 kg of food F and C_{P_F} is the emissions burden (kg CO_2e/kg) associated with that packaging production.

Processing emissions E_X (kg CO_2e) are calculated as:

$$E_{X_F} = Q_{X_F} * C_{X_F}$$

Where C_{X_F} (kg CO_2e/kg) is the emissions burden from processing. C_{X_F} is the electricity grid emissions factor for electricity used and/or the combustion emissions for fuels used in processing.

The emissions from truck distribution E_T (kg CO_2e) are:

$$E_{T_F} = Q_{X_F} * L_F * D_T * C_T$$

Where C_T is trucking emissions (kg CO_2e/pallet-km) including truck operation and associated refrigerant leakage, D_T is km traveled, and L_F is the multipler reflecting kg of food F per shipping pallet.

Regional Distribution Center (RDC) storage emissions E_{S_F} are computed as

$$E_{S_F} = Q_{R_F} * C_{S_F}$$

Where C_{S_F} (kg CO_2e/kg) is the emissions associated with storing food F at an RDC.

Grocery store retailing emissions E_{G_F} (kg CO_2e) are

$$E_{G_F} = [Q_{R_F} * H_{D_F} * C_{D_F}] + [Q_{R_F} * H_{W_F} * C_{A_F}]$$

C_{D_F} is display cabinet operation including refrigerant leakage emissions (kg CO_2e/kg-h)

H_{D_F} is hours in refrigerated display cabinet by food type

$H_{W_F}$is hours in walk-in refrigeration by food type

C_{A_F} is walk-in refrigeration emissions, including refrigerant leakage (kg CO_2e/kg-h)

Interventions are modeled using multipliers to reflect the percentage difference between GHG emissions in the baseline case and those recorded after the intervention. Interventions were selected to reflect typically-recommended solutions for supply chain emissions reductions, and narrowed down to ones with existing, detailed data for supplying a specific food type. For example, a 25% decrease in electricity grid emissions-intensity applies a multiplier of .75 to the Monte Carlo value drawn for the electricity grid emissions factor. For technology-substitution interventions (e.g. switching supermarket refrigeration systems), multipliers are calculated from the ratio of emissions from the new technology compared with that from the original technology. The 26 interventions evaluated and relevant data sources are summarized as follows in Table 5.1. These interventions were selected because they have been identified in the literature as possible means for cold chain emissions mitigation (Garnett, 2011; Heard and Miller, 2016; Niles et al., 2018) and have studies available specifying their emissions impacts in sufficient detail for modeling.

Intervention	**Notes**
5% Reduction in Truck Refrigerant Leakage	Results in 10% refrigerant leakage rate (baseline leakage rate is 15% as per (Defra, 2008))
10% Reduction in Truck Refrigerant Leakage	Results in 5% refrigerant leakage rate (baseline leakage rate is 15% as per (Defra, 2008))
100% Reduction in Truck Refrigerant Leakage	Results in 0% refrigerant leakage rate (baseline leakage rate is 15% as per (Defra, 2008))
10% Reduction in electricity grid emissions-intensity	
25% Reduction in electricity grid emissions-intensity	
Decarbonized electricity (100% Reduction in electricity grid emissions-intensity)	
10% Reduction in total trucking distance	

25% Reduction in total trucking distance	
Upgrading truck refrigeration unit to an R404a "Precedent" model (higher efficiency from condenser system, fuel injection, and device architecture)	Baseline is a typical R404a model. Replacement refrigeration unit modeled by Li.(Li, 2017)
Upgrading truck refrigeration unit to an R452a model	Baseline is a typical R404a model. Replacement refrigeration unit modeled by (Li, 2017)
10% Reduction in processing losses	
25% Reduction in processing losses	
10% Reduction in retail losses	
25% Reduction in retail losses	
100% Reduction in food losses (processing and retail)	
Changing retail refrigeration system to a floating head R404a system	Baseline is conventional R404a retail refrigeration system. Substitution

	modeled by (Davies and Caretta, 2004)
Changing retail refrigeration system to a floating head CO2-NH3 system	Baseline is conventional R404a retail refrigeration system. Substitution modeled by (Davies and Caretta, 2004)
Changing retail refrigeration system to a two stage R404A with TES	Baseline is conventional R404a retail refrigeration system. Substitution modeled by (Davies and Caretta, 2004)
Changing retail refrigeration system to a two stage CO2-NH3 with TES	Baseline is conventional R404a retail refrigeration system. Substitution modeled by (Davies and Caretta, 2004)
Energy savings from retailing fresh broccoli in closed refrigerator case instead of open	(Koiwanit, 2018)
Ambient retailing for fresh broccoli and apples	

10% Reduction in hours subject to grocery store retailing	
25% Reduction in hours subject to grocery store retailing	
Supermarket refrigerated display case energy efficiency improvements (28% refrigerated, 12% freezer)	Energy efficiency improvements made possible through a 2014 Department of Energy efficiency standards rule (Mauer, 2014)

Table 5.1: Cold chain emissions reduction interventions modeled

Interventions are modeled independently, though some interventions are interdependent. Emissions resulting from the energy consumption from refrigeration systems, influenced by changes in supermarket refrigeration systems, display cases, and hours, are also influenced by the electricity grid emissions factor. When the ambient retailing scenario for fresh broccoli and apples is modeled, no retail refrigeration emissions burdens are applied, but the retail loss rate is increased by the difference between a "fresh" and "processed" version of the food category (vegetables and fruit, respectively), reflecting available per-product loss rate variance provided by (Buzby et al., 2014).

This baseline assumes the use of an R404a refrigerant for transportation, and trucking refrigerant substation is modeled using data from (Li, 2017), who compares alternative truck refrigeration systems to a typical R404a system. Similarly, the supermarket modeled assumes the use of an R404a refrigeration system operated in England, with interventions modeled from (Davies and Caretta, 2004) who compared alternative supermarket refrigeration systems to an R404a system operating in this country.

The multipliers for the effects of refrigeration system changes are reflect the Total Equivalent Warming Index (TEWI) values for each refrigeration's system. TEWI values reflect both the direct impacts of refrigeration from coolant emissions and indirect impacts from energy consumption (Makhnatch and Khodabandeh, 2014).

4.3 Results

Median values from the Monte Carlo simulation are taken from the model, comparing the emissions for baseline results and each intervention. All results are reported as one kg of food supplied to the point of purchase by the consumer. The results of this comparison, both in terms of percentage change from the baseline and in absolute changes, are displayed in Table 4.2.

Interventions and Percentage Change in Emissions (kg CO_2e/kg food)	Fresh Broccoli	Frozen Broccoli	Fresh Chicken	Frozen Chicken	Apples	Fresh Fish	Frozen Fish	Milk
5% Lower Truck Refrigeration Leakage	-0.3%	0.0%	0.0%	0.0%	-0.4%	-1.2%	-0.2%	0.0%
10% Lower Truck Refrigeration Leakage	-0.3%	-0.1%	0.0%	0.0%	-0.6%	-1.7%	-0.4%	-0.1%
100% Lower Truck Refrigeration Leakage	-0.4%	-0.6%	-0.1%	-0.2%	-0.7%	-1.8%	-0.4%	-0.2%
10% Less-Emitting Electricity Grid	-3.2%	-4.6%	-0.9%	-1.8%	-3.3%	-2.3%	-4.2%	-0.4%
25% Less-Emitting Electriciy Grid	-8.4%	-12.6%	-2.1%	-4.5%	-8.6%	-8.0%	-9.7%	-0.9%
Zero-Emissions Electricity Grid	-32.2%	-49.2%	-8.0%	-17.4%	-33.2%	-26.5%	-38.8%	-3.0%
10% Shorter Distances	-0.2%	-0.2%	-0.2%	0.0%	-0.8%	-1.2%	-0.2%	-0.2%
25% Shorter Distances	-1.1%	-0.7%	-0.4%	-0.2%	-2.0%	-3.2%	-0.3%	-0.4%
Truck Refrigeration: R404a Precedent	-0.7%	-1.4%	-0.2%	-0.1%	-1.8%	-0.7%	-0.7%	-0.4%
Truck Refrigeration: R452a	0.1%	-0.2%	0.0%	-0.2%	-0.4%	-2.7%	0.4%	0.0%
10% Lower Processing Losses	-0.5%	-0.2%	-0.8%	-0.4%	-0.2%	-2.2%	0.0%	-0.6%
25% Lower Processing Losses	-0.3%	-0.3%	-1.7%	-1.5%	-0.4%	-3.6%	-1.3%	-1.4%
100% Lower Processing Losses	-2.1%	-2.2%	-6.1%	-5.1%	-1.8%	-3.3%	-4.3%	-5.3%
10% Lower Retail Losses	-2.3%	-2.8%	-1.2%	-1.3%	-2.3%	-6.7%	-1.8%	-1.4%
25% Lower Retail Losses	-5.5%	-4.7%	-2.9%	-3.1%	-5.3%	-2.5%	-4.1%	-3.4%
100% Lower Retail Losses	-18.5%	-16.0%	-10.6%	-11.7%	-18.9%	-12.9%	-14.7%	-12.0%
0% Food Losses (Processing & Retail)	-20.1%	-17.3%	-15.9%	-16.5%	-20.5%	-18.6%	-18.2%	-16.1%
Retail Refrigeration: Floating Head R404A	-15.8%	-12.5%	-3.4%	-5.3%	-14.2%	-5.8%	-7.5%	-0.6%
Retail Refrigeration: Floating Head CO2 NH3	-37.3%	-25.5%	-7.8%	-11.2%	-32.8%	-14.6%	-15.3%	-1.6%
Retail Refrigeration: Two Stage R404A with Thermal Energy Storage	-6.7%	-3.3%	-1.4%	-1.3%	-6.0%	-2.2%	-2.2%	-0.3%
Retail Refrigeration: Two stage CO2 NH3 with Thermal Energy Storage	-35.4%	-22.9%	-7.5%	-10.0%	-31.3%	-12.2%	-14.0%	-1.7%
Retail Refrigeration in Closed Chest Cabinet	-7.5%		-1.7%		-6.7%	-4.2%		
Ambient Retailing	-64.4%				-56.3%			
10% Lower Hours Retailed	-6.4%	-5.9%	-1.4%	-2.4%	-6.2%	-1.5%	-3.8%	-0.4%
25% Lower Hours Retailed	-7.8%	-9.2%	-3.5%	-6.4%	-14.4%	-4.7%	-9.4%	-0.7%
Zero Hours in Retail	-30.8%	-36.7%	-13.9%	-25.5%	-57.4%	-21.0%	-35.3%	-2.7%
Retail Refrigeration Display Case Efficiency Improvements	-9.0%	-4.5%	-1.9%	-2.1%	-8.0%	-3.0%	-2.8%	-0.4%
0% Retail Refrigerant Leakage	-34.3%	-21.7%	-7.4%	-9.4%	-30.1%	-12.1%	-13.1%	-1.5%

Interventions and Absolute Change in Emissions (kg CO2e/kg food)	Fresh Broccoli	Frozen Broccoli	Fresh Chicken	Frozen Chicken	Apples	Fresh Fish	Frozen Fish	Milk
5% Lower Truck Refrigeration Leakage	0.00	0.00	0.00	0.00	-0.01	-0.03	0.00	0.00
10% Lower Truck Refrigeration Leakage	-0.01	0.00	0.00	-0.01	-0.01	-0.04	-0.01	0.00
100% Lower Truck Refrigeration Leakage	-0.01	-0.01	0.00	-0.01	-0.01	-0.04	-0.01	0.00
10% Less-Emitting Electricity Grid	-0.05	-0.09	-0.03	-0.08	-0.06	-0.05	-0.13	-0.01
25% Less-Emitting Electriciy Grid	-0.14	-0.24	-0.08	-0.19	-0.16	-0.19	-0.30	-0.02
Zero-Emissions Electricity Grid	-0.53	-0.92	-0.29	-0.74	-0.63	-0.64	-1.20	-0.05
10% Shorter Distances	0.00	0.00	-0.01	0.00	-0.02	-0.03	-0.01	0.00
25% Shorter Distances	-0.02	-0.01	-0.01	-0.01	-0.04	-0.08	-0.01	-0.01
Truck Refrigeration: R404a Precedent	-0.01	-0.03	-0.01	0.00	-0.03	-0.02	-0.02	-0.01
Truck Refrigeration: R452a	0.00	0.00	0.00	-0.01	-0.01	-0.07	-0.01	0.00
10% Lower Processing Losses	-0.01	0.00	-0.03	-0.02	0.00	-0.05	0.00	-0.01
25% Lower Processing Losses	0.00	-0.01	-0.06	-0.06	-0.01	-0.09	-0.04	-0.03
100% Lower Processing Losses	-0.04	-0.04	-0.22	-0.22	-0.03	-0.08	-0.13	-0.09
10% Lower Retail Losses	-0.04	-0.05	-0.04	-0.06	-0.04	-0.16	-0.06	-0.02
25% Lower Retail Losses	-0.09	-0.09	-0.10	-0.13	-0.10	-0.06	-0.13	-0.06
100% Lower Retail Losses	-0.31	-0.30	-0.39	-0.49	-0.36	-0.31	-0.46	-0.22
0% Food Losses (Processing & Retail)	-0.33	-0.32	-0.58	-0.70	-0.39	-0.45	-0.56	-0.29
Retail Refrigeration: Floating Head R404A	-0.26	-0.24	-0.12	-0.23	-0.27	-0.14	-0.23	-0.01
Retail Refrigeration: Floating Head CO2 NH3	-0.62	-0.48	-0.29	-0.48	-0.62	-0.35	-0.47	-0.03
Retail Refrigeration: Two Stage R404A with Thermal Energy Storage	-0.11	-0.06	-0.05	-0.05	-0.11	-0.05	-0.07	-0.01
Retail Refrigeration: Two stage CO2 NH3 with Thermal Energy Storage	-0.58	-0.43	-0.27	-0.42	-0.59	-0.29	-0.43	-0.03
Retail Refrigeration in Closed Chest Cabinet	-0.12		-0.06		-0.13	-0.10		
Ambient Retailing	-1.06				-1.06			
10% Lower Hours Retailed	-0.11	-0.11	-0.05	-0.10	-0.12	-0.04	-0.12	-0.01
25% Lower Hours Retailed	-0.13	-0.17	-0.13	-0.27	-0.27	-0.11	-0.29	-0.01
Zero Hours in Retail	-0.51	-0.69	-0.51	-1.08	-1.09	-0.51	-1.09	-0.05
Retail Refrigeration Display Case Efficiency Improvements	-0.15	-0.08	-0.07	-0.09	-0.15	-0.07	-0.09	-0.01
0% Retail Refrigerant Leakage	-0.57	-0.41	-0.27	-0.40	-0.57	-0.29	-0.41	-0.03

Table 5.2: Percentage (top) and absolute reductions (bottom) from the baseline emissions resulting from each intervention modeled. Values are shaded to correspond to the magnitude of emissions reductions compared with the baseline. Unpopulated cells indicate that the intervention is not applicable to that food type.

There is a notable range in the magnitude of effects from cold chain interventions, observable for both an absolute and a percentage basis. The largest emissions reduction (1.20 kg CO_2e/kg) results from supplying frozen fish with a decarbonized electricity grid and the largest percentage reduction (64%) is from retailing fresh broccoli in an ambient setting. The smallest reductions are from reducing trucking refrigerant leakage by both 5 and 10 percent, resulting in near-zero percentage and absolute emissions changes.

Emissions reductions are discussed in further detail by cold chain intervention type, discussed in terms of percentage reductions, absolute emissions changes, as well as differences between and within food types. Broccoli, apples, and fish are typically the most-responsive to cold chain interventions, given the relatively high amounts of their emissions total contributed by post-production cold chain emissions: 69% for fresh broccoli, 76% for frozen broccoli, 71% for apples, 41% for fresh fish, and 54% for frozen fish. Milk is one of the least responsive food types to cold chain interventions, with only 6% of its emissions total contributed from cold chain processes. Milk is a dense, heavy product; given the functional unit of 1 kg food supplied, milk's density results in a high contribution of agricultural production to its emissions total. The extent to which different interventions are effective at reducing the emissions for supplying different food types are discussed in terms of the cold chain components altered.

5.3.1 Supermarket Refrigeration

The most-direct interventions to mitigate emissions from the cold chain address refrigerants and refrigeration system operation. The extent to which refrigeration and refrigerant-based changes present meaningful emissions reductions varies dramatically by the section of the supply chain in which it is applied.

Improving the supermarket refrigeration system is one of the most-effective interventions for directly reducing emissions from the cold chain. Changing a typical R404a system to a “floating head” system (decreasing pressure exiting the compressor) alone presents reductions up to 0.27 kg CO_2e/kg (-14%) for apples and 0.26 kg CO_2e/kg (-16%) for fresh broccoli, with average reductions of 0.19 kg CO_2e/kg (-8%) across all food types tested. Traditional refrigerants have high global warming potentials (GWP), connected with large amount of global warming (Makhnatch and Khodabandeh, 2014). Replacing these high-GWP refrigerants with less-warming natural refrigerants could dramatically reduce the global warming impacts from refrigeration (Project Drawdown, 2019). Adopting a floating head natural refrigerant-based system (CO_2 NH_3) presents even larger average savings: of up to 0.62 kg CO_2e/kg for fresh broccoli (-37%) and apples (-33%), and an average reduction of 0.42 kg CO_2e/kg (-18%) across the food types. Using a two-stage thermal energy storage system which allows for the use of off-peak electricity decreases modeled emissions reductions slightly, by an average of 0.12 kg CO_2e (-5%) for the R404a system and 0.03 kg CO_2e/kg (1%) for the natural refrigerant-based system.

An additional means for reducing the emissions burden from supermarket refrigeration is through equipment upgrades or substitution. Increasing the efficiency of refrigerator chests as specified by the Department of Energy rules modeled can reduce emissions ranging from 0. kg CO_2e/kg for fresh broccoli (-9%) and apples (-8%) to 0.01 kg CO_2e/kg (-0.4%) for milk. Fresh foods are modeled (Defra, 2008) as using an open-chest refrigerator: a model with substantially lower efficiency than the closed-door model used for frozen foods (Fricke and Becker, 2010). Switching the retailing of fresh foods to a closed chested refrigerator results in emissions savings ranging from 0.13 kg CO_2e/kg (-7%) for apples to 0.06 kg CO_2e/kg (2%) for fresh chicken.

5.3.2 Trucking Refrigeration

Refrigeration system change for trucking is a technical intervention presenting distinctly smaller magnitudes of emissions savings on a life cycle basis than for supermarket refrigeration systems. Reducing refrigerant leak rates and upgrading the truck refrigeration system present distinctly small changes in life cycle emissions (with the largest decrease being 0.4 kg CO_2e/kg for fresh fish, a change of 2% from its baseline, resulting from a 100% leak reduction), with many foods experiencing near-zero reductions in emissions from leakage reductions. Upgrading a truck's refrigeration system from a typical R404a system to a "precedent" (higher efficiency) system results in emissions decreases of up to 0.03 kg CO_2e/kg or frozen broccoli (-1%) and apples (-2%), and substituting an HFO-based refrigeration system (using lower-GWP refrigerants) yields reductions of up to 0.07 kg CO_2e/kg for fresh fish (-3%).

The limited effects seen from these interventions are in part due to the limited time that food spends subject to trucking refrigeration when compared with other elements of its supply chain. Assuming that trucks travel at 55 miles per hour, reflecting typical U.S. practices (Office of Energy Efficiency & Renewable Energy, 2011), the modal transportation distances in the supply chains modeled reflect travel times of 2.2 hours. This value can be compared with the range of 24 to 120 hours that food resides in grocery retailing (display case and/or walk-in refrigeration), providing insight into why refrigerant-base**d** changes in retail refrigeration yield notably larger emissions reductions. This different does not imply that improvements to trucking in the cold chain should not be considered in emissions reduction, they can present aggregate savings. However, on a functional unit basis, the reductions potential from trucking interventions are limited.

5.3.3 Logistics

Emissions savings may also be achieved in the cold chain by optimizing logistics. An average emissions reduction of up to 0.29 kg CO_2e/kg for frozen fish, and a relative savings of up to 14% for apples can be attributed to a 25% reduction retail storage residence time. Even a 10% reduction in hours can yield up to a 0.12 kg CO_2e/kg reduction for apples and frozen fish, and relative reductions of 6% for fresh broccoli and apples. E-commerce could present the potential to circumvent brick-and-mortar grocery retailing, eliminating the emissions burdens from supermarket refrigeration. The effects of eliminating the energy consumption and refrigerant leakage from supermarkets can be modeled as food subject to zero hours of retailing, resulting in reductions of up to 1.09 kg CO_2e/kg for apples (-57%) and frozen fish (-35%). It should be emphasized that this is a theoretical maximum reduction, as circumventing brick-and-mortar supermarket retailing would likely create changes in food storage and transportation practices, altering emissions outcomes. Shortening transportation distances had limited effects, with a 25% reduction in transportation distance mitigating up to 0.08 kg CO_2e/kg (-3%) for fresh fish. In this way, logistics improvements are similar to those for refrigeration systems: the savings from transportation changes are limited on a life cycle basis, but the potential emissions reductions from retailing improvements are notable.

The most-effective way to reduce refrigeration emissions is, when appropriate for a product, not to refrigerate it during retailing. Ambient retailing is the most-effective intervention modeled for its relevant food types, presenting an emissions savings of 1.06 kg CO_2e/kg for fresh broccoli (-64%) and apples (-56%), highlighting the extent to which a product's emissions burden is attributable to retail refrigeration. Ambient retailing does, however, present increases in food losses: amounting to 0.11 kg CO_2e/kg.

5.3.4 Food Loss Reductions

Within the cold chain, processors and retailers could reduce the emissions footprint associated with supplying food through efforts to reduce food loss. At the processor this could involve reducing edible food losses from the trimming and cleaning processes (Gustavsson et al., 2011), while for retailers, efforts to reduce overstocking, damage to packaging, and culling of unattractive produce would stem food loss from grocery stores (Buzby et al., 2014). These changes may be undertaken by the same operators along the cold chain who would be able to implement the other interventions tested, especially since product loss results in profit loss for a retailer.

The production emissions for each product are important to consider if targeting specific foods for food loss reduction efforts. A reduction in food loss for a product with higher agricultural production and supply chain emissions prior to the point-of-loss yield a greater emissions savings than a reduction for a less-intensive product. For this reason, chicken, fish, and milk experience the largest potential savings from food loss reduction efforts; with these interventions being some of the only instances where milk's emissions decreases are in the same magnitude of that for other food types. A retail food loss reduction of 25% yields emissions decreases of up 0.13 kg CO_2e/kg for frozen chicken (-3%) and fish (-4%), with the smallest reduction from milk still resulting in a reduction of 0.06 kg CO_2e/kg (-3%). Processing food loss reductions yield smaller, but still meaningful savings, with a 25% decrease in processing losses resulting in decreases of 0.09 kg CO_2e/kg for fresh fish (-3.6%) and 0.06 for fresh (-1.7%) and frozen chicken (-1.5%). A theoretical maximum of 100% of food loss eliminated across processing and retail presents emissions savings of up to 0.49 kg CO_2e/kg for frozen chicken (17%), illustrating that the maximum attainable emission decreases from food loss reduction efforts are in the same approximate magnitude as supermarket refrigeration system changes or decreases in electricity grid emissions-intensity.

5.3.5 Electricity

One way in which an operator along the cold chain could reduce emissions without equipment changes is through consumption of less-emitting electricity. Converting to decarbonized electricity presents emissions savings of up to 1.2 kg CO_2e/kg for frozen fish (-27%), the largest reduction of any intervention tested. Decarbonized electricity presents similarly large reductions for frozen broccoli (0.92 kg CO_2e/kg, -49%), frozen chicken (0.74 kg CO_2e/kg, -17%), and fresh fish (0.64 kg CO_2e/kg, -27%), all of which consume notable quantities of electricity in their processing.

Electricity grid emissions reductions still present notable emissions improvements even when not decarbonized. A 25% reduction in electricity emissions-intensity yields reductions of up to 0.30 kg CO_2e/kg for frozen fish (-10%), and an average reduction of 0.16 kg CO_2e/kg across the tested food types. This average reduction is approximately the same as that from implementing a floating head R404a retail refrigeration system, or decreasing the hours in retail by 25%.

5.3.6 Most-Effective Interventions and Combinations

The majority of interventions modeled result in small emissions changes, with 84 of the 214 observations yielding a decrease of 5% of lower, and 52 yielding decreases greater than 10%. However, notable emissions decreases can be obtained from some single interventions. The largest emissions reductions involve changes to the electricity grid, ambient food retailing when possible, and changes to grocery store refrigeration system types, refrigerants, or the elimination of leaks. Foods other than milk are found to experience the largest emissions changes, reflecting the larger relative role agricultural production in its emissions burden compared with those added by the cold chain.

Interventions can be combined to attain even larger emissions reductions. Combinations were tested of zero-emissions electricity with floating head R404a and CO_2NH_3 supermarket refrigeration systems were tested, targeting the energy and refrigeration-intensive supermarket supply chain stage. Additionally, these interventions were tested in combination with complete food loss reductions in the supply chain, incorporating another commonly-advocated means for supply chain operators to reducing emissions burdens. The results of these combinations are displayed by food type in Figure 5.2 as follows.

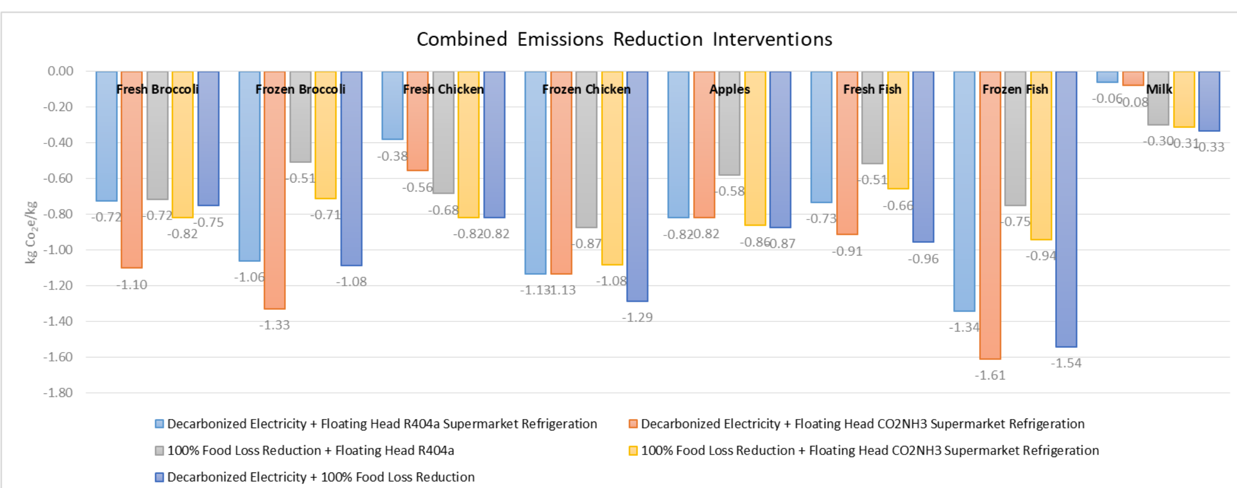


Figure 5.2.: Emissions reductions per kg food supplied when implementing combinations of the floating head supermarket refrigeration, food loss reduction, and decarbonized electricity emissions interventions modeled

Including decarbonized electricity as an intervention presents the largest emissions reductions of any of the combinations: creating reductions of up to 1.61 kg CO_2e/kg for frozen fish (-52%) when combined with the floating head CO_2NH_3 supermarket refrigeration system, and up to 1.54 (also for frozen fish, -50%) when combined with a complete postharvest supply chain food loss reduction. While both supermarket refrigeration system changes yield meaningful reductions, the CO_2NH_3 system provides an average 0.16 kg CO_2e/kg greater reduction across all food types when combined with both the electricity and the food loss interventions. These combinations illustrate the additional gains which can be provided if an operator along the cold chain has the ability to influence change in multiple inputs and management practices.

5.4 Discussion

The global cold chain market is rapidly expanding, with a predicted compound annual growth rate of 15% between 2019-2023 (Bussinesss Wire, 2019). Cold chain presence and operation is connected with notable direct and indirect environmental impacts (Heard and Miller, 2016), and is expanding in a period of time when climate change mitigation is a critical consideration for human livelihoods and the stability of ecological systems (IPCC, 2018). The extent to which the cold chain's expansion may add or reduce overall environmental impacts has been assessed in some modeling studies (Heard and Miller, 2019; Hu et al., 2019), but still remains an area in need of further study, and in particular, in need of improved data sources. Focusing on mitigation opportunities in developed refrigerated food supply chains, this analysis provides insights into the most-effective GHG emissions mitigations opportunities available for either already-existing cold chains, or for cold chain decision-makers to adopt when developing future refrigerated supply chains.

This analysis models emissions reductions interventions in a way intended to be representative of their effects in a typical industrialized refrigerated food supply chain. Zero-emissions electricity is found to be one of the most-effective means for reducing the emissions for supplying food, but also has spillover benefits for supermarkets not captured in this study, which is primarily focused on refrigeration: with substantial electricity consumption going to the store lighting system as well (Energy Star, n.d.). The adoption of supermarket refrigeration systems with higher efficiencies and, natural refrigerants, and minimal leaks also provides notable reductions in GHG emissions associated the food supply and retailing, further-supporting the use of these systems for improved environmental practices. Food loss reduction efforts along the supply chain have also been promoted as key means for reducing unnecessary environmental burdens from our food system, particularly for higher-emissions foods to produce (Gustavsson et al., 2011; Lipinski et al., 2016). This study finds food loss reduction to present meaningful emissions reductions at high levels, indicating that these initiatives are effective at reducing the environmental burdens from food supply chains when they are realized in high-efficacy ways. Emerging internet-of-things technologies could enable reductions in retail food losses from overstocking (Buzby et al., 2014), informed by analytics on customer behavior and preferences. These technologies provide the capacity to improve supply chain optimization, reducing the time goods are subject to refrigerated storage (Sun et al., 2019). At their best deployment, internet-of-things technologies in a supply chain could provide results similar to the modeled scenarios for zero hours in supermarket retailing (either through direct-to-consumer delivery, circumventing the store, or through minimizing time spent in retail). That being said, the overall energy use implications of internet-of-things technologies remains unknown, as the operation of these technologies in places where they were previously not present adds energy use into the system (Hittinger and Jaramillo, 2019). The energy demand from the internet-of-things may present a trade-off between the emissions savings from optimized logistics and increases in direct energy demand by technologies along the supply chain.

Perhaps unsurprisingly, the largest recorded emissions reductions modeled involve the ambient retailing of goods which would otherwise be refrigerated, with the displaced refrigeration burden for fresh broccoli and apples offsetting the environmental burdens from corresponding food loss increases modeled. That being said, the precise changes in spoilage and loss rates which occur as a trade-off with the ambient retailing of a previously-refrigerated product remain a data gap in the literature. The role of cultural practices for refrigeration certain food types varies throughout the world, with some cultures not commonly refrigerating eggs or butter, for example. As the cold chain expands, whether there are changes in cultural refrigeration practices will play a role in determining emissions outcomes associated with food storage and provision (Hu et al., 2019). The extent to which ambient retailing of produce influences consumer preference and willingness-to-pay for foods is a related research need, whose results may influence the extent to which increased ambient retailing is a viable option for grocery retailers to pursue. In general, the cost-effectiveness of suggested emissions-reducing interventions should be evaluated and remains as a research need.

Finally, the role of functional unit in influencing the relative effectiveness of the interventions modeled must be acknowledged. Emissions are calculated on per kg basis for food supplied through retail. This per-unit basis (mass, kcal, meal, serving of food) is often used in the food life cycle assessment literature (Heller et al., 2013), and reveals the impacts of marginal decision-making. However, considering cold chain impacts on a per-unit basis presents the limitation of not accounting for emissions contributions which are small on per-kg terms, but aggregate to be substantial GHG emissions contributions. One example of this may be refrigerated trucking, where interventions decreasing truck refrigerant leak rates and decreasing trucking distances yielded per-unit emissions decreases averaging less than 1% across food types. While these emissions reductions are small per kg of food retailed, when scaled across the amount of all food and the number of trucks operating within refrigerated food supply chain contexts, a small emissions decrease could aggregate to present meaningful mitigation. Similarly, this study is limited by its scope: not including consumer refrigerated storage of food, with the household typically being the largest source of food waste in the U.S. (Buzby et al., 2014); but also not incorporating the production of refrigerated equipment used in the cold chain or its end-of-life, with substantial potential for refrigerant emissions if not properly managed (Duan et al., 2018).

Greenhouse gas emissions mitigation is a critical environmental priority. Cold chain interventions present notable opportunities for reducing food supply chain emissions, especially as refrigerated supply chains grow worldwide. The relative effectiveness of different intervention options, and their appropriateness in different contexts, remains as an important topic for research and investigation.

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5.5 References

Blanke, M.M., Burdick, B., 2005. Food (miles) for Thought: Energy Balance for Locally-Grown versus Imported Apple Fruit. Environ. Sci. Pollut. Res. 12, 125–127. doi:http://dx.doi.org/10.1065/espr2005.05.252

Business Wire, 2019. Global Cold Chain Market 2019-2023 | 15 % CAGR Projection over the Next Five Years | Technavio [WWW Document]. Bus. Wire. URL https://www.businesswire.com/news/home/20190802005120/en/Global-Cold-Chain-Market-2019-2023-15-CAGR

Buzby, J.C., Farah-Wells, H., Hyman, J., 2014. The Estimated Amount, Value, and Calories of Postharvest Food Losses at the Retail and Consumer Levels in the United States, Economic Information Bulletin. doi:10.2139/ssrn.2501659

Calm, J.M., 2008. The next generation of refrigerants - Historical review, considerations, and outlook. Int. J. Refrig. 31, 1123–1133. doi:10.1016/j.ijrefrig.2008.01.013

Canals, L.M.I., Muñoz, I., Hospido, A., Plassmann, K., McLaren, S., 2008. Life Cycle Assessment (LCA) of domestic vs. imported vegetables. Case studies on broccoli, salad crops and green beans (No. 01/08), Centre for Environmental Strategy Working Paper.

doi:1464-8083
Coulomb, D., Dupon, J.L., Pichard, A., 2015. The role of refrigeration in the global economy, IIR Informatory Note was.
Davies, T.W., Caretta, O., 2004. A low carbon, low TEWI refrigeration system design. Appl. Therm. Eng. 24, 1119–1128. doi:10.1016/j.applthermaleng.2003.12.026
Defra, 2008. Greenhouse Gas Impacts of Food Retailing (No. Defra Project code FO405).
Duan, H., Miller, T.R., Liu, G., Zeng, X., Yu, K., Huang, Q., Zuo, J., Qin, Y., Li, J., 2018. Chilling Prospect: Climate Change Effects of Mismanaged Refrigerants in China. Environ. Sci. Technol. 52, 6350–6356. doi:10.1021/acs.est.7b05987
Energy Star, n.d. Supermarkets: An Overview of Energy Use and Energy Efficiency Opportunities.
Fricke, B., Becker, B., 2010. Energy Use of Doored and Open Vertical Refrigerated Display Cases, in: International Refrigeration and Air Conditioning Conference.
Garnett, T., 2011a. Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? Food Policy 36, S23–S32. doi:10.1016/j.foodpol.2012.04.006
Garnett, T., 2011b. Where are the best opportunities for reducing greenhouse gas emissions in the food system (including the food chain)? Food Policy 36, S23–S32. doi:10.1016/j.foodpol.2010.10.010
González-García, S., Gomez-Fernández, Z., Dias, A.C., Feijoo, G., Moreira, M.T., Arroja, L., 2014. Life Cycle Assessment of broiler chicken production: a Portuguese case study. J. Clean. Prod. 74, 125–134.
Gustavsson, J., Cederberg, C., Sonesson, U., 2011. Global Food Losses and Food Waste: Extent, Causes and Prevention, Food and Agriculture Organization of the United Nations (FAO).
Halldórsson, Á., Kovács, G., 2010. The sustainable agenda and energy efficiency: Logistics solutions and supply chains in times of climate change. Int. J. Phys. Distrib. Logist. Manag. 40, 5–13. doi:10.1108/09600031011018019
Heard, Brent R., Miller, S.A., 2019. Potential Changes in Greenhouse Gas Emissions from Refrigerated Supply Chain Introduction in a Developing Food System. Environ. Sci. Technol. 53, 251–260. doi:10.1021/acs.est.8b05322
Heard, Brent R, Miller, S.A., 2019. Potential Changes in Greenhouse Gas Emissions from Refrigerated Supply Chain Introduction in a Developing Food System. Environ. Sci. Technol. 53, 251–260. doi:10.1021/acs.est.8b05322
Heard, B.R., Miller, S.A., 2016. Critical Research Needed to Examine the Environmental Impacts of Expanded Refrigeration on the Food System. Environ. Sci. Technol. 50, 12050–12071. doi:10.1021/acs.est.6b02740
Heller, M.C., Keoleian, G.A., Willett, W.C., 2013. Toward a life cycle-based, diet-level framework for food environmental impact and nutritional quality assessment: A critical review. Environ. Sci. Technol. 47, 12632–12647. doi:10.1021/es4025113
Hittinger, E., Jaramillo, P., 2019. Internet of Things: Energy boon or bane? Science (80-.). 364, 326–328. doi:10.1126/science.aau8825

Hospido, A., Moreira, M.T., Feijoo, G., 2003. Simplified life cycle assessment of galician milk production. Int. Dairy J. 13, 783–796. doi:10.1016/S0958-6946(03)00100-6

Hu, G., Mu, X., Xu, M., Miller, S.A., 2019. Potentials of GHG emission reductions from cold chain systems: case studies of China and the United States. J. Clean. Prod. 239, 118053. doi:10.1016/j.jclepro.2019.118053

IPCC, 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, Intergovernmental Panel on Climate Change.

James, S.J., James, C., 2013. Sustainable Cold Chain, in: Tiwari Brijesh K., Norton, T., Holden, N.M. (Eds.), Sustainable Food Processing. John Wiley & Sons, Ltd, pp. 463–496. doi:10.1002/9781118634301.ch19

James, S.J., James, C., 2010. The food cold-chain and climate change. Food Res. Int. 43, 1944–1956. doi:10.1016/j.foodres.2010.02.001

Koiwanit, J., 2018. Energy efficiency and environmental impact analysis in grocery store market in Canada. Int. J. GEOMATE 15, 30–36. doi:10.21660/2018.49.3602

Li, G., 2017. Comprehensive investigation of transport refrigeration life cycle climate performance. Sustain. Energy Technol. Assessments 21, 33–49. doi:10.1016/j.seta.2017.04.002

Lipinski, B., Hanson, C., Lomax, J., Kitinoja, L., Waite, R., Searchinger, T., 2016. Reducing Food Loss and Waste, Creating a Sustainable Food Future. Washington, DC. doi:10.2499/9780896295827_03

Makhnatch, P., Khodabandeh, R., 2014. The role of environmental metrics (GWP, TEWI, LCCP) in the selection of low GWP refrigerant. Energy Procedia 61, 2460–2463. doi:10.1016/j.egypro.2014.12.023

Mauer, J., 2014. New Refrigeration Efficiency Standards To Take a Bite out of Supermarket and Restaurant Energy Costs [WWW Document]. Am. Counc. an Energy-Efficient Econ. URL https://aceee.org/blog/2014/02/new-refrigeration-efficiency-standard

Niles, M.T., Ahuja, R., Barker, T., Esquivel, J., Gutterman, S., Heller, M.C., Mango, N., Portner, D., Raimond, R., Tirado, C., Vermeulen, S., 2018. Climate change mitigation beyond agriculture : a review of food system opportunities and implications. Renew. Agric. Food Syst. 13, 1–12. doi:10.1017/S1742170518000029

Office of Energy Efficiency & Renewable Energy, 2011. Fact #671: April 18, 2011 Average Truck Speeds | Department of Energy [WWW Document]. Facts Week. URL httphttps://www.energy.gov/eere/vehicles/fact-671-april-18-2011-average-truck-speedss://energy.gov/eere/vehicles/fact-671-april-18-2011-average-truck-speeds

Project Drawdown, 2019. Refrigerant Management [WWW Document].

Salin, V., 2018. 2018 Global Cold Storage Capacity Report.

Sun, X., Gao, L., Liang, Y., 2019. Research on Big Data Acquisition and Application of Cold Chain Logistics Based on Artificial Intelligence and Energy Internet of Things. IOP Conf. Ser. Earth Environ. Sci. 252, 052052. doi:10.1088/1755-1315/252/5/052052

Svanes, E., Vold, M., Hanssen, O.J., 2011. Environmental assessment of cod (Gadus morhua) from autoline fisheries. Int. J. Life Cycle Assess. 16, 611–624. doi:10.1007/s11367-011-0298-2

United Nations Environment Programme, 2016. The Kigali Amendment to the Montreal Protocol: HFC Phase-down, 28th Meeting of the Parties to the Montreal Protocol, 10-14 October, 2016, Kigali, Rwanda.

Chapter 6

Comparison of Life Cycle Environmental Impacts from Meal Kits and Grocery Store Meals

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Abstract

Meal kits contain ingredients for cooking a meal that are pre-portioned, packaged, and delivered to a consumer's residence. Life cycle environmental impacts associated with climate change, acidification, eutrophication, land use, and water use are compared for five dinner recipes sourced as meal kits and through grocery store retailing. Inventory data are obtained from direct measurement of ingredients and packaging, supplemented with literature data for supply chain and production parameters. Results indicate that, on average, grocery meal greenhouse gas emissions are 33% higher than meal kits (8.1 kg CO_2e/meal compared with 6.1 kg CO_2e/meal kit). Other impact categories follow similar trends. A Monte Carlo analysis finds higher median emissions for grocery meals than meal kits for four out of five meals, occurring in 100% of model runs for two of five meals. Results suggest that meal kits' streamlined and direct-to-consumer supply chains (-1.05 kg CO_2e/meal), reduced food waste (-0.86 kg CO_2e/meal), and lower last-mile transportation emissions (-0.45 kg CO_2e/meal), appear to be sufficient to offset

observed increases in packaging (0.17 kg CO_2e/meal). Additionally, meal kit refrigeration packs present an average emissions decrease compared with retail refrigeration (-0.37 kg CO_2e/meal).

Meals with the largest environmental impact either contain red meat or are associated with large amounts of wasted food. The one meal kit with higher emissions is due to food mass differences rather than supply chain logistics. Meal kits are an evolving mode for food supply, and the environmental effects of potential changes to meal kit provision and grocery retailing are discussed.

6.1 Introduction

Meal kit services are rapidly emerging, with transformative potential in the food industry. This study is a life cycle assessment of the greenhouse gas emissions for supplying a meal as a meal kit, compared with the emissions for supplying the same meal through traditional grocery retailing.

Meal kits are delivered in boxes containing a recipe and its ingredients, which are pre-portioned and often individually-packaged. Meal kit delivery services ship their meals in boxes containing refrigeration packs through a mail delivery service that delivers the meal kits to consumers' homes. Meal kits are an alternative to the traditional means of preparing meals from ingredients purchased at a grocery store. Grocery store meals are typically comprised of ingredients shipped to stores from a regional distribution center, retailed at a store, and purchased by consumers who travel round-trip to that store.

The meal kit industry is valued at approximately $1.5 billion in the United States and is experiencing annual growth of 25% (Wilson et al., 2017). 9% of U.S. consumers surveyed by The Nielsen Company have purchased a meal kit, and 25% of total consumers reported that they would consider trying a meal kit in the next six months following the survey date, presenting this industry with a substantial opportunity for growth (The Nielsen Company, 2018).

It is essential that the environmental impacts of food production, provision, and use be assessed. The food system is estimated to comprise 19-29% of global anthropogenic greenhouse gas (GHG) emissions (Vermeulen et al., 2012), and changes in retail stocking and sourcing, food preservation technologies, and consumer behavior have been identified as key GHG mitigation opportunities in high income countries (Niles et al., 2018). In addition, consumer perceptions of packaging waste often dominate conversations about the environmental impact of meal kit services (Stein, 2017); however, a full life cycle perspective that takes into account the entire food supply chain is required to understand the actual impact of these services relative to traditional methods of food procurement.

Meal kits represent a fundamental shift in how food is supplied. Meals are pre-portioned for consumers and delivered to their doorsteps, circumventing the process of consumers acquiring and portioning ingredients for a meal themselves, but still providing the experience of cooking their meal at home. In this way, meal kits are not just a novel physical product, but also displace the typical grocery shopping experience for U.S. consumers, creating a systemic change. As such, meal kits are a transformative technology (Miller and Keoleian, 2015), presenting both direct changes to meals themselves (pre-portioning and packaging ingredients), but also indirect changes to the food supply chain (delivering food to the household, rather than retailing in a grocery store followed by consumer transportation).

6.2 The Environmental Impacts of Meal Kits

The popular perception of meal kits' environmental impacts tends to be negative, with many consumers expressing concerns regarding the amount of packaging included in meal kits (Stein, 2017) and the contents of their refrigeration packs (Butler, 2017). This study compares the life cycle environmental impacts of meals sourced from meal kit services and a grocery store to determine whether the increased packaging associated with meal kits is offset by potential reductions in food waste.

Pre-portioning food has the potential to reduce household food waste; however, pre-portioning also requires individual packaging with higher surface-to-volume ratios than packaging bulk foods. Therefore, pre-portioned food included in a meal kit has an inherent environmental tradeoff between reduced emissions associated with lower food loss and increased emissions associated with additional packaging.

The environmental impacts of household and retail food waste are substantial, and are the stages in the food chain responsible for the largest percentages of food waste in the developed world (Gustavsson et al., 2011). Total food waste comprises an estimated 2% of the U.S.' national greenhouse gas emissions (Venkat, 2011). The potential for reducing food waste with the addition of packaging has been studied, though the net emissions change is dependent on food type (Heller et al., 2018). For the overall food sector, food packaging has long been a subject of environmental concern, with packaging for food comprising nearly two-thirds of total packaging waste volume, and with 31% of U.S. municipal solid waste in 2005 found to be packaging-related (Marsh and Bugusu, 2007).

Meal kit delivery services are one manifestation of the emergence of e-commerce shopping as an alternative to traditional retailing. Technical considerations for online grocery shopping with home delivery have been assessed in the transportation and logistics literatures (Marker Jr and Goulias, 2007; Pan et al., 2017; Punakivi et al., 2001; Yang and Strauss, 2017; Yrjölä, 2001), with their findings likely applying to meal kit delivery as well.

As an emerging food product, the environmental impacts of meal kits are still in the early stages of being evaluated. It is critical that the environmental implications of supplying meals as meal kits be understood, providing an opportunity to identify areas of high environmental impacts which can be mitigated, and elements providing relative environmental improvements which can be promoted, while this product is still developing and expanding in the marketplace. Additionally, e-commerce and direct-to-consumer supply chains present the potential to replace traditional brick-and-mortar supermarket retailing in developing food systems. Estimations of the relative emissions impacts of meal kits compared with grocery store meals present valuable contributions to the growing literature on food e-commerce and alternative meal provisioning.

6.3 Methods

This study is a comparative life cycle assessment of meal kits and grocery store meals. The recipes for five two-person meals containing a range of proteins were sourced and prepared from both a meal kit service and a grocery store. Inventory data was collected for climate change, acidification, eutrophication, land use, and water use impact categories these meals.

The functional unit of the analysis is one prepared meal, using a two-person serving recipe. Five different proteins were selected to analyze the range of results associated with different meal ingredients: one containing seafood, one red meat, one poultry, and two vegetarian recipes. These are referred to as salmon, cheeseburger, chicken, pasta, and salad meals, respectively. Meal kits were purchased from Blue Apron and selected from the available options at the time of analysis, based on supplying the most diverse set of proteins. Grocery meals were purchased from a local grocery store and cooked to match the recipes supplied with the meal kits in the closest quantity available to recipe requirements. While meals from only one meal kit vendor and one grocery store chain are tested, these sources are considered representative of the two systems being studied, with the potential for variation in factors such as individual ingredient packaging and supply chains affecting both meal kits and grocery meals. The choice of functional unit as "one prepared meal" rather than a mass-based functional unit is intentional and reflects the assumption that consumers are likely to follow quantities stated in the recipe and will not adjust for mass. The researchers followed the recipe provided by the meal kit, which specifies quantities of items (e.g. 2 hamburger buns, 3 carrots) which do not control for mass differences between sourced ingredients, which a typical consumer would be unlikely to adjust for. The implications and sensitivity of results to this choice are discussed in the results section.

Direct measurements for the mass of all meal components were obtained using a standard digital kitchen scale. Masses were obtained for the food and packaging for each meal, including food which had to be purchased from the grocery store in a larger quantity than that specified by the recipe and leftover food generated during cooking exceeding the intended meal portion prescribed by the recipe. To the extent possible, researchers prepared the meal in the way a typical consumer would. Measurements collected are detailed in Appendix D.1. Assessing dimensions of sustainability beyond GHGs is an important element in providing a comprehensive assessment of a food product (Nemecek et al., 2016; Pelletier, 2015). Environmental impact factors for greenhouse gases, eutrophication, acidification, land use, and water use for food, packaging, distribution, and end-of-life processes were collected from the literature and life cycle assessment databases, detailed in Appendix D.2. These impact categories are selected due to the relevance of these impacts for the food system and their interpretability for stakeholders, corresponding to considerations for inclusion identified by (Schaubroeck et al., 2018), in addition to considerations of data availability.

GHG emissions are estimated for the agricultural production, packaging, distribution, supply chain losses, consumption, and waste generation associated with each meal. Due to data limitations, other impact categories are estimated for food production, waste, and packaging production

The methods description which follows explicitly describes the calculation of GHG emissions, as that is the most-comprehensive assessment made of the meals in this study. The calculations of environmental impacts for food production, losses, and waste as well as for packaging follow the same steps for other impact categories as for emissions; just using characterization factors for those impacts rather than CO_2e.

This study's boundary begins with the production of food and packaging materials and concludes with the end-of-life for food waste and packaging. A visual depiction of the supply chains compared is displayed in Figure 6.1.

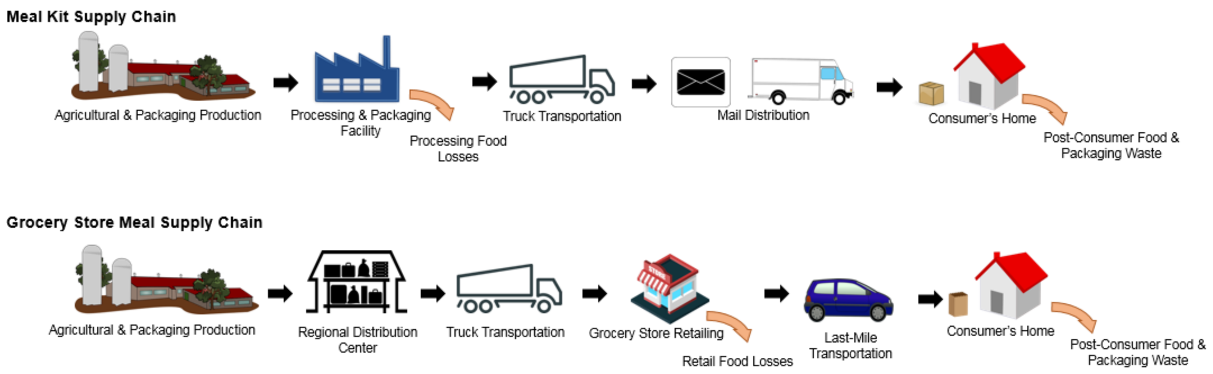

Figure 6.1: Visual depiction of the meal kit and grocery meal supply chains examined.

Cradle-to-gate emissions factors for food and packaging production were obtained from the literature and used to characterize these processes. The quality and agricultural inputs associated with ingredients are assumed to be the same between both meals. In some cases, these emission factors include transportation to wholesaler, depending on data availability. Transportation emissions between production processes and processing and packaging or regional distribution centers modeled in this study are assumed to be equivalent between both meal kits and grocery store meals, and are not explicitly estimated. For meal kits, emissions from processing losses, transportation to a mail distribution center by truck, last-mile distribution by package delivery vehicle, and end-of-life disposal are assessed. Emissions for grocery meals include the transportation of grocery meal ingredients from a regional distribution center to grocery store, retail refrigeration in the store and retailing losses, consumer round-trip transportation to the store, and end-of-life disposal. The emissions burden for household food waste includes emissions embodied from the production and supply of that food, in addition to an assessment of end-of-life waste disposal emissions.

Unconsumed food from both the unused, sourced ingredients and prepared meal can become either leftovers or food waste. Leftovers are assumed to be food consumed at a later time, either reheating an uneaten portion of the prepared meal or using the unused, raw ingredients in a different meal preparation. Leftovers are treated as a co-product of the meal, and are not reported in meal or waste totals. Co-product allocation is conducted on a mass basis. Food waste refers to excess ingredients that are not used for the prepared meal or subsequent meals, as well as uneaten portions of the meal that are discarded. The proportion of food that ends up as food waste are taken from literature values based on U.S. consumption patterns, further described in Table 6.1. End-of-life emissions are calculated for food waste and packaging materials for both meals, with landfilling considered in the default scenario, though packaging recycling is also examined as an alternative.

Emissions from cooking at home, refrigerated storage at the meal kit processing facility and grocery regional distribution center, and all processing and logistics are considered to be approximately equivalent between the two systems, and are not estimated due to data limitations. Potential correlation in the impacts of systems considered in this study is not assessed due to data limitations. Allocation is conducted on a mass basis for foreground and background systems. Capital goods (i.e. buildings, processing machinery, transportation vehicles) are outside of this study's scope. For the recycling scenario, net emissions factor data uses the typical "zero burden approach," not carrying emissions occurring prior to the waste material arriving at the plant (Turner et al., 2015). Allocation choices for multifunctional processes are accepted from the databases and literature studies drawn upon.

The calculation procedure for meal kit and grocery meal emissions is detailed as follows.

The food comprising the meals studied is

Eqn. 6.1

$$Q_{M_F} = Q_{E_F} + Q_{L_F} + Q_{W_F}$$

where Q_{M_F} is the vector of mass of food entering the household by food type (F) (in grams)

Q_{E_F} is the food prepared and eaten by the consumer,

Q_{L_F} is leftover food not eaten at the meal but consumed at a later time, either as reheated portion of the cooked meal or using the unused, raw ingredients in a different meal preparation

and Q_{W_F} is the food waste associated with discarded ingredients that are not used for the prepared meal or subsequent meals, as well as uneaten portions of the cooked meal.

Food produced to create the meal is:

Eqn. 6.2

$$Q_{C_F} = \frac{Q_{M_F}}{(1 - R_{X_F})}$$

where Q_{C_F} is the vector of food created (g)

and R_{X_F} is the loss rate from processing for the meal kit, or grocery store retailing for the grocery meal (%).

For the grocery meal, where food is packaged prior to loss at retail, the quantity of packaging created is calculated in the same way.

Environmental impacts from the agricultural production of foods E_C are calculated as:

Eqn. 6.3

$$E_C = \sum_{F_1}^{F_n} Q_{C_F} * C_F$$

Food production emissions E_C are allocated to food consumed the meal considered E_F (kg CO_2e), leftovers, and food waste by mass.

Packaging emissions are calculated and allocated the same way, with emissions from packaging allocated to the meal consumed as E_P (kg CO_2e). Supply chain emissions are also allocated to the meal consumed, leftovers, and food waste by mass (unless otherwise noted), reflecting how these emissions are embodied in these foods. The emissions total allocated to post-consumer food waste emissions total (kg CO_2e) is described by E_W.

Meal kit processing food losses and grocery meal retail losses Q_X (kg CO_2e) are calculated as:

Eqn. 6.4

$$Q_X = \sum_{F_1}^{F_n} Q_{C_F} * R_{X_F}$$

Emissions from processes occurring prior to losses (food production for meal kits, food production along with transportation to retail and grocery store operation for grocery meals) are allocated by mass to Q_M and Q_X in the supply chain, with emissions allocated to losses E_X (kg CO_2e).

Food loss is distinct from food waste in that it occurs prior to reaching the consumer, reflecting definitions recommended in the literature (Corrado et al., 2017). In this study, food waste refers to edible food which has reached the consumer, but is ultimately not consumed (either as unused, discarded ingredients or as uneaten portions of the cooked meal).

Multiple meals can be delivered in the same box and purchased during the same grocery store trip. Emissions associated with these shared emissions (i.e. last-mile transportation, meal kit box, refrigeration packs, and grocery store bags) are allocated based on the number of meals. The reported mass of shipping boxes, refrigeration packs, and plastic bags is an average among those procured.

Emissions from packaging not specific to individual foods E_B(kg CO_2e) are calculated as Eqn. 6.6

$$E_B = \sum \frac{Q_B * C_B}{N}$$

where Q_B is the vector of packaging elements in a meal kit box, or quantity of plastic for a grocery store bag (in g)

C_B is the vector of production emissions for each packaging type and meal kit box element (in kg CO_2e/g)

and N is the number of meal kits per box or grocery meals per bag. Emissions are allocated based on number of meals according to the definition of functional unit as one prepared meal.

Emissions from freight truck transportation are calculated based on the mass transported Q_{T_F}, which includes food and packaging. Trucking transportation emissions for the transportation of meals E_S (kg CO_2e) are calculated as:

Eqn. 6.7

$$E_S = \sum_{F_1}^{F_n} Q_{T_F} * D_T * C_T$$

where C_T is trucking emissions (kg CO_2e/ g-km)

and D_T is km traveled.

Transportation emissions allocated by mass to the meal considered are E_T.

Grocery store operation emissions E_G (kg CO_2e) are assigned as:

Eqn. 6.8

$$E_G = \sum_{F_1}^{F_n}([Q_{C_F} * H_{D_F} * C_D] + [Q_{C_F} * H_{W_F} * C_A]) * R$$

Where Q_{C_F} is food entering the store (g), some of which is retailed with refrigeration

H_{D_F} is hours in display cabinet by food type

C_D is display cabinet operation and refrigerant leakage emissions (kg CO_2e/g-h)

H_{W_F} is hours in walk-in cooler by food type

C_A is walk-in cooler emissions (kg CO_2e/g-h)

and R is equal to one if food is retailed in grocery stores with refrigeration, and zero if not (resulting in no assigned emissions, see Appendix D.3).

Emissions from store operation allocated by mass to the meal are E_R.

Last-mile emissions for grocery meals E_{M_G} (kg CO_2e) are assumed to be dedicated trips to the grocery store conducted in a personal vehicle, and defined as:

Eqn. 6.9

$$E_{M_G} = \left(\frac{\frac{D_L}{V} * C_G}{N}\right)$$

where D_L is the last-mile distance, calculated on a round-trip basis (km)

V is vehicle fuel efficiency (km/liter gasoline)

C_G is emissions from gasoline combustion (kg CO_2e/liter)

N is the number of grocery meals transported per trip,

and for meal kits E_{M_K} (kg CO_2e) as:

Eqn. 6.10

$$E_{M_K} = \frac{Y * C_I}{N}$$

where Y is energy consumed per package delivered by a mail service on a typical route (MJ/package)

and

C_I are emissions from the combustion of diesel fuel (kg CO_2e/MJ).

End-of-life emissions from waste treatment E_O (kg CO_2e) are calculated for food waste generated as:

Eqn. 6.11

$$E_O = \sum_{F_1}^{F_n} Q_{W_F} * C_E$$

where C_E is the emissions for landfilling food waste (kg CO_2e/g), with U.S. food waste typically disposed of in landfills (Gunders, 2012). End-of-life emissions are calculated the same way for packaging specific to foods, and meal kit boxes and grocery bags, and allocated by mass to the meal and to food waste. End-of-life emissions allocated to the meal assessed are E_E.

The emissions total for meals kits is calculated as:

$$T_M = E_F + E_P + E_B + E_X + E_T + E_{M_K} + E_W + E_E$$

And for grocery meals as:

$$T_G = E_F + E_P + E_B + E_X + E_T + E_R + E_{M_G} + E_W + E_E$$

A Monte Carlo simulation is used to estimate uncertainty and variability in results, using 10,000 parameter simulations and conducted in the statistical software R. A table of Monte Carlo parameters, distribution definitions, and data sources is as follows in Table 6.1.

Best available data for supply chain parameters and associated parameter distributions are drawn from the literature and consultations with individuals working within the meal kit industry. When actual distribution data were unavailable, distributions were assigned triangular distributions associated with an estimated data range due to lack of specific distribution information. Assignment of triangular distributions is a common practice in life cycle assessment (Bjrklund, 2002; Lloyd and Ries, 2007), and alternative distribution selection in Monte Carlo analysis has been demonstrated to have a limited impact on expected values (Lipton et al., 1995).

Parameter	Distribution Type	Key Parameters	Data Source	Comments
Meal kits per box	Binomial	3 (85% probability), 2 (15% probability)	Miller, S.A. (2018, June 21). Personal interview.	
Food retail loss and home waste rates (%)	Triangular distribution	Most-likely percentages described. Retail grain product losses: 12% Consumer grain products waste: 19% Retail fruit loss rate: 9% Consumer fruit waste: 19% Retail vegetables product losses: 8% Consumer vegetables waste: 22% Retail dairy losses: 11% Consumer dairy waste: 20% Retail meat losses: 5% Consumer meat waste: 22% Retail poultry losses: 4% Consumer poultry waste: 18%	(Buzby et al., 2014)	(Buzby et al., 2014)'s report details determinants of loss and waste, which for retail loss includes unpurchased food, damaged food, overstocking, and the culling of aesthetically unpleasing food. At the consumer level, leftovers, misjudged portion sizes, spillage and damage, and psychological attitudes towards food are cited as determinants of food waste, among others. The most-likely percentage is the loss/waste rate for the most-relevant food category (e.g. vegetables for butternut squash), bounded by the minimum and maximum values of retail loss or home waste rates reported. Waste rates are set to zero for select spices and

		Retail fish and seafood losses: 8% Consumer fish and seafood waste: 31% Retail eggs losses: 7% Consumer eggs waste: 21%		common non-perishables, see Appenidx C.3 for details.
Meal kit processing loss rate	Triangular distribution	Most-common loss rate: 10%	(Buzby et al., 2014)	These processing loss rates are defined by general food retail loss rates for food types recorded, with the general retail loss rate set as the most-common value. These values are used as a proxy for processing and packaging losses in meal kit processing facility due to data limitations.
Grocery store retailing	Triangular distributions	Most-common residence time in display cabinets: 48.5 hours Most-common residence time in walk-in coolers: 18.23 hours Most-common emissions from cabinets: 6.62 g CO_2e/kg-hr	(Defra, 2008)	Distributions are bounded by the minimum, average, and maximum emissions values for food types.

		Most-common emissions from refrigerant leakage: 6.01 g CO_2e/kg-hr Emissions from walk-in coolers: 0.43 g CO_2e/kg-hr		
Trucking emissions	Triangular distribution	Most-common emissions: 0.28 g CO_2e/kg-km	(Defra, 2008)	Bounded by the minimum, average, and maximum emissions values for the transportation of food types to retail.
Grocery meal last-mile distance	Normal distribution truncated at zero	Mean one-way distance: 4.43 miles	(USDA Economic Research Service, 2018)	Mean and standard deviation defined from survey question on driving distance between household residence and primary food store.
Grocery meal last-mile vehicle fuel efficiency	Normal distribution truncated at zero	Mean: 23.36 miles per gallon	(U.S. Department of Energy, 2018)	Mean and standard deviation for conventional fuel vehicles.
Number of meals purchased at grocery store	Uniform distribution	Range: 1-5	Practice used by the researchers	The minimum value models a dedicated grocery store trip for the meal considered, and the maximum value models all meals considered being purchased in a single trip

Number of meals per grocery store bag	Uniform distribution	2, 3 (equal probability)	Practice used by the researchers	
Meal kit last-mile delivery energy	Triangular distribution	Most-common value: 10 MJ/package	(Weber et al., 2010)	Energy values are then characterized by diesel's combustion emissions.
Meal kit distance between processing facility and mail distribution center	Triangular distribution	Most-common value: 976.87 km	Researchers' observation from meal kit shipping information	Maximum value defined as 25% greater than this mode, and a minimum value of 50 km is assumed.
Distance between grocery store distribution center and retail store	Triangular distribution.	Most-common value: 47.15 km	Researchers' observation and (The Kroger Co., 2018)	Most-likely value determined with Google Maps as the distance between the closest-identified grocery store brand distribution center and the store used by researchers to purchase grocery store meals. Distribution is bounded with maximum and minimum values defined as plus or minus 25% of the most-likely value

Table 6.1: Monte Carlo Model and Parameter Descriptions

Additional environmental impacts reflecting the production of food, wasted food, and packaging are calculated for acidification, eutrophication, land use, and water use. Overall results for these impact categories are discussed alongside those for GHGs below, with full results tables and details on their calculation available in Appendix D.5.

6.4 Results and Discussion

Differences in emissions for each meal are influenced by two key factors: the overall quantities of food waste and packaging, and the supply chain structure. Generally speaking, meal kits contain larger amounts of packaging but less food due to pre-portioning. Meanwhile, grocery meals have less packaging per meal but larger quantities of food must be purchased, leading to higher household food waste. The two meals also exhibit inherent differences in supply chain structure, particularly with respect to the method of last-mile transportation (delivery truck for a meal kit, consumer vehicle trip for the grocery meal) and food losses in the pre-consumer supply chain (processing losses for meal kits, retail losses for the grocery meal).

Emissions reported for the five meals studied are median values for each meal, unless otherwise noted. For simplicity, greenhouse gas equivalent emissions are the focus of the discussion in the main text. Results for other impact categories are summarized at the end of the results section, as the overall trends are largely similar across impact categories.

Emissions totals and ranges for each meal studied are displayed in Figure 6.2. The average grocery store meal is calculated as having 2 kg CO_2e/meal higher emissions than an equivalent meal kit. For context, the average emissions were calculated to be 6.1 kg CO_2e/meal for a meal kit and 8.1 kg CO_2e/meal for a grocery store meal, with the latter exceeding meal kit emissions by a 33% difference. Median grocery store meal emissions exceed the median meal kit emissions for four out of five meal types examined. The grocery store meal emissions exceed those for meal kits by 28% for the salmon, 23% for the chicken, 124% for the pasta, and 43% for the salad. Emissions for the meal kit cheeseburger are 15% higher than those for the grocery store. Emissions for the grocery store meal exceed those for meal kits in over 95% of Monte Carlo model runs for the pasta and salad meals (in 100% of model runs), as well as 84% of model runs for the salmon, and 86% for the chicken. Meal kit emissions exceed those from the grocery store for the cheeseburger in 90% of runs.

Figure 3 provides an analysis of the contributions of each life cycle stage to emissions totals, with 3a displaying median emissions contributions and 3b showing the relative contribution of each element to the meal's emissions total.

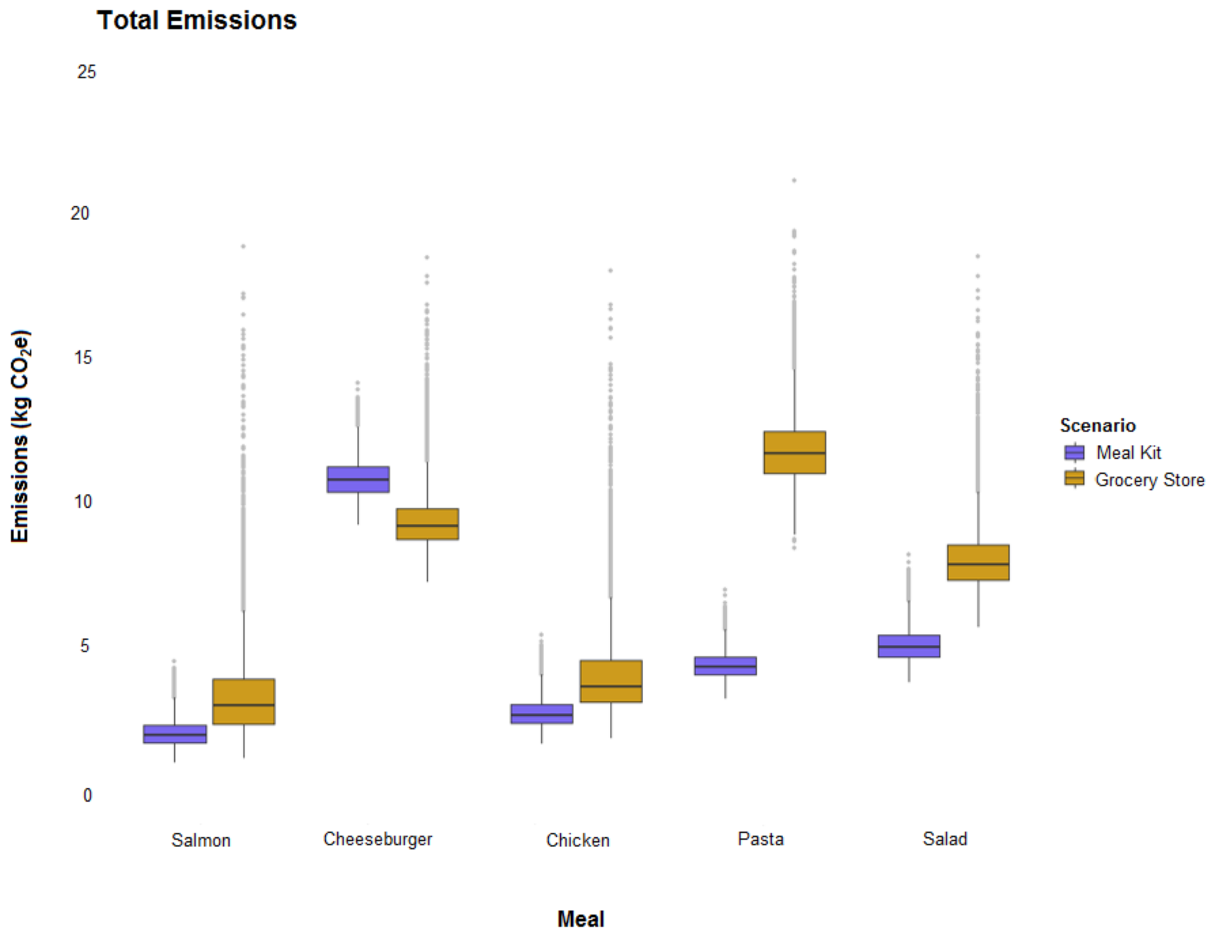

Figure 6.2: Total estimated emissions (kg CO_2e) for the five meals studied supplied as a meal kit or via a grocery store. Black lines indicate median emissions for each meal by type, and boxes indicate emissions within the 25th and 75th percentiles of model runs. Grey dots indicate values falling outside of this range, which may be considered outliers. These more-extreme values have an upward bias, reflecting higher-emissions intensity cases to create, supply, and consume meals.

A)

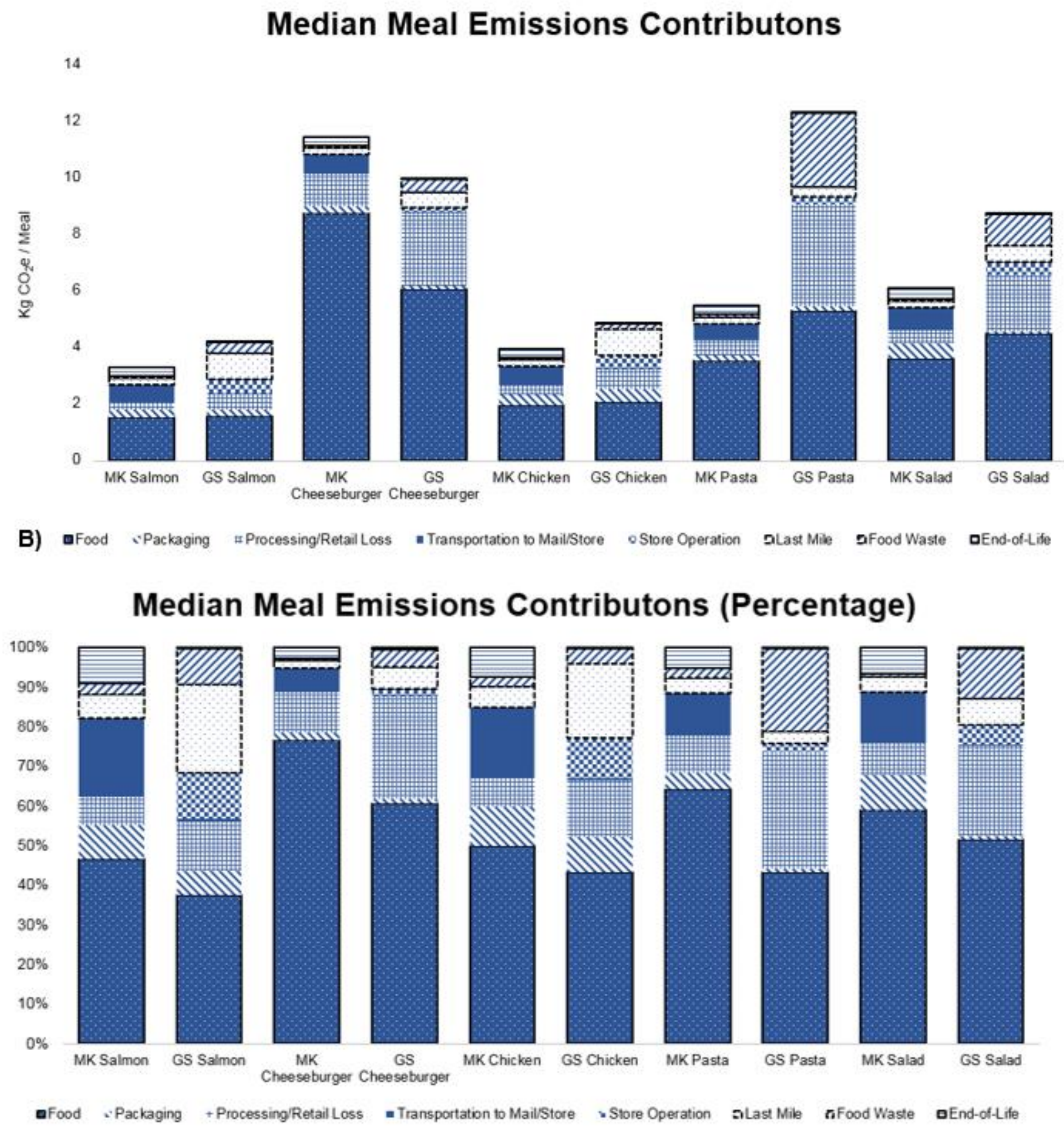

Figure 6.3: Median emissions (kg CO_2e) for each contributing element to meal emissions by meal type. MK indicates meal kit and GS indicates grocery store meals. Solid lines surround portions of the supply chain more-directly within a consumers' control. Emissions and contributions are displayed in absolute terms in the upper chart, and by percentage of total emissions in the lower chart.

The most noticeable supply chain difference presented by meal kits is skipping brick-and-mortar retailing. This direct-to-consumer model presents a large emissions savings through retail food loss reduction: averaging 1.35 kg CO_2e/meal. The quantity of retail losses for the pasta and salad meals are over three times larger than the quantity of food loss in the meal kit supply chain (processing losses) by 361 g and 325 g, respectively. Many grocery store retailing losses occur in connection to inherent challenges from this business model, including overstocking food due to difficulty in predicting the number of customers, eliminating blemished or unappealing foods which may not appeal to shoppers, and holiday food items which remain unpurchased following the holiday (Buzby and Hyman, 2012).

Additionally, the embodied emissions in grocery retail loss are higher than those for meal kit processing losses since they occur further down the supply chain. As such, retail food loss contains embodied transportation and store refrigeration emissions not included in meal kit processing losses. Retail losses comprise 29% of the emissions total reported for the pasta grocery meal and 23% for the salad, compared with 10% and 8% from meal kit processing losses for the same meals.

Post-consumer food waste is also major driver in the environmental impact of meals. Emissions from food waste from grocery meals exceeds those for meal kits in all five meals by an average difference of 0.86 kg CO_2e/meal, ranging from a difference of 0.1 kg CO_2e for the chicken meal to 2.5 kg CO_2e for the pasta meal. Food waste comprises an average of 10% of a grocery store meal's emissions, compared with 2% of average meal kit emissions. This difference is attributable to meal kits pre-portioning ingredients, leaving fewer ingredients that are later subject to household food waste rates. The median values of food waste per meal are shown in absolute (kg CO_2e) and percentage terms in Figure 3 and detailed in Appendix D.4. Note that the food waste contributions in Figure 3 refer only to post-consumer wastes; processing and retail losses are displayed separately.

Post-consumer food waste is particularly large for the pasta and salad grocery meals. Food waste generated at the household comprises a much greater share of emissions for the pasta and salad grocery meals than the others, at 21% and 13%, respectively, compared to 9% for the salmon, 4% for the cheeseburger, and 4% for the chicken. Both of these meals are comprised of a number of ingredients which must be purchased from grocery stores in larger quantities than called for in the recipe studied, yielding larger quantities of unused foods than for meal kits, which are then subject to household waste rates. These include kale, butternut squash, pasta, farro, cheese, eggs, and mushrooms (see Appendix D.1). For some items with a long shelf life (i.e. vinegars, spices), the waste rates are extremely low and modeled at 0%, whereas products such as fresh vegetables and dairy products have higher expected waste rates (24%, 20% (Buzby et al., 2014)). Unused quantities of these ingredients are multiplied by their corresponding consumer level food waste rates, which is based on estimates of post-consumer food waste for a variety of items for American households. It is possible that the home cook would not purchase every ingredient in a recipe or provide substitutions for less common items, in which case the difference emissions between the grocery store and meal kit recipes would be less.

Since the meal kit supply chain bypasses brick-and-mortar retailing, there is higher supply chain truck transportation emissions (0.67 kg CO_2e/meal), and more-robust packaging for shipping the meal to the consumer. Meal kits also present the means to reduce post-consumer food waste through pre-portioning, but have added individual packaging for the portioned ingredients. As Figure 3a indicates, packaging emissions for meal kits (including their shipping boxes) exceed those for grocery store meals (including grocery store bags) for four out of five meals studied, with the average increase being 0.17 kg CO_2e/meal. The exception is the chicken meal, in part due to some of the grocery meal's ingredients being packaged with metal and styrofoam instead of plastic. When analyzing overall contributions to total meal kit emissions, packaging emissions represent a larger share of meal kit emissions for all five meals (with an average of 7% compared to 4% of emissions from grocery store).

The environmental impacts associated with the production of food packaging have found to typically be less than those for food (Silvenius et al., 2011), indicating that if the addition of packaging would reduce food loss and waste, it may be a net environmental benefit. However, engaging with consumers and retailers in reducing food waste also presents a means through which to decrease these emissions without adding emissions burdens from packaging. Retail food loss could be reduced through interventions including lowering the storage temperature for food (Eriksson et al., 2016), the recovery of retail food loss to provide nutrition for the undernourished and/or socioeocnomically disadvantaged (Giuseppe et al., 2014), and the improved use of analytics to predict customer shopping behavior which could mitigate overstocking. (Neff et al., 2015) find that many consumers are recepetive to food waste prevention efforts, and perceive themselves as wasting less food than they do: with nearly ¾ of (U.S.) respondants believing they dispose of less food than the average American. Behaviors leading to the creation of food waste are complex and cannot be reduced to a single variable

(Schanes et al., 2018); however, establishing household routines surrounding food such as meal planning (including leftover reuse and planned shopping) (Stancu et al., 2016) present promise in reducing post-consumer food waste generation.

Irrespective of the method of procurement, embodied emissions of food dominate all other sources of emissions, for all meals analyzed. Emissions from food production comprise an average of 59% of meal kit emissions and 47% of grocery store emissions, highlighing the substantial role which agricultural production emissions play in determining overall food product emissions. These emissions range from comprising 77% of the meal kit cheeseburger meal to 37% of the salmon meal kit's emissions, which is expected given the high emission-intensity of beef production. Food production emissions are the key reason that emissions for the meal kit exceed those of the grocery meal for the cheeseburger. The beets and hamburger buns received in the meal kit had masses over two-and-a-half times in excess of those purchased at the grocery store. These differences highlight the heterogenity in food ingredients, and how customer purchasing decisions associated with size of ingredients can affect the emissions associated with a recipe. The methodological choice of a functional unit of "one prepared meal" rather than "kg prepared meal" was intentional to highlight the importance of how variability in masses of ingredients that meet a recipes specifications (e.g 2 hamburger buns) can impact an analysis. Figure 4 depicts emissions contributions showing the relative differences in meal kits and grocery meals if the masses of food prepared in the recipe were identical.
For meals comprised of emissions-intense ingredients (such as beef), whether the food is supplied as a meal kit or through a grocery store effects the overall emissions total less, since

agricultural production comprises most of its emissions footprint. In this case, the choice of protein source affects the meal's emissions to a greater degree than how it's supplied.

In the meal kit box, refrigeration is provided by refrigeration packs. Median emissions from meal kit shipping packaging amount to approximately 3% of the average meal kit's emissions, with refrigeration packs contributing the smallest quantity of emissions to this total (0.3%). Despite having the largest mass of any box element, the refrigeration packs are assumed to be entirely water, reflecting a water-based formulation used by the meal kits studied (Miller, S.A. (2018, June 21). Personal interview.). It should be noted, however, that not all meal kits may use water-based refrigerant packs, and that the use of chemical-based refrigerants would increase emissions. If the refrigerant pack mass is characterized by an emissions factor for 98% water and 2% ethylene glycol, it's per-meal emissions increase from 0.0004 kg CO_2e to 0.0427 kg CO_2e, increasing median emissions associated with the meal kit shipping packaging by 25%, but not altering overall study results. A fundamental difference in the supply chain for meal kits is that they are not subject to retail refrigeration, instead receiving refrigeration from refrigeration packs. Refrigeration packs present a new, non-traditional means of achieving food refrigeration within the food supply chain. The emissions associated with supplying water for these packs is dwarfed by the emissions of retail refrigeration, with an average of 0.37 kg CO_2e/meal. Refrigeration is an essential element of a modern food supply chain and connected with notable direct and indirect environmental impacts (Heard and Miller, 2016). It should be noted that the relative emissions in this comparison has the potential to vary based on refrigeration pack composition, and to change with improvements to grocery stores. The grocery store system modeled uses an HFC refrigerant (Defra, 2008) which are being phased down resulting from the Kigali Amendment to the Montreal Protocol (United Nations Environment Programme, 2016).

The environmental impacts of supermarket refrigeration may be reduced in the future with the substitution of natural refrigerants and energy efficiency improvements.

Last-mile emissions comprise a greater share of the grocery store meal emissions than for meal kits (11% compared to 4% for an average meal). Average grocery meal last-mile emissions exceed those for meal kits by 0.45 kg CO_2e/meal. Last-mile transportation for a grocery meal is a round-trip made by the consumer, with variance in vehicle type, distance, and number of meals transported per trip. On the other hand, the last-mile transportation emissions for meal kits is delivery by a package or mail service via truck on an optimized route.

These findings align with those from studies of grocery home delivery services, estimating that grocery delivery reduces emissions compared to traditional consumer grocery shopping. In examining a system of grocery orders in Finland, (Siikavirta et al., 2003) find that depending on the delivery mode examined, last-mile emissions with grocery home delivery range from 0.25 to 0.96 kg CO_2e/order compared with 1.17 kg CO_2e/order if all ordering customers used their own cars to make shopping trips. (Wygonik and Goodchild, 2012) estimate emissions of 0.326 kg CO_2e/customer when delivering stores are randomly-assigned to customers, and 0.079 kg CO_2e/customer when stores are proximity-assigned to customers. Optimizing delivery with respect to customer distance yields the highest emissions savings estimated by Siikavirta, as well. Wygonik & Goodchild estimate emissions of 0.595 and 0.567 kg CO_2e/customer for passenger travel to obtain groceries, with and without proximity-assignment, respectively. Our study estimates average meal kit last-mile emissions at 0.22 kg CO_2e/meal, compared with 0.67 kg CO_2e/meal for the grocery meal. These values align with Wygonik & Goodchild's per-order estimates for randomly-assigned grocery delivery and consumer travel to the grocery store, respectively. While lower than Siikavirta et al.'s estimates, the estimated percentage reduction in last-mile emissions presented by average meal kit emissions compared to grocery meals is 68%, falling within the upper range of improvement calculated by Siikavirta (18-87%).

The end-of-life impacts for both meals are small relative to their other emissions contributions: comprising an average of 6% for the meal kits' and 0.4% for the grocery meals' emissions. End-of-life emissions are higher for the meal kit for all five meals, attributable to the emissions associated with landfilling the packaging from the meal kit box. Recycling meal packaging results in an emissions decrease for meals and meal types, by an average of 14% for meal kits and 4% for grocery meals, reflecting the larger quantity of packaging associated with the meal kit. An analysis of end-of-life treatment options for plastic film recycling finds recycling to present substantial environmental benefits over landfilling or incineration through allowing the substitution of recycled plastics for the production of plastic from virgin materials (Hou et al., 2018); relevant to meal kits given their prominent use of individual plastic packaging for ingredients.

A thesis by Fenton studies the relative environmental impacts of meal kits and grocery store equivalent meals, finding that meal kits provide an average GHG reduction of 4% (and average energy use reduction of 20%) (Fenton, 2017). Our study's overall findings align with those from Fenton, whose analysis finds meal kits yielding lower food waste, higher packaging, and lower last-mile transportation emissions (Fenton, 2017). Fenton's study measures total emissions for meal kits and grocery meals as the sum of emissions from building energy use, last-mile transportation, product packaging, food waste (both at retail/warehousing and post-consumer), and end-of-life material management. In contrast to this study, emissions for the production of food consumed in the studied meal, and meal kit transportation to the mail distribution center are not included in the emissions total assessed. Additionally, Fenton's analysis differs from this study in how supply chain boundaries are defined, beginning the meal kit supply chain at a post-processing regional refrigerated warehouse, and the grocery store supply chain at the retail store. When subtracting the average food production emissions for food consumed at the meal from average meal emissions, this study's estimates for meal kit emissions are 0.3 kg CO_2e lower than Fenton's, and 1.5 kg CO_2e higher for the grocery meal.

The environmental impacts of alternative meal structures have also been studied. (Davis and Sonesson, 2008) compare the environmental impacts of a homemade and frozen "semi-prepared" chicken meals, though differing in ingredients and recipe. They find the semi-prepared meal to have higher GHG emissions than the homemade alternative, largely due to the emissions associated with waste treatment in its supply chain. In a comparison of ready-made meals and home-cooked equivalents, Rivera et al. find home-cooked meals to have lower environmental impacts due to a lack of meal manufacturing, reduced refrigeration, and lower waste quantities in the meal's life cycle (Rivera et al., 2016). Sonneson et al. compare the environmental impacts of home-cooked, semi-prepared, and ready-to-eat meals and found the three meal types to have very similar environmental impacts, concluding that the differences between them were too small to draw meaningful comparisons of their relative environmental impacts (Sonesson et al., 2005).

Additional impact categories for food, food loss, food waste, and packaging have also been assessed. The acidification and land use impacts for the grocery meal exceed those for meal kits for all five meals, by an average difference of 57% and 56%, respectively. Due to data constraints, packaging is considered separately for eutrophication and water use (see Appendix D.5). The impacts of grocery meal food, food loss, and food waste exceed those for meal kits for all five meals, by an average of 69% for eutrophication and 67% for water use. The water use burdens for meal kit packaging exceed those for grocery meals for four out of five meals (the exception being the pasta meal, attributable to glass, metal, and cardboard in its ingredients' packaging). Eutrophication impacts for packaging are small for both meal types, but with meal kit packaging eutrophication exceeding that for grocery meals for salmon, chicken, and salad meals (with the grocery meal cheeseburger and pasta meals containing greater amounts of cardboard, paper, or glass than for the other meals). These results broadly align with trends seen in emissions: typically higher impacts from food categories for grocery meals, and typically higher impacts from packaging for meal kits.

Figure 6.4 depicts the results from actual meals prepared using the masses of ingredients sourced via both a meal kit service and the grocery store. This study assumes that consumers cook meals according to a recipe, which often lists quantities of ingredients rather than a specific mass of food, despite large potential variability in ingredient mass. Figure 6.4 shows how the variability in the masses of ingredients used to cook the same recipe can affect overall results, which are particularly evident in the cheeseburger, pasta, and salad meals. In order to isolate the differences associated with the actual procurement mechanism of grocery store versus meal kit, Figure 4 depicts a scenario where the mass of food procured from the grocery store is assumed to be equal to the mass of food supplied by the meal kit company, controlling for heterogeneity in ingredient masses.

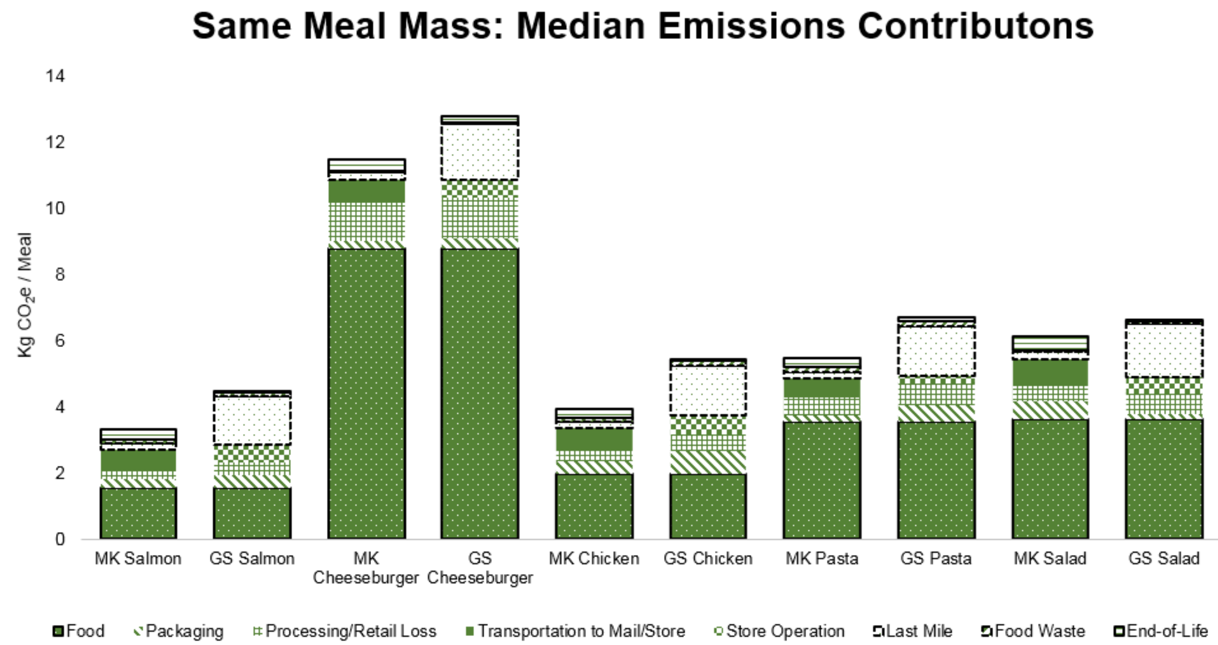

Figure 6.4: Median emissions (kg CO_2e) for contributing elements to meal emissions by meal type if grocery meal ingredients have identical mass to meal kit ingredients. MK indicates meal kit and GS indicates grocery store meals. Solid lines surround portions of the supply chain more-directly within a consumers' control.

If it is assumed that the mass of food purchased at the grocery store is identical to that delivered in a meal kit, grocery meal emissions are 10% lower than the scenario using actual measured values; however, emissions from grocery store meals exceed the emissions from meal kits in all five meals under this scenario, exceeding meal kit emissions by an average of 1.1 kg CO_2e. Grocery meal emissions remain higher than those for meal kits due to the added burden of grocery store operation, higher supply chain losses (during retailing, compared with losses during meal kit processing), and more-emitting last-mile transportation. With this change, grocery store emissions now exceed those for meal kits for the cheeseburger meal (by 1.3 kg CO_2e), since larger ingredient masses were responsible for the meal kit cheeseburger having higher emissions when actual data were used. Grocery meal emissions for the pasta and salad meals still exceed those for the meal kits, but by smaller quantities and with less statistical certainty: with grocery store pasta meal emissions exceeding those for meal kits in 85% of model and grocery store salad meal emissions exceeding the meal kit's in 63% of runs (compared with 100%, for both). This alternative scenario of a standardized meal mass does not alter the overall comparative results of this analysis, but does illustrate that the grocery meal supply chain is a more-emissions intensive way to supply a given mass of food. Additionally, these results reveal the notable extent to which grocery meal emissions can be mitigated by reducing over-purchasing.

6.5 Sensitivity Analysis

In addition to the Monte Carlo analysis that provided a range of potential parameter results, a one-at-a-time perturbation helps determine the extent to which emissions for both meal types are sensitive to their supply chain parameters. Each parameter in the model is fixed at its median value, excepting the parameter of interest, which is individually fixed at a value 25% larger or smaller than its median (or in a few cases, as noted below, at plausible extreme values). Results from this analysis are displayed in Figure 5. Additional sensitivity analysis was conducted by examining changes to some elements of the materials modeled, supply chain scenarios, and additional assumptions.

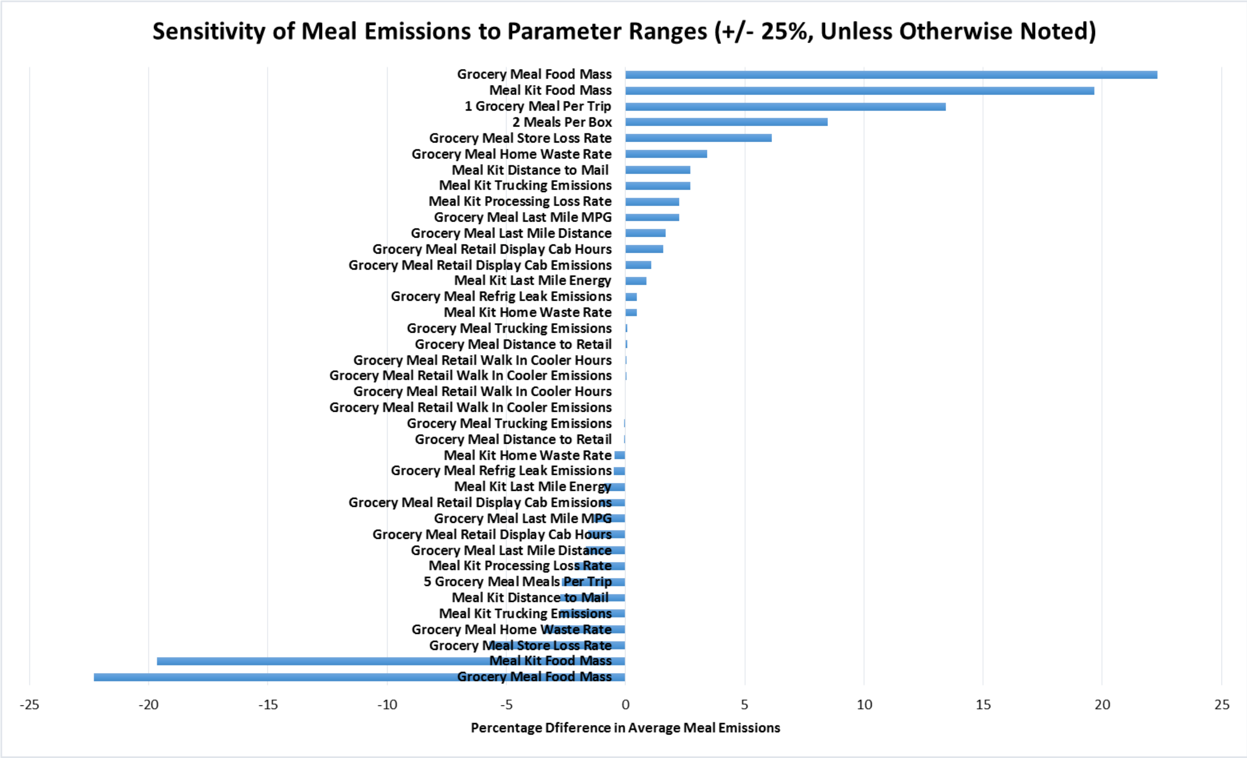

Figure 6.5: Percentage difference between emissions (kg CO_2e) for an average meal kit or grocery store meal calculated when each parameter of interest is fixed to 25% greater or less than its median value (or as otherwise noted) and other parameters held at their median values.

Proportioning ingredients for meals, and the quantities of food losses and waste are connected with the most-substantial emissions increases or savings. The largest emissions changes in this sensitivity analysis result from a 25% increase or decrease in food mass for both grocery meals and meal kits (22% and 20% changes, respectively). Some consumers may be more diligent in consuming leftovers than others. Grocery meals are sensitive to loss and waste rates for food, with a retail loss rate 25% higher or lower than the median value resulting in a 6% change in average meal emissions, and a 25% change in the home waste rate corresponding with a 3% change. The emissions for both meal types are also sensitive to changes in transportation parameters, as reflected graphically.

If dried foods, which are less-sensitive to spoilage (beans and breadcrumbs in the chicken meal, pasta in the pasta meal, and farro and dried mushrooms in salad meal), are not subject to a waste rate, the emissions for these three meals decrease by an average of 0.3% and 2% for the meal kit and grocery meals, respectively.

Substituting polylactide (a bioplastic) for all plastics does not change average meal emissions, increasing packaging emissions by an average of 0.4 kg CO_2e through increased production emissions, but also decreasing end-of-life emissions by an average of 0.4 kg CO_2e. Bioplastics are still emerging and developing, with a review of life cycle assessments including polylactide noting a wide range of uncertainty associated with overall greenhouse gas emissions associated with these plastics (Hottle et al., 2013).

6.6 Meal Kits and the Future of Food

The results of this analysis indicate that meals supplied from a grocery store tend to have higher life cycle environmental impacts than meal kits, despite popular perceptions of meal kits having worse environmental impacts.

Grocery meal emissions exceed those for meal kits in part due to differences in food loss and waste. Pre-portioning ingredients for individual meals helps ensure minimal post-consumer food waste, whereas purchasing ingredients in larger quantities than those called for in the recipes increases the probability of food waste. Additionally, brick-and-mortar grocery retailing practices resulting in food loss are connected to elements of this business model including changes in consumer volume and the incentive to sell visually-appealing food. Food loss and waste carries a substantial environmental burden (FAO Natural Resources and Management Department, 2013; Gustavsson et al., 2011), reflecting the environmental-intensity of food production and supply up until the point of loss.

An important consideration for potential food waste reduction is the subscription model for meal kits and grocery e-commerce. In an modeling analysis of online grocery retailing with home delivery where consumers either pay per order, or with a one-time subscription fee, it was found that the subscription model incentivized smaller and more-frequent grocery orders, reducing food waste (Belavina et al., 2017). The authors report that the reduction in food waste emissions is larger than emissions added through increased delivery. Additionally, if a meal kit subscription replaces a consumers' grocery store trips, the potential for impulse purchases which may result in food waste is decreased (Graham-Rowe et al., 2014).

One consideration not in the scope of this study is the environmental burdens of leftover storage, with a comparison of glass and plastic reusable food containers finding the use phase (consisting of washing containers) to be the hot spot for all environmental impacts (Gallego-Schmid et al., 2018). This finding would indicate that increased instances of meals generating leftovers would be associated with greater use of these containers, which would add an additional environmental burden connected with meals which aren't well-portioned for the consumer.

Systems of packaging for distribution in the food supply chain are examined in an integrated framework by (Accorsi et al., 2014) who find a system using reusable plastic containers producing fewer GHG emissions than single-use plastic crates. Multi-use plastic packaging systems decrease the environmental burdens of manufacturing, but the reusable plastic containers system emissions are found to be sensitive to transportation. The transportation system was also found to be an important determinant of the environmental impact of these containers by (Levi et al., 2011) who also note that a lower ratio of packaging weight with respect to the transported product's weight reduces impacts. It should be noted, however, that cardboard and wooden single-use containers are found to have lower emissions than plastic single-use containers (Accorsi et al., 2014), and a cardboard container is found to have lower lifecycle GHG emissions than a reusable plastic container independently of size (Levi et al., 2011).

It is also important to note that the largest emissions impacts for both meal kits and grocery store meals is from the production of food, highlighting the necessity of considering the impacts of agricultural production when examining the greenhouse gas emissions associated with meals. For the grocery store meal supply chain, a clear opportunity through which GHG emissions-intensity could be reduced is by improving last-mile transportation. Possible means of decreasing these emissions include grocery home-delivery (Brown and Guiffrida, 2014; Wygonik and Goodchild, 2012), increased use of public transportation (Wiese et al., 2012), and public policy to increase population density, a factor connected to last-mile travel distances (Matthews et al., 2002). Additionally, the transition to low-GWP refrigerants (US Environmental Protection Agency, 2016) and energy efficiency improvements (Leach et al., 2009) may decrease the environmental burdens of grocery store operation.

The structure of last-mile delivery may change notably in the coming years from the use of drone delivery. An analysis of life cycle greenhouse gas emissions finds that home-delivery by small drones could produce fewer emissions than ground-based delivery (Stolaroff et al., 2018). Whether these savings would be realized for meal kit or grocery delivery, however, is an open question, with both feasibly requiring the use of larger drones, whose life cycle emissions may exceed those from delivery by a diesel-powered truck (Stolaroff et al., 2018).

The relative environmental impacts of meal kits have implications for sustainable development, as well. Lu and Reardon extend an economic modeling framework analyzing competition between supermarket and traditional food retailing in the developing world to also assess competition between supermarkets and e-commerce in the context of retail transition (Lu and Reardon, 2018). Meal kits present the potential to provide access to non-seasonal or non-regional foods, which could increase dietary diversity and reduce variability in food availability. However, these shifts could also increase supply chain distances that could offset these benefits.

The pre-portioning aspect of meal kits may also provide the ability to mitigate potential increases in post-consumer food waste occurring with development.

The way consumers purchase and receive food is undergoing substantial transformation, and meal kits are likely to be part of it in some way. This analysis indicates that meal kits may offer some improvements over grocery store meals, largely due to reduced food loss and waste throughout the supply chain, and a direct-to-consumer supply chain structure. In order to minimize overall impacts of the food system, there is a need to continue to reduce food loss and waste, while also creating advances in transportation logistics to reduce last-mile emissions and packaging to reduce material use.

6.7 References

Accorsi, R., Cascini, A., Cholette, S., Manzini, R., Mora, C., 2014. Economic and environmental assessment of reusable plastic containers: A food catering supply chain case study. Intern. J. Prod. Econ. 152, 88–101. doi:10.1016/j.ijpe.2013.12.014

Belavina, E., Girotra, K., Kabra, A., 2017. Online Grocery Retail: Revenue Models and Environmental Impact. Manage. Sci. 63, 1781–1799. doi:10.2139/ssrn.2520529

Bjrklund, A.E., 2002. Survey of Approaches to Improve Reliability in LCA. Int. J. Life Cycle Assess. 7, 64–72.

Brown, J.R., Guiffrida, A.L., 2014. Carbon emissions comparison of last mile delivery versus customer pickup. Int. J. Logist. Res. Appl. 17, 503–521. doi:10.1080/13675567.2014.907397

Butler, K., 2017. The Truth About Meal-Kit Freezer Packs [WWW Document]. Mother Jones. URL https://www.motherjones.com/environment/2017/06/meal-kit-freezer-packs-blue-apron-hello-fresh/ (accessed 2.8.18).

Buzby, J.C., Farah-Wells, H., Hyman, J., 2014. The Estimated Amount, Value, and Calories of Postharvest Food Losses at the Retail and Consumer Levels in the United States, Economic Information Bulletin. doi:10.2139/ssrn.2501659

Buzby, J.C., Hyman, J., 2012. Total and per capita value of food loss in the United States. Food Policy 37, 561–570. doi:10.1016/j.foodpol.2013.04.003

Corrado, S., Ardente, F., Sala, S., Saouter, E., 2017. Modelling of food loss within life cycle assessment: From current practice towards a systematisation. J. Clean. Prod. 140, 847–859. doi:10.1016/j.jclepro.2016.06.050

Davis, J., Sonesson, U., 2008. Life cycle assessment of integrated food chains - A Swedish case study of two chicken meals. Int. J. Life Cycle Assess. 13, 574–584. doi:10.1007/s11367-008-0031-y

Defra, 2008. Greenhouse Gas Impacts of Food Retailing (No. Defra Project code FO405).

Eriksson, M., Strid, I., Hansson, P.A., 2016. Food waste reduction in supermarkets - Net costs and benefits of reduced storage temperature. Resour. Conserv. Recycl. 107, 73–81. doi:10.1016/j.resconrec.2015.11.022

FAO Natural Resources and Management Department, 2013. Food Wastage Footprint Impacts on natural resources: Technical Report (No. AR429).

Fenton, K., 2017. Unpacking the Sustainability of Meal Kit Delivery: A Comparative Analysis of Energy Use, Carbon Emissions, and Related Costs for Meal Kit Services and Grocery Stores. The University of Texas at Austin.

Gallego-Schmid, A., Mendoza, J.M.F., Azapagic, A., 2018. Science of the Total Environment Improving the environmental sustainability of reusable food containers in Europe. Sci. Total Environ. 628–629, 979–989. doi:10.1016/j.scitotenv.2018.02.128

Giuseppe, A., Mario, E., Cinzia, M., 2014. Economic benefits from food recovery at the retail stage : An application to Italian food chains. Waste Manag. 34, 1306–1316. doi:10.1016/j.wasman.2014.02.018

Graham-Rowe, E., Jessop, D.C., Sparks, P., 2014. Identifying motivations and barriers to minimising household food waste. Resour. Conserv. Recycl. 84, 15–23. doi:10.1016/j.resconrec.2013.12.005

Gunders, D., 2012. Wasted: How America is losing up to 40 percent of its food from farm to fork to landfill, NRDC Issue Paper. doi:12-06-B

Gustavsson, J., Cederberg, C., Sonesson, U., 2011. Global Food Losses and Food Waste: Extent, Causes, and Prevention.
Heard, B.R., Miller, S.A., 2016. Critical research neeeded to examine the environmental impacts of expanded refrigeration on the food system. Environ. Sci. Technol. 50, 12050–12071. doi:10.1021/acs.est.6b02740
Heller, M.C., Selke, S.E.M., Keoleian, G.A., 2018. Mapping the Influence of Food Waste in Food Packaging Environmental Performance Assessments. J. Ind. Ecol. 00, 1–16. doi:10.1111/jiec.12743
Hottle, T.A., Bilec, M.M., Landis, A.E., 2013. Sustainability assessments of bio-based polymers. Polym. Degrad. Stab. 98, 1898–1907.
Hou, P., Xu, Y., Taiebat, M., Lastoskie, C., Miller, S.A., 2018. Life cycle assessment of end-of-life treatments for plastic film waste. J. Clean. Prod. 201, 1052–1060. doi:10.1016/j.jclepro.2018.07.278
Leach, M., Hale, E., Hirsch, A., Torcellini, P., 2009. Grocery Store 50% Energy Savings Technical Support Document.
Lipton, J., Shaw, W.D., Holmes, J., Patterson, A., 1995. Short Communication: Selecting Input Distributions for Use in Monte Carlo Simulations. Regul. Toxicol. Pharmacol. 21, 192–198.
Lloyd, S.M., Ries, R., 2007. Characterizing, Propagating, and Analyzing Uncertainty in Life-Cycle Assessment: A Survey of Quantitative Approaches. J. Ind. Ecol. 11, 161–179.
Lu, L., Reardon, T., 2018. An Economic Model of the Evolution of Food Retail and Supply Chains from Traditional Shops to Supermarkets to E-Commerce. Am. J. Agric. Econ. 0, 1–16. doi:10.1093/ajae/aay056
Marker Jr, J.T., Goulias, K., 2007. Framework for the Analysis of Grocery Teleshopping (No. 0–566), Transportation Research Record. doi:10.3141/1725-01
Marsh, K., Bugusu, B., 2007. Food packaging — Roles, Materials, and Environmental Issues. J. Food Sci. 72. doi:10.1111/j.1750-3841.2007.00301.x
Matthews, H.S., Williams, E., Tagami, T., Hendrickson, C.T., 2002. Energy implications of online book retailing in the United States and Japan. Environ. Impact Assess. Rev. 22, 493–507. doi:10.1016/S0195-9255(02)00024-0
Miller, S.A., Keoleian, G.A., 2015. Framework for Analyzing Transformative Technologies in Life Cycle Assessment. Environ. Sci. Technol. 49, 3067–3075. doi:10.1021/es505217a
Neff, R.A., Spiker, M.L., Truant, P.L., 2015. Wasted Food: U.S. Consumers' Reported Awareness, Attitudes, and Behaviors. PLoS One 1–16. doi:10.1371/journal.pone.0127881
Nemecek, T., Jungbluth, N., i Canals, L.M., Schenck, R., 2016. Environmental impacts of food consumption and nutrition: where are we and what is next? Int. J. Life Cycle Assess. 21, 607–620. doi:10.1007/s11367-016-1071-3
Niles, M.T., Ahuja, R., Barker, T., Esquivel, J., Gutterman, S., Heller, M.C., Mango, N., Portner, D., Raimond, R., Tirado, C., Vermeulen, S., 2018. Climate change mitigation beyond agriculture : a review of food system opportunities and implications. Renew. Agric. Food Syst. 13, 1–12. doi:10.1017/S1742170518000029
Pan, S., Giannikas, V., Han, Y., Gover-Silva, E., Qiao, B., 2017. Using customer-related data to enhance e-grocery home delivery. Ind. Manag. Data Syst. 117, 1917–1933. doi:10.1108/IMDS-10-2016-0432
Pelletier, N., 2015. Life Cycle Thinking, Measurement and Management for Food System Sustainability. Environ. Sci. Technol. 49, 7515–7519. doi:10.1021/acs.est.5b00441

Punakivi, M., Yrjölä, H., Holmström, J., 2001. Solving the last mile issue: reception box or delivery box? Int. J. Phys. Distrib. Logist. Manag. 31, 427–439. doi:10.1108/09600030110399423
Rivera, X.C.S., Orias, N.E., Azapagic, A., 2016. Life cycle costs and environmental impacts of production and consumption of ready and home-made meals. J. Clean. Prod. 112, 214–228. doi:10.1016/j.jclepro.2015.07.111
Schanes, K., Dobernig, K., Burcu, G., 2018. Food waste matters - A systematic review of household food waste practices and their policy implications. J. Clean. Prod. 182, 978–991. doi:10.1016/j.jclepro.2018.02.030
Schaubroeck, T., Ceuppens, S., Duc, A., Benetto, E., Meester, S. De, Lachat, C., Uyttendaele, M., 2018. A pragmatic framework to score and inform about the environmental sustainability and nutritional pro fi le of canteen meals , a case study on a university canteen. J. Clean. Prod. 187, 672–686. doi:10.1016/j.jclepro.2018.03.265
Siikavirta, H., Punakivi, M., Ka, M., Linnanen, L., 2003. Effects of E-Commerce on Greenhouse Gas Emissions A Case Study of Grocery Home Delivery. J. Ind. Ecol. 6, 83–97. doi:10.1162/108819802763471807
Silvenius, F., Katajajuuri, J., Grönman, K., 2011. Role of Packaging in LCA of Food Products, in: Finkbeiner, M. (Ed.), Towards Life Cycle Sustainability Management. Springer, pp. 359–370. doi:10.1007/978-94-007-1899-9
Sonesson, U., Mattsson, B., Nybrant, T., Ohlsson, T., 2005. Industrial processing versus home cooking: an environmental comparison between three ways to prepare a meal. Ambio 34, 414–421. doi:10.1579/0044-7447-34.4.414
Stancu, V., Haugaard, P., Lähteenmäki, L., 2016. Determinants of consumer food waste behaviour: Two routes to food waste. Appetite 96, 7–17. doi:10.1016/j.appet.2015.08.025
Stein, R., 2017. Meal kits have a packaging problem [WWW Document]. WIRED. URL https://www.wired.com/story/meal-kits-too-much-packaging/ (accessed 10.9.18).
Stolaroff, J.K., Samaras, C., O'Neill, E.R., Lubers, A., Mitchell, A.S., Ceperley, D., 2018. Energy use and life cycle greenhouse gas emissions of drones for commercial package delivery. Nat. Commun. 9, 1–13. doi:10.1038/s41467-017-02411-5
The Nielsen Company, 2018. Meal Kit Mania: Innovation For Foodies [WWW Document]. URL http://www.nielsen.com/us/en/insights/news/2018/meal-kit-mania-innovation-for-foodies.print.html
Turner, D.A., Williams, I.D., Kemp, S., 2015. Greenhouse gas emission factors for recycling of source-segregated waste materials. Resour. Conserv. Recycl. 105, 186–197. doi:10.1016/j.resconrec.2015.10.026
U.S. Department of Energy, 2018. Fuel Economy [WWW Document]. Fuel Econ. Data. URL https://www.fueleconomy.gov/
United Nations Environment Programme, 2016. The Kigali Amendment to the Montreal Protocol: HFC Phase-down, 28th Meeting of the Parties to the Montreal Protocol, 10-14 October, 2016, Kigali, Rwanda.
US Environmental Protection Agency, 2016. Transitioning to Low-GWP Alternatives in Commercial Refrigeration.
USDA Economic Research Service, 2018. FoodAPS National Household Food Acquisition and Purchase Survey [WWW Document]. FoodAPS Natl. Househ. Food Acquis. Purch. Surv. URL https://www.ers.usda.gov/data-products/foodaps-national-household-food-acquisition-and-purchase-survey.aspx

Venkat, K., 2011. The Climate Change and Economic Impacts of Food Waste in the United States. Int. J. Food Syst. Dyn. 2, 431–446.
Vermeulen, S.J., Campbell, B.M., Ingram, J.S.I., 2012. Climate change and food systems. Annu. Rev. Environ. Resour. 37, 195–222. doi:10.1146/annurev-environ-020411-130608
Weber, C.L., Koomey, J.G., Matthews, H.S., 2010. The energy and climate change implications of different music delivery methods. J. Ind. Ecol. 14, 754–769. doi:10.1111/j.1530-9290.2010.00269.x
Wiese, A., Toporowski, W., Zielke, S., 2012. Transport-related CO2effects of online and brick-and-mortar shopping: A comparison and sensitivity analysis of clothing retailing. Transp. Res. Part D Transp. Environ. 17, 473–477. doi:10.1016/j.trd.2012.05.007
Wilson, R., Steingoltz, M., Craigwell-Graham, J., 2017. Why a Shakeout in the Meal Kit Industry Is Likely.
Wygonik, E., Goodchild, A., 2012. Evaluating the Efficacy of Shared-use Vehicles for Reducing Greenhouse Gas Emissions : A U .S. Case Study of Grocery Delivery. J. Transp. Res. Forum 51, 111–126. doi:10.5399/OSU/JTRF.51.2.2926
Yang, X., Strauss, A.K., 2017. An approximate dynamic programming approach to attended home delivery management. Eur. J. Oper. Res. 263, 935–945. doi:10.1016/j.ejor.2017.06.034
Yrjölä, H., 2001. Physical distribution considerations for electronic grocery shopping. Int. J. Phys. Distrib. Logist. Manag. 31, 746–761. doi:10.1108/09600030110411419

Chapter 7

Conclusion

This dissertation assesses the sustainability implications of refrigerated food supply chains from a systems perspective. The presence of refrigeration in a food system prompts changes beyond the directly-observable effects of this technology on energy use, refrigerant release, and food spoilage — also prompting changes in connected supply chain elements and consumer diets. In this way, refrigeration is a transformative technology, with this dissertation drawing on the framework for the environmental assessment of these technologies developed by (Miller and Keoleian, 2015). The scope of this work expands beyond the technically-oriented assessments of refrigeration in supply chains previously published in the literature (James and James, 2013, 2010), modeling the transformative effect of this technology on food systems, building on existing qualitative scholarship (Garnett, 2007).

This dissertation develops a systems-level examination of the sustainability implications of this technology. First, how refrigeration has been studied in the academic literature up to this point is established, presenting a number of key research gaps. A bounding study is then conducted to examine a key environmental question pertaining to the operation and introduction of the cold chain, followed by a more-refined assessment of refrigeration's influence on dietary outcomes. After examining the current state of this technology, potential improvements and innovations are tested. This is first conducted in the context of a typical refrigerated supply chain, studying different interventions and the extent to which they change GHG emissions for supplying food types. Then, changes are assessed in the form of the alternative supply chain structure observed for meal kits, notably, circumventing brick-and-mortar retailing and altering last-mile transportation. A perspective informed by systems thinking is applied in these studies, attempting to capture more than just direct impacts from refrigeration's operation, but also thinking about how this technology influences supply chain context and behavior, and how these elements then influence the technology itself. Additionally, considering the implications of refrigeration on the concept of sustainability requires considerations extending beyond evaluating a single environmental impact metric (e.g. greenhouse gas emissions), also including economic and social elements, such as diet. While this dissertation is far from exhaustive in how refrigeration can be studied in a sustainability context, it does build an understanding of the extent of refrigeration's sustainability connections, and identifies means for reducing its environmental impacts.

Refrigeration connects to sustainability in a number of direct and indirect ways, with a number of important avenues for research remaining. In particular, the role of functional units in determining emissions outcomes (e.g. identifying processes whose sustainability impacts differ when considered on a mass basis, compared with aggregate operation) will be of importance. There are cold chain processes which have small impacts on a per-unit basis, but when viewed in aggregate, produce large and important impacts (for example, the GHG emissions from refrigerated trucking, as seen in Chapter 5). What processes are excluded from study boundaries is also an area in need of consideration. In this dissertation, as with many supply chain and refrigeration studies, the sustainability implications of refrigerant manufacturing and end-of-life disposal (both of refrigerants and the refrigerated equipment itself) are not assessed, but do create notable impacts. Assessing these issues of scope and accounting will be important to creating informed assessments of the cold chain's environmental impact, and presenting potential avenues for improvement.

Additionally, research more-thoroughly parameterizing the dynamics between the introduction and availability of refrigeration technology and food systems changes (such as diet, retailing modes and structures) would be of benefit to both sustainable development efforts, but also to better-understanding the way refrigeration has shaped food systems and lifestyles in the Global North. Finally, there is the general increased quantity and quality of data pertaining to the cold chain's operation and its environmental impacts. Data on cold chain operations and the impacts of refrigeration is somewhat scarce, and increased data availability and granularity would likely increase the quality and quantities of cold chain studies.

This dissertation seeks to characterize the systemic sustainability implications of the cold chain, but has limitations stemming from generalizations, study structure, and data availability. In particular, Chapter 3's the simplified food systems models, aggregated and more-expansive definition of the cold chain to include supply chain developments and infrastructure connected to refrigeration, and assumption of dietary convergence through development are limitations which make this study more-abstract and less directly-applicable to particular regions or technologies. The limited quantity and granularity of refrigerated supply chain data, is a limitation affecting the scope of interventions and equipment types which could be modeled in Chapter 4, as well as in Chapter 6. The data included in the Vietnam Household Living Standards Survey limits the types of regression specifications which could be tested in Chapter 5, and the coding of households differently by survey wave prevented connecting the same households between survey years, limiting the depth of statistical analysis which could be conducted on refrigerator ownership and diet.

Refrigeration is a transformative technology which is connected with numerous dimensions of sustainability. Despite the environmental impacts of cooling beginning to attract broader attention, refrigerated food supply chains are still relatively understudied in the academic literature, and will be of growing importance as the cold chain continues to expand and change. This dissertation provides a groundwork for future investigation into the sustainability implications of refrigerated food supply chains as they expand and experience innovation.

7.1 References

Garnett, T., 2007. Food Refrigeration: What is the Contribution to Greenhouse Gas Emissions and How Might Emissions Be Reduced? (No. April 2007), FCRN Working Paper.

James, S.J., James, C., 2013. Sustainable Cold Chain, in: Tiwari Brijesh K., Norton, T., Holden, N.M. (Eds.), Sustainable Food Processing. John Wiley & Sons, Ltd, pp. 463–496. doi:10.1002/9781118634301.ch19

James, S.J., James, C., 2010. The food cold-chain and climate change. Food Res. Int. 43, 1944–1956. doi:10.1016/j.foodres.2010.02.001

Miller, S.A., Keoleian, G.A., 2015. Framework for analyzing transformative technologies in life cycle assessment. Environ. Sci. Technol. 49, 3067–3075. doi:10.1021/es505217a

Appendix A

Supporting Information for Chapter 3

Appendix A.1

Data:

115 million cubic meters of refrigerated storage in the United States in 2014 (AGRO Merchants Group, 2018)

U.S. 2014 population: 308,745,538 (United States Census Bureau, 2014)

$$\frac{\mathbf{115}\ \boldsymbol{million\ cubic\ meters}}{\mathbf{308,745,538}} = \mathbf{0.37}\ \boldsymbol{cubic\ meters\ per\ capita}$$

Cold storage capacity per capita for:

(Food and Agriculture Organization of the United Nations; International Institute of Refrigeration, 2016)

Ethiopia: 2 litres/capita in urban areas

United Republic of Tanzania: 2 litres/capita in urban areas

Namibia: 5.1 litres/capita in urban areas

South Africa: 15 litres/capita in urban areas

Converting litres to cubic meters (1 litre = 0.001 cubic meters):

Ethiopia: 0.002 cubic meters/capita in urban areas

United Republic of Tanzania: 0.002 cubic meters/capita in urban areas

Namibia: 0.0051 cubic meters/capita in urban areas

South Africa: 0.015 cubic meters/capita in urban areas

Appendix A.2

Sub-Saharan Africa (SSA) is a pre-aggregated category in (Gustavsson et al., 2011)'s report and (Porter et al., 2016)'s analysis but not in the FAOSTAT food balances (Food and Agriculture Organization of the United Nations, n.d.). Therefore, FAOSTAT data was aggregated to the Sub-Saharan African levels from data for the regions Middle, Eastern, Western, and Southern Africa. While there are distinct variations between the culture, diets, and development levels in these areas of the continent, this broad aggregation was chosen as it corresponds with the construction of the category in the other two data sources. Due to aggregation in the data, loss rates and emissions factors applied for North America are values for North America & Oceania.

Appendix A.3

Loss rates for each FSC stage are drawn from a triangular distribution, where the peak value is the region-specific loss rate value provided by (Gustavsson et al., 2011), and the maximum and minimum are the largest and smallest loss rate values recorded for the regions in the same development classifications ("Low-income countries" for SSA, and "Medium/High-income countries" for North America and Europe).

Agricultural emissions factors and cold chain emissions factors are defined as lognormal distributions, due to this distribution having favorable properties (non-negative, non-zero values) at its lower bound. Lognormal distributions have been found to best describe Life Cycle Inventory data in the literature (Qin and Suh, 2017), and in this analysis are bounded at an upper bound of five standard deviations above the median to prevent unrealistic values from being drawn. Mean and standard deviation values for emissions factors are related to their corresponding logarithmized sample values and used to define distributions by food type. Agricultural and cold chain emissions factors reflect emissions burdens added during the upstream processes of agricultural production (FSC stage 1, per definition in "Methods"), and cold chain operation (FSC stages 2 and 3). These emissions are embodied in food which is supplied out of each FSC stage, as well as in the emissions footprint of the losses produced from each process.

Food demand is defined as a normal distribution, truncated at zero, with a mean and standard deviation taken from the 2013 FAOSTAT Balance Sheet data for the countries comprising each region (Food and Agriculture Organization of the United Nations, n.d.). A normal distribution was found to be a better-fit for demand data than a lognormal distribution, through a comparison of AIC and BIC statistics.

Emissions factors for each food type are averages of the emissions factors for foods by type recorded by (Porter et al., 2016), weighted by the corresponding demand for the foods which compose that category for each region in FAOSTAT when data allows (Food and Agriculture Organization of the United Nations, n.d.). There is sufficient data in (Porter et al., 2016) to weigh the averages for cereals, fruits, and meat. For SSA, the relative standard deviation value for fruits is used for vegetables as well, since there is no reported standard deviation for vegetables. The fruit agricultural emissions factors for North America and Europe exclude the sub-category "fruits, other" from (Porter et al., 2016) as it displays a substantial and likely-unrealistic increase between the baseline and developed cases (over 400% for North America and over 1100% for Europe). This category has been noted in an FAO report as containing a wide variety of products which could not be disaggregated (FAO Natural Resources and Management Department, 2013). The cold chain emissions factor for vegetables for Europe contains values from a study specifically examining domestic and imported produce, which includes scenarios of importing vegetables to the UK from Africa via air freight (Canals et al., 2008). Data on the amount of food imported to nations by air is sparse given the infrequency of this transportation mode in the FSC. An examination of food transportation for the US records air import as comprising less than 1% of total t-km for the food system (Weber and Matthews, 2008). Given the focus of this study, the high magnitude of these emissions values, and their infrequency, a mixed lognormal distribution is defined with a 99% probability of a value being drawn from a distribution defined without these parameters, and 1% probability of being imported via air. Due to limited data, the European cereals cold chain emissions factor standard deviation was also applied to the North American values.

Distribution Parameters

SSA = Sub-Saharan Africa

NA = North America

Eur. = Europe

Avg. = Average Value

Min. = Minimum Value

Max. = Maximum Value

S.D. = Standard Deviation Value

Food	SSA Min.	SSA Avg.	SSA Max.	NA Min.	NA Avg.	NA Max.	Eur. Min.	Eur. Avg.	Eur. Max.
Cereals	6	6	6	2	2	2	2	2	2
Roots and Tubers	6	14	14	20	20	20	20	20	20
Fruits	10	10	20	10	20	20	10	20	20
Vegetables	10	10	20	10	20	20	10	20	20
Meat	5.1	15	15	2.9	3.5	3.5	2.9	3.1	3.5
Fish and Seafood	5.7	5.7	8.2	9.4	12	15	9.4	9.4	15
Milk	3.5	6	6	3.5	3.5	3.5	3.5	3.5	3.5

Table A.1: Agricultural Production Loss Rate (R_1) Triangular Distribution Parameters by Region and Food Type (% Loss at each FSC Stage)

Food	SSA Min.	SSA Avg.	SSA Max.	NA Min.	NA Avg.	NA Max.	Eur. Min.	Eur. Avg.	Eur. Max.
Cereals	4	8	8	2	2	10	2	4	10
Roots and Tubers	10	18	19	7	10	10	7	9	10
Fruits	9	9	10	4	4	8	4	5	8
Vegetables	9	9	10	4	4	8	4	5	8
Meat	0.2	0.7	1.1	0.6	1	1	0.6	0.7	1
Fish and Seafood	5	6	6	0.5	0.5	2	0.5	0.5	2
Milk	6	11	11	0.5	0.5	1	0.5	0.5	1

Table A.2 Postharvest Handling and Storage Loss Rate (R_2) Triangular Distribution Parameters by Region and Food Type (% Loss at each FSC Stage)

Food	SSA Min.	SSA Avg.	SSA Max.	NA Min.	NA Avg.	NA Max.	Eur. Min.	Eur. Avg.	Eur. Max.
Cereals	3.5	3.5	9	10.5	10.5	10.5	10.5	10.5	10.5
Roots and Tubers	10	15	15	15	15	15	15	15	15
Fruits	20	25	25	2	2	2	2	2	2
Vegetables	20	25	25	2	2	2	2	2	2
Meat	5	5	5	5	5	5	5	5	5
Fish and Seafood	9	9	9	6	6	6	6	6	6
Milk	0.1	0.1	2	1.2	1.2	1.2	1.2	1.2	1.2

Table A.3: Processing and Packaging Loss Rate (R_3) Triangular Distribution Parameters by Region and Food Type (% Loss at each FSC Stage)

Food	SSA Min.	SSA Avg.	SSA Max.	NA Min.	NA Avg.	NA Max.	Eur. Min.	Eur. Avg.	Eur. Max.
Cereals	2	2	4	2	2	2	2	2	2
Roots and Tubers	3	5	11	7	7	9	7	7	9
Fruits	10	17	17	8	12	12	8	10	12
Vegetables	10	17	17	8	12	12	8	10	12
Meat	5	7	7	4	4	6	4	4	6
Fish and Seafood	4	15	15	9	9	11	9	9	11
Milk	4	10	10	0.5	0.5	0.5	0.5	0.5	0.5

Table A.4: Retail Distribution Loss Rate (R_4) Triangular Distribution Parameters by Region and Food Type (% Loss at each FSC Stage)

Food	SSA Avg.	SSA S.D.	NA Avg.	NA S.D.	Eur. Avg.	Eur. S.D.
Cereals	134	43	96	30	130	22
Roots and Tubers	127	104	48	30	73	32
Fruits	66	63	152	57	102	38
Vegetables	41	24	131	34	122	50
Meat	21	15	99	14	73	17
Fish and Seafood	11	9	30	14	22	17
Milk	39	39	178	82	233	69

Table A.5: Demand (F_5) Normal Distribution Parameters by Region and Food Type (kg food per capita)

Food Type	SSA Avg.	SSA S.D.	NA Avg.	NA S.D.	Eur. Avg.	Eur. S.D.
Cereals	0.97	0.19	0.49	0.09	0.68	0.25
Roots and Tubers	0.52	0.09	0.17	0.08	0.25	0.09
Fruits	0.43	0.00	0.20	0.02	0.33	0.12
Vegetables	1.53	0.01	0.58	0.71	0.84	0.46
Meat	17.16	11.24	10.04	2.26	8.62	2.66
Fish and Seafood	9.19	7.45	4.42	1.17	4.09	0.93
Milk	4.16	2.81	1.13	0.20	1.33	0.26

Table A.6: Demand-Weighted Agricultural Emissions Factor (E_A) Normal Distribution by Region and Food Type Parameters (kg CO_2e/kg food)

Food Type	NA Avg. (w/ SSA Demand)	NA S.D. (w/ SSA Demand)	Eur. Avg. (w/ SSA Demand)	Eur. S.D. (w/ SSA Demand)
Cereals	0.66	0.02	0.89	0.37
Roots and Tubers	0.17	0.08	0.25	0.09
Fruits	0.21	0.04	0.35	0.07
Vegetables	0.58	0.71	0.84	0.46
Meat	12.44	3.85	13.80	4.22
Fish and Seafood	4.42	1.17	4.09	0.93
Milk	1.13	0.20	1.33	0.26

Table A.7: SSA Demand-Weighted Agricultural Emissions Factor (E_A) Normal Distribution by Developed Region and Food Type Parameters (kg CO_2e/kg food)

Cold chain emissions factors for North America & Oceania and Europe were computed from the studies in Porter et al. which contained post-farm gate data. Due to aggregation in the data, these values include emissions from infrastructure connected with the cold chain including transportation and processing. The values are reported and summarized with the references from which observations were obtained below:

Food	NA Avg.	NA S.D.	Eur. Avg.	Eur. S.D.
Cereals	0.03 (Biswas et al., 2008)	0.16	0.17 (Blengini and Busto, 2009; Carlsson-Kanyama, 1998; Defra, 2008; Korsaeth et al., 2012)	0.16
Roots and Tubers	0.2 (Webb et al., 2013)	0.14	0.03 (Carlsson-Kanyama, 1998; Defra, 2008)	0.03
Fruits	0.45 (Gunady et al., 2012; Webb et al., 2013)	0.39	0.04 (Defra, 2008)	0.04
Vegetables	0.55 (Gunady et al., 2012; Plawecki et al., 2014; Webb et al., 2013)	0.50	Distribution 1 (99% probability) = 0.16 (Carlsson-Kanyama,	Distribution 1 (99% probability) = 0.14

			1998; Defra, 2008) Distribution 2 (1% probability) = 4.64 (Canals et al., 2008)	Distribution 2 (1% probability) = 0.05
Meat	1.51 (Hamerschlag and Venkat, 2011; Opio et al., 2013; Thoma et al., 2011; Webb et al., 2013; Wiedemann et al., 2015, 2010)	1.62	0.34 (Carlsson-Kanyama, 1998; Defra, 2008; Opio et al., 2013)	0.40
Fish and Seafood	3.12 (Farmery et al., 2015; Hamerschlag	5.23	2.08 (Schmidt and Thrane, 2007;	0.88

	and Venkat, 2011)		Vázquez-Rowe et al., 2011)	
Milk	0.26 (Gerber et al., 2010; Hamerschlag and Venkat, 2011; Opio et al., 2013; Vergé et al., 2013)	0.22	0.15 (Gerber et al., 2010; Opio et al., 2013; Sheane et al., 2010)	0.09

Table A.8: Cold Chain Emissions Factor (E_C) Normal Distribution Parameters by Region and Food Type Parameters (kg CO_2e/kg food)

Appendix A.4

Sensitivity of each parameter for each food type is examined by taking the percentage difference between per-unit upstream emissions when computed with 95th and 5th percentile values versus the median calculated emissions.

Results of this one-at-a-time sensitivity analysis are displayed in Figure A.1.

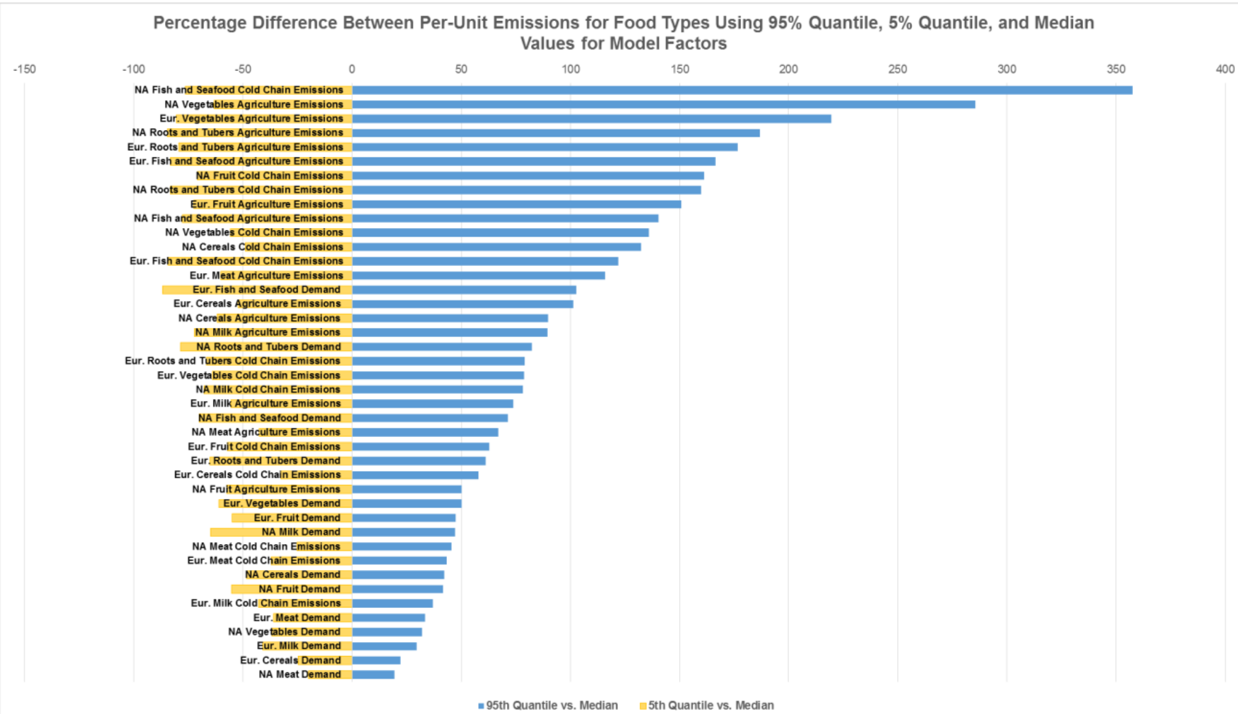

Figure A.0.1: Sensitivity of model parameters to uncertainty. Filtered to include factors whose different between their 95th percentile and/or 5th percentile values and median varies by 10% or greater.

The most significant range observed is between the 95th percentile and median for fish and seafood cold chain emissions in the North American scenario. This difference is due to the wide variety of fish processing practices (e.g. canning, freezing, fresh provision). The other more-sensitive parameters are foods which contain larger standard deviations for their cold chain emissions factors, agricultural emissions factors or demand. The uncertainty for agricultural and cold chain emissions factors may reflect either uncertainty in the data due to the number of available studies, differing study methods, boundaries, and/or there being a variety of production means used for the same food type. Uncertainty in the demand parameters reflects intra-regional variation in diet, where different countries in a region consume notably different amounts of that food product per-capita.

Loss rates do not appear on this chart due to the standard deviations calculated from (Gustavsson et al., 2011) (defined by including the range of loss percentage values by food type for all "Medium/High-income countries" for North America and Europe, and values for "Low-income countries" for SSA) being small. While these values reflect the small ranges included in this report, these values have been subject to critique (Xue et al., 2017), though even in the most recent comprehensive database of food loss and waste rates, there remain very few observations for upstream loss rates across the world (Xue et al., 2017). While greater variance in loss rates than is recorded should be expected, upstream loss rates in from Gustavsson et al.'s data do not exceed 25%, but do approach zero (0.1%) providing a sense of plausible upper and lower bounds for these values.

Appendix A.5

The modeled National Recommended Diet for South Africa from (Behrens et al., 2017) is used to model an alternative developed diet for Sub-Saharan Africa. The quantity of grains was allocated to cereals and the joined category of fruits and vegetables was allocated 50% to fruit and 50% to vegetables. Quantities from this study's "default portions" for when National Recommended Diets do not include quantities of food types were applied for potatoes (allocated to roots and tubers), "Non-specified Meat" to meat, "Lean meat" to meat, and whole grains to cereals.

Per capita consumption of each food type under this diet is scaled up to quantities per 365-day year:

Food	**kg/year**
Cereals	151.48
Roots and Tubers	18.25
Fruit	73
Vegetables	73
Meat	93.08
Fish and Seafood	10.22
Milk	169.178

Table A.9: 365-Day Per Capita Consumption of Each Food Type for Modeled Nationally Recommended Diet for Sub-Saharan Africa

These values and the standard deviation for Sub-Saharan Africa's demand are used to define a truncated normal distribution (with a lower bound of zero).
Per-unit emissions are calculated using this diet projection and changing other parameters from their baseline values to their North American or European values. Due to the limited detail in diet data for this projection, agricultural emissions factors were not re-weighted to reflect the composition of each food category.

The median per-unit emissions calculated are 2.52 kg CO_2e/representative kg for this diet projection with North American food system parameters, and 2.26 kg CO_2e/representative kg for this diet projection with European parameters.

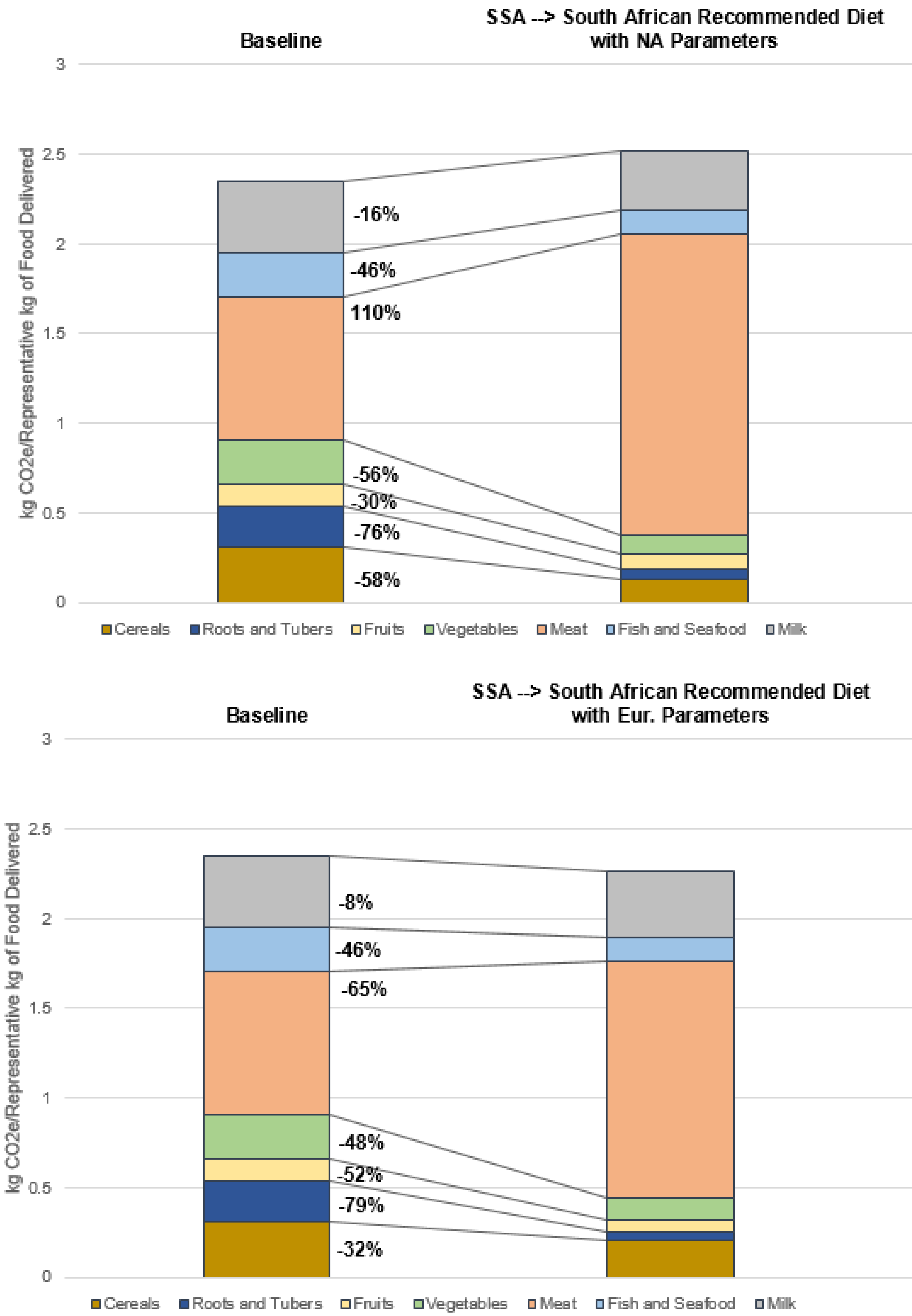

Figure A.0.2: Changes in upstream food supply emissions (kg CO_2e) required to deliver one kg of food, based on a weighted average of each food type within the modeled Nationally Recommended Diet. Percentage differences in emissions are displayed by food type in the graph

Appendix A References

AGRO Merchants Group, 2018. Worldwide Cold Storage Capacity estimated at 552 Mi Cubic Meters.

Behrens, P., Kiefte-de Jong, J.C., Bosker, T., Rodrigues, J.F.D., de Koning, A., Tukker, A., 2017. Evaluating the environmental impacts of dietary recommendations. Proc. Natl. Acad. Sci. 114, 13412–13417. doi:10.1073/pnas.1711889114

Biswas, W.K., Barton, L., Carter, D., 2008. Global warming potential of wheat production in Western Australia: A life cycle assessment. Water Environ. J. 22, 206–216. doi:10.1111/j.1747-6593.2008.00127.x

Blengini, G.A., Busto, M., 2009. The life cycle of rice: LCA of alternative agri-food chain management systems in Vercelli (Italy). J. Environ. Manage. 90, 1512–1522. doi:10.1016/j.jenvman.2008.10.006

Canals, L.M.I., Muñoz, I., Hospido, A., Plassmann, K., McLaren, S., 2008. Life Cycle Assessment (LCA) of domestic vs. imported vegetables. Case studies on broccoli, salad crops and green beans. United Kingdom, Cent. Environ. Strateg. Univ. Surrey 46. doi:1464-8083

Carlsson-Kanyama, A., 1998. Climate change and dietary choices - how can emissions of greenhouse gases from food consumption be reduced? Food Policy 23, 277–293. doi:10.1016/S0306-9192(98)00037-2

Defra, 2008. Greenhouse Gas Impacts of Food Retailing (No. Defra Project code FO405).

FAO Natural Resources and Management Department, 2013. Food Wastage Footprint Impacts on natural resources: Technical Report (No. AR429).

Farmery, A.K., Gardner, C., Green, B.S., Jennings, S., Watson, R.A., 2015. Domestic or imported? An assessment of carbon footprints and sustainability of seafood consumed in Australia. Environ. Sci. Policy 54, 35–43. doi:10.1016/j.envsci.2015.06.007

Food and Agriculture Organization of the United Nations; International Institute of Refrigeration, 2016. Developing the cold chain in the agrifood sector in sub-Saharan Africa.

Food and Agriculture Organization of the United Nations, n.d. FAOSTAT [WWW Document].

Gerber, P., Vellinga, T., Dietze, K., 2010. Greenhouse Gas Emissions from the Dairy Sector: A Life Cycle Assessment. doi:10.1016/S0301-4215(01)00105-7

Gunady, M.G.A., Biswas, W., Solah, V.A., James, A.P., 2012. Evaluating the global warming potential of the fresh produce supply chain for strawberries, romaine/cos lettuces (Lactuca sativa), and button mushrooms (Agaricus bisporus) in Western Australia using life cycle assessment (LCA). J. Clean. Prod. 28, 81–87. doi:10.1016/j.jclepro.2011.12.031

Gustavsson, J., Cederberg, C., Sonesson, U., 2011. Global Food Losses and Food Waste: Extent, Causes, and Prevention.

Hamerschlag, K., Venkat, K., 2011. Meat Eater's Guide to Climate Change + Health: Lifecycle Assessments: Methodology & Results.

Korsaeth, A., Jacobsen, A.Z., Roer, A.G., Henriksen, T.M., Sonesson, U., Bonesmo, H., Skjelvåg, A.O., Strømman, A.H., 2012. Environmental life cycle assessment of cereal and bread production in Norway. Acta Agric. Scand. A Anim. Sci. 62, 242–253. doi:10.1080/09064702.2013.783619

Opio, C., Gerber, P., Mottet, A., Falcucci, A., Tempio, G., MacLeod, M., Vellinga, T., Henderson, B., Steinfeld, H., 2013. Greenhouse gas emissions from ruminant supply

chains–A global life cycle assessment, Food and agriculture organization of the United Nations (FAO), Rome.
Plawecki, R., Pirog, R., Montri, A., Hamm, M.W., 2014. Comparative carbon footprint assessment of winter lettuce production in two climatic zones for Midwestern market. Renew. Agric. Food Syst. 29, 310–318. doi:10.1017/S1742170513000161
Porter, S.D., Reay, D.S., Higgins, P., Bomberg, E., 2016. A half-century of production-phase greenhouse gas emissions from food loss & waste in the global food supply chain. Sci. Total Environ. 571, 721–729. doi:10.1016/j.scitotenv.2016.07.041
Qin, Y., Suh, S., 2017. What distribution function do life cycle inventories follow? Int. J. Life Cycle Assess. 22, 1138–1145. doi:10.1007/s11367-016-1224-4
Schmidt, J., Thrane, M., 2007. LCA case study of pickled herring, in: Tools for Sustainable Development. pp. 81–104.
Sheane, R., Lewis, K., Hall, P., Holmes-Ling, P., Kerr, A., Stewart, K., Webb, D., 2010. Scottish Dairy Supply Chain Greenhouse Gas Emissions, Identifying opportunities to reduce the carbon footprint associated with the Scottish dairy supply chain – Main report.
Thoma, G., Nutter, D., Ulrich, R., Charles, M., Frank, J., East, C., 2011. National Life Cycle Carbon Footprint Study for Production of US Swine.
United States Census Bureau, 2014. Annual Estimates of the Resident Population for Selected Age Groups by Sex for the United States, States, Counties, and Puerto Rico Commonwealth 2014 Population Estimates [WWW Document]. doi:10.5860/CHOICE.43-1925
Vázquez-Rowe, I., Moreira, M.T., Feijoo, G., 2011. Life Cycle Assessment of fresh hake fillets captured by the Galician fleet in the Northern Stock. Fish. Res. 110, 128–135. doi:10.1016/j.fishres.2011.03.022
Vergé, X.P.C., Maxime, D., Dyer, J.A., Desjardins, R.L., Arcand, Y., Vanderzaag, A., 2013. Carbon footprint of Canadian dairy products: Calculations and issues. J. Dairy Sci. 96, 6091–6104. doi:10.3168/jds.2013-6563
Webb, J., Williams, A.G., Hope, E., Evans, D., Moorhouse, E., 2013. Do foods imported into the UK have a greater environmental impact than the same foods produced within the UK? Int. J. Life Cycle Assess. 18, 1325–1343. doi:10.1007/s11367-013-0576-2
Weber, C.L., Matthews, H.S., 2008. Food-Miles and the Relative Climate Impacts of Food Choices in the United States. Environ. Sci. Technol. 42, 3508–3513. doi:10.1021/es702969f
Wiedemann, S., McGahan, E., Grist, S., Grant, T., 2010. Environmental Assessment of Two Pork Supply Chains Using Life Cycle Assessment.
Wiedemann, S., McGahan, E., Murphy, C., Yan, M.J., Henry, B., Thoma, G., Ledgard, S., 2015. Environmental impacts and resource use of Australian beef and lamb exported to the USA determined using life cycle assessment. J. Clean. Prod. 94, 67–75. doi:10.1016/j.jclepro.2015.01.073
Xue, L., Liu, G., Parfitt, J., Liu, X., Van Herpen, E., Stenmarck, A., O'Connor, C., Östergren, K., Cheng, S., 2017. Missing food, missing data? A critical review of global food losses and food waste data. Environ. Sci. Technol. 51, 6618–6633. doi:10.1021/acs.est.7b00401

Appendix B

Supporting Information for Chapter 4

Appendix B.1

Calculating per capita calorie intake and daily energy intake per adult equivalent by food group

Total food acquired by households is converted from expenditure values into grams with a food composition table from the (National Institute of Nutrition, 2013). Kcal per adult equivalent per day in the household is then computed for all observations. Kcal values per food type are displayed in Table B.1 as follows:

Groups	***Food items***	***Calories per 100 grams***	***Groups***	***Food items***	***Calories per 100 grams***
Starchy Staple Foods	Plain rice	344.5	Nuts and seeds	Tofu	95
	Normal plain rice	344		Peanuts, sesame	**570.5**
	Flagrant and specialty plain rice	345	Vegetable	Fresh peas of various kinds	59
	Sticky rice	**347**		Morning glory vegetables	**25**
	Maize	354		Kohlrabi	36
	Cassava	146		Cabbage	29
	Potato of various kinds	**106**		Tomato	20
	Wheat grains, bread, wheat powder	**314**		Other vegetables	-
	Floor noodle, instant rice noodle, porridge	349	Fruit	Orange	37
	Fresh rice noodle, dried rice noodle	143		Banana	**81.5**
	Vermicelli	110		Mango	69
Flesh Foods	Pork	260		Other fruits	-
	Beef	**142.5**	Dairy	Condensed milk, milk powder	**396**
	Buffalo meat	122		Ice cream, yogurth	-
	Chicken meat	199		Fresh milk	61
	Duck and other poultry meat	**275**	Others	Sugars, molasses	**390**
	Other types of meat	-		Confectionery	**412**
	Processed meat	-		Alcohol of various kinds	47
	Fresh shrimp, fish	83		Beer of various kinds	11
	Fresh shrimp	**86**		Bottled, canned, boxed beverages	47

	Fresh fish	80	Coffee powder	353
	Dried and processed shrimps, fish	**361**	Lard, cooking oil	827
	Other aquatic products and seafoods	-	Lard	827
	Fish sauce	60	Cooking oil	900
Eggs	Eggs of chicken, ducks, geese	104	Outdoor meals and drinks	-
Pulses	Beans of various kinds	73	Other foods and drinks	-

Notes: (1) Unit = kcal per 100 g. (2) Source:(National Institute of Nutrition, 2013).

(2) Food categories without calories are approximated from price of one calorie of all food items (Fao and World Bank, 2018)

Table B.1:Conversion table and food groups

Appendix B.2

Vietnam Household Living Standards Survey (VHLSS) Data Summary

All data in Table B.2 is number of observations except those for Per Capita Expenditure, which indicates means and (in parenthesis) standard deviations.

Variable		**2004**	**2006**	**2008**	**2010**	**2012**	**2014**
Observations		8182	8328	8320	7627	7214	8463
Per Capita Expenditure (2014 USD)		746.61 (471.38)	836.97 (535.33)	973.42 (607.45)	1261.12 (730.93)	1295.48 (719.43)	1391.65 (768.64)
Refrigerator Dummy Variable	**1**	1104	1615	2401	2805	3294	5025
	0	7078	6713	5919	4822	3920	3438
Urban Indicator Variable	**1**	1858	2035	2094	2094	1955	2465
	0	6324	6293	6226	5533	5259	5998
Household Size	**≥ 2**	855	1007	1167	1246	1250	1599
	3	1258	1379	1419	1540	1356	1689

	4	2503	2601	2645	2520	2315	2633
	5	1775	1727	1615	1269	1281	1408
	≥ 6	1791	1614	1474	1052	1012	1134
Area of Country	**Red River Delta**	1728	1748	1746	1429	1350	1800
	Midlands Northern Mountains	1609	1629	1575	1141	1145	1535
	Northern Central Coast	1649	1688	1702	1856	1666	1818
	Central Highlands	518	518	535	584	546	548
	South East	972	1017	1044	954	864	993
	Mekong River Delta	1706	1728	1718	1663	1643	1769
Education Level	**Below Primary**	4504	4433	4325	4022	3785	4187
	Secondary/ High School	3551	3545	3649	3224	3094	3766
	University	327	350	346	381	335	510
Ethnic Minority Indicator	**0**	1238	1311	1266	1152	1160	1457
	1	6944	7017	7054	6475	6054	7006

Clean Water for Cooking Indicator	**0**	2518	3287	2995	2826	2509	2625
	1	5664	5041	5325	4801	4705	5838

Table B.2: VHLSS Summary Statistics (2004-2014)

Appendix B.3

Full Regression Model Outputs

	Estimate	Std. Error	t value	Pr(> | t|)
***μ* coefficients**				
(Intercept)	7.70	0.01	1035.61	0.00
Year = 2006	-0.02	0.01	-3.61	0.00
Year = 2008	-0.16	0.01	-35.49	0.00
Year = 2010	-0.06	0.01	-11.99	0.00
Year = 2012	-0.09	0.01	-17.20	0.00
Year = 2014	-0.10	0.01	-20.79	0.00
Refrigerator Ownership Indicator	-0.06	0.00	-17.97	0.00
Per Capita Expenditure (2014 USD)	0.00	0.00	-9.18	0.00
Urban Indicator	-0.10	0.00	-30.01	0.00
Household Size = 3	0.15	0.01	32.61	0.00
Household Size = 4	0.18	0.00	42.39	0.00
Household Size = 5	0.20	0.01	40.94	0.00
Household Size = 6	0.19	0.01	37.45	0.00
Area = Midlands and Northern Mountainous Areas	0.08	0.01	16.42	0.00
Area = Northern and Coastal Central Region	-0.02	0.00	-4.92	0.00
Area = Central Highlands	0.03	0.01	5.20	0.00

Area = Southeastern Area	-0.15	0.01	-30.55	0.00
Area = Mekong Delta	-0.02	0.00	-4.95	0.00
Education Level = 2	0.00	0.00	-0.70	0.48
Education Level = 2	-0.09	0.01	-12.63	0.00
Ethnic Minority Indicator	-0.08	0.00	-16.76	0.00
Clean Water for Cooking Indicator	-0.03	0.00	-10.64	0.00
ν coefficients				
(Intercept)	-7.05	1.04	-6.80	0.00
Year = 2006	0.28	0.92	0.31	0.76
Year = 2008	0.16	0.92	0.18	0.86
Year = 2010	1.36	0.77	1.76	0.08
Year = 2012	1.16	0.80	1.46	0.15
Year = 2014	1.08	0.79	1.37	0.17
Refrigerator Ownership Indicator	-1.86	0.43	-4.29	0.00
Per Capita Expenditure (2014 USD)	0.00	0.00	3.57	0.00
Urban Indicator	0.83	0.35	2.39	0.02
Household Size = 3	-2.34	0.61	-3.84	0.00
Household Size = 4	-2.06	0.50	-4.15	0.00
Household Size = 5	-12.84	86.37	-0.15	0.88
Household Size = 6	-2.67	1.03	-2.58	0.01
Area = Midlands and Northern Mountainous Areas	-11.69	84.00	-0.14	0.89

Area = Northern and Coastal Central Region	-0.41	0.59	-0.69	0.49
Area = Central Highlands	-0.87	1.11	-0.79	0.43
Area = Southeastern Area	1.29	0.44	2.91	0.00
Area = Mekong Delta	-0.06	0.54	-0.10	0.92
Education Level = 2	0.22	0.35	0.62	0.54
Education Level = 2	0.63	0.55	1.14	0.25
Ethnic Minority Indicator	-0.46	0.62	-0.74	0.46
Clean Water for Cooking Indicator	0.03	0.44	0.07	0.94

Table B.3: Starchy Staple Foods GAMLSS ZAGA Regression Output

	Estimate	Std. Error	t value	Pr(> | t|)
***μ* coefficients**				
(Intercept)	4.03	0.02	166.71	0.00
Year = 2006	-0.01	0.02	-0.77	0.44
Year = 2008	-0.23	0.02	-15.23	0.00
Year = 2010	0.11	0.02	6.72	0.00
Year = 2012	-0.11	0.02	-6.99	0.00
Year = 2014	-0.09	0.02	-5.40	0.00
Refrigerator Ownership Indicator	-0.08	0.01	-6.94	0.00
Per Capita Expenditure (2014 USD)	0.00	0.00	113.89	0.00
Urban Indicator	-0.07	0.01	-6.45	0.00
Household Size = 3	-0.05	0.02	-3.33	0.00
Household Size = 4	-0.13	0.01	-9.03	0.00
Household Size = 5	-0.15	0.02	-9.24	0.00
Household Size = 6	-0.22	0.02	-13.18	0.00
Area = Midlands and Northern Mountainous Areas	0.19	0.02	12.37	0.00
Area = Northern and Coastal Central Region	-0.43	0.01	-32.45	0.00
Area = Central Highlands	-0.53	0.02	-26.72	0.00
Area = Southeastern Area	-0.72	0.02	-44.65	0.00
Area = Mekong Delta	-1.04	0.02	-69.74	0.00

Education Level = 2	0.08	0.01	7.62	0.00
Education Level = 2	-0.03	0.02	-1.27	0.21
Ethnic Minority Indicator	0.14	0.02	9.51	0.00
Clean Water for Cooking Indicator	-0.08	0.01	-8.58	0.00
***ν* coefficients**				
(Intercept)	-2.18	0.10	-22.40	0.00
Year = 2006	0.09	0.05	1.81	0.07
Year = 2008	-0.11	0.05	-2.13	0.03
Year = 2010	0.70	0.05	13.97	0.00
Year = 2012	0.89	0.05	17.64	0.00
Year = 2014	0.80	0.05	15.75	0.00
Refrigerator Ownership Indicator	-0.22	0.04	-5.26	0.00
Per Capita Expenditure (2014 USD)	0.00	0.00	-8.71	0.00
Urban Indicator	-0.30	0.04	-7.86	0.00
Household Size = 3	-0.16	0.05	-3.31	0.00
Household Size = 4	-0.33	0.04	-7.57	0.00
Household Size = 5	-0.43	0.05	-8.79	0.00
Household Size = 6	-0.50	0.05	-9.70	0.00
Area = Midlands and Northern Mountainous Areas	0.12	0.08	1.41	0.16
Area = Northern and Coastal Central Region	1.79	0.07	25.17	0.00
Area = Central Highlands	1.73	0.08	20.87	0.00

Area = Southeastern Area	1.85	0.08	24.39	0.00
Area = Mekong Delta	2.85	0.07	40.74	0.00
Education Level = 2	-0.12	0.03	-3.66	0.00
Education Level = 2	0.00	0.09	-0.02	0.99
Ethnic Minority Indicator	-1.09	0.04	-24.86	0.00
Clean Water for Cooking Indicator	0.07	0.03	2.40	0.02

Table B.4 Nuts and Seeds GAMLSS ZAGA Regression Output

	Estimate	Std. Error	t value	Pr(> | t|)
***μ* coefficients**				
(Intercept)	1.68	0.04	45.38	0.00
Year = 2006	0.03	0.02	1.40	0.16
Year = 2008	-0.20	0.02	-11.29	0.00
Year = 2010	0.87	0.03	34.96	0.00
Year = 2012	0.77	0.03	26.44	0.00
Year = 2014	0.86	0.03	30.63	0.00
Refrigerator Ownership Indicator	-0.09	0.02	-5.21	0.00
Per Capita Expenditure (2014 USD)	0.00	0.00	61.96	0.00
Urban Indicator	0.00	0.02	0.05	0.96
Household Size = 3	-0.09	0.03	-3.54	0.00
Household Size = 4	-0.20	0.02	-8.74	0.00
Household Size = 5	-0.26	0.02	-10.61	0.00
Household Size = 6	-0.36	0.03	-14.39	0.00
Area = Midlands and Northern Mountainous Areas	0.23	0.02	9.63	0.00
Area = Northern and Coastal Central Region	0.14	0.02	7.53	0.00
Area = Central Highlands	0.29	0.03	10.09	0.00
Area = Southeastern Area	0.29	0.02	12.22	0.00
Area = Mekong Delta	0.34	0.02	16.02	0.00

Education Level = 2	0.03	0.01	1.75	0.08
Education Level = 2	-0.07	0.03	-2.26	0.02
Ethnic Minority Indicator	-0.46	0.03	-17.76	0.00
Clean Water for Cooking Indicator	-0.04	0.01	-3.11	0.00
***ν* coefficients**				
(Intercept)	0.71	0.06	11.79	0.00
Year = 2006	0.26	0.03	7.94	0.00
Year = 2008	0.12	0.03	3.78	0.00
Year = 2010	1.73	0.04	44.80	0.00
Year = 2012	2.16	0.04	49.85	0.00
Year = 2014	2.26	0.04	52.46	0.00
Refrigerator Ownership Indicator	-0.12	0.03	-4.01	0.00
Per Capita Expenditure (2014 USD)	0.00	0.00	-16.07	0.00
Urban Indicator	0.07	0.03	2.52	0.01
Household Size = 3	-0.29	0.04	-7.53	0.00
Household Size = 4	-0.42	0.04	-11.75	0.00
Household Size = 5	-0.56	0.04	-14.42	0.00
Household Size = 6	-0.64	0.04	-15.84	0.00
Area = Midlands and Northern Mountainous Areas	0.54	0.04	14.18	0.00
Area = Northern and Coastal Central Region	0.33	0.03	10.27	0.00
Area = Central Highlands	0.49	0.05	10.06	0.00

Area = Southeastern Area	0.78	0.04	19.53	0.00
Area = Mekong Delta	0.77	0.04	22.29	0.00
Education Level = 2	-0.03	0.02	-1.02	0.31
Education Level = 2	-0.10	0.05	-1.89	0.06
Ethnic Minority Indicator	-0.64	0.04	-16.77	0.00
Clean Water for Cooking Indicator	-0.10	0.02	-4.26	0.00

Table B.5: Pulses GAMLSS ZAGA Regression Output

	Estimate	Std. Error	t value	Pr(> | t|)
***μ* coefficients**				
(Intercept)	2.24	0.02	120.28	0.00
Year = 2006	0.01	0.01	0.70	0.49
Year = 2008	-0.04	0.01	-3.66	0.00
Year = 2010	0.72	0.01	59.41	0.00
Year = 2012	0.38	0.01	30.27	0.00
Year = 2014	0.43	0.01	35.23	0.00
Refrigerator Ownership Indicator	0.01	0.01	1.60	0.11
Per Capita Expenditure (2014 USD)	0.00	0.00	127.57	0.00
Urban Indicator	0.14	0.01	16.35	0.00
Household Size = 3	-0.10	0.01	-8.57	0.00
Household Size = 4	-0.16	0.01	-14.40	0.00
Household Size = 5	-0.26	0.01	-21.45	0.00
Household Size = 6	-0.37	0.01	-29.19	0.00
Area = Midlands and Northern Mountainous Areas	0.00	0.01	-0.12	0.91
Area = Northern and Coastal Central Region	-0.30	0.01	-28.58	0.00
Area = Central Highlands	-0.15	0.02	-9.88	0.00
Area = Southeastern Area	-0.02	0.01	-1.63	0.10
Area = Mekong Delta	-0.22	0.01	-20.02	0.00

Education Level = 2	0.09	0.01	11.69	0.00
Education Level = 2	0.07	0.02	3.88	0.00
Ethnic Minority Indicator	0.11	0.01	10.07	0.00
Clean Water for Cooking Indicator	-0.03	0.01	-4.12	0.00
***ν* coefficients**				
(Intercept)	-0.75	0.08	-9.74	0.00
Year = 2006	0.23	0.05	4.61	0.00
Year = 2008	-0.17	0.05	-3.15	0.00
Year = 2010	0.65	0.05	12.65	0.00
Year = 2012	0.65	0.05	12.30	0.00
Year = 2014	0.70	0.05	13.31	0.00
Refrigerator Ownership Indicator	-0.19	0.05	-4.00	0.00
Per Capita Expenditure (2014 USD)	0.00	0.00	-13.10	0.00
Urban Indicator	-0.29	0.04	-6.68	0.00
Household Size = 3	-0.33	0.05	-6.94	0.00
Household Size = 4	-0.51	0.04	-11.76	0.00
Household Size = 5	-0.58	0.05	-11.77	0.00
Household Size = 6	-0.67	0.05	-12.79	0.00
Area = Midlands and Northern Mountainous Areas	0.24	0.05	4.74	0.00
Area = Northern and Coastal Central Region	0.08	0.05	1.68	0.09
Area = Central Highlands	0.00	0.07	-0.05	0.96

Area = Southeastern Area	-0.29	0.07	-4.38	0.00
Area = Mekong Delta	0.33	0.05	7.06	0.00
Education Level = 2	-0.07	0.03	-2.03	0.04
Education Level = 2	-0.40	0.12	-3.40	0.00
Ethnic Minority Indicator	-0.51	0.04	-12.06	0.00
Clean Water for Cooking Indicator	-0.11	0.03	-3.68	0.00

Table B.6: Eggs GAMLSS ZAGA Regression Output

	Estimate	Std. Error	t value	Pr(> | t|)
μ coefficients				
(Intercept)	5.50	0.01	503.56	0.00
Year = 2006	0.05	0.01	8.05	0.00
Year = 2008	-0.16	0.01	-22.94	0.00
Year = 2010	0.08	0.01	11.09	0.00
Year = 2012	0.07	0.01	10.25	0.00
Year = 2014	0.11	0.01	15.47	0.00
Refrigerator Ownership Indicator	0.03	0.01	6.03	0.00
Per Capita Expenditure (2014 USD)	0.00	0.00	79.77	0.00
Urban Indicator	0.05	0.01	10.52	0.00
Household Size = 3	0.06	0.01	8.65	0.00
Household Size = 4	0.06	0.01	9.94	0.00
Household Size = 5	0.02	0.01	2.30	0.02
Household Size = 6	-0.06	0.01	-8.72	0.00
Area = Midlands and Northern Mountainous Areas	0.03	0.01	4.03	0.00
Area = Northern and Coastal Central Region	-0.12	0.01	-18.68	0.00
Area = Central Highlands	-0.02	0.01	-2.29	0.02
Area = Southeastern Area	-0.05	0.01	-6.41	0.00
Area = Mekong Delta	0.06	0.01	9.09	0.00

Education Level = 2	0.04	0.00	8.24	0.00
Education Level = 2	-0.03	0.01	-2.92	0.00
Ethnic Minority Indicator	0.08	0.01	12.77	0.00
Clean Water for Cooking Indicator	-0.02	0.00	-5.54	0.00
***ν* coefficients**				
(Intercept)	-6.68	0.86	-7.77	0.00
Year = 2006	-0.07	0.64	-0.12	0.91
Year = 2008	-0.41	0.68	-0.60	0.55
Year = 2010	0.80	0.52	1.54	0.12
Year = 2012	-0.40	0.63	-0.63	0.53
Year = 2014	-0.20	0.60	-0.34	0.74
Refrigerator Ownership Indicator	-2.16	0.47	-4.63	0.00
Per Capita Expenditure (2014 USD)	0.00	0.00	4.15	0.00
Urban Indicator	0.99	0.32	3.14	0.00
Household Size = 3	-2.55	0.61	-4.22	0.00
Household Size = 4	-2.28	0.49	-4.67	0.00
Household Size = 5	-13.13	86.40	-0.15	0.88
Household Size = 6	-3.05	1.03	-2.97	0.00
Area = Midlands and Northern Mountainous Areas	-1.49	1.11	-1.34	0.18
Area = Northern and Coastal Central Region	0.14	0.59	0.23	0.82
Area = Central Highlands	-0.39	1.11	-0.35	0.73

Area = Southeastern Area	1.82	0.48	3.84	0.00
Area = Mekong Delta	0.20	0.58	0.34	0.73
Education Level = 2	0.14	0.32	0.44	0.66
Education Level = 2	-0.56	0.69	-0.82	0.42
Ethnic Minority Indicator	-0.52	0.55	-0.93	0.35
Clean Water for Cooking Indicator	0.31	0.41	0.78	0.44

Table B.7: Flesh Foods GAMLSS ZAGA Regression Output

	Estimate	Std. Error	t value	Pr(> | t|)
***μ* coefficients**				
(Intercept)	4.45	0.02	289.50	0.00
Year = 2006	-0.04	0.01	-3.67	0.00
Year = 2008	-0.11	0.01	-10.98	0.00
Year = 2010	0.19	0.01	18.74	0.00
Year = 2012	0.10	0.01	9.95	0.00
Year = 2014	0.08	0.01	7.40	0.00
Refrigerator Ownership Indicator	-0.01	0.01	-1.15	0.25
Per Capita Expenditure (2014 USD)	0.00	0.00	168.13	0.00
Urban Indicator	0.08	0.01	11.04	0.00
Household Size = 3	-0.13	0.01	-13.50	0.00
Household Size = 4	-0.23	0.01	-24.93	0.00
Household Size = 5	-0.30	0.01	-30.22	0.00
Household Size = 6	-0.43	0.01	-41.68	0.00
Area = Midlands and Northern Mountainous Areas	0.09	0.01	8.84	0.00
Area = Northern and Coastal Central Region	-0.13	0.01	-14.70	0.00
Area = Central Highlands	-0.01	0.01	-1.08	0.28
Area = Southeastern Area	-0.08	0.01	-7.44	0.00
Area = Mekong Delta	0.04	0.01	4.02	0.00

Education Level = 2	0.02	0.01	3.57	0.00
Education Level = 2	0.01	0.02	0.34	0.74
Ethnic Minority Indicator	0.07	0.01	6.99	0.00
Clean Water for Cooking Indicator	0.01	0.01	1.56	0.12
ν coefficients				
(Intercept)	-5.27	0.46	-11.46	0.00
Year = 2006	-0.22	0.34	-0.64	0.52
Year = 2008	-0.29	0.36	-0.82	0.41
Year = 2010	0.67	0.30	2.23	0.03
Year = 2012	0.70	0.30	2.30	0.02
Year = 2014	1.56	0.27	5.70	0.00
Refrigerator Ownership Indicator	-0.89	0.23	-3.81	0.00
Per Capita Expenditure (2014 USD)	0.00	0.00	-0.91	0.37
Urban Indicator	-0.02	0.22	-0.07	0.95
Household Size = 3	-0.63	0.24	-2.65	0.01
Household Size = 4	-0.70	0.22	-3.26	0.00
Household Size = 5	-0.69	0.25	-2.80	0.01
Household Size = 6	-0.83	0.26	-3.25	0.00
Area = Midlands and Northern Mountainous Areas	1.34	0.34	3.90	0.00
Area = Northern and Coastal Central Region	0.21	0.37	0.57	0.57
Area = Central Highlands	1.17	0.38	3.08	0.00

Area = Southeastern Area	1.50	0.35	4.26	0.00
Area = Mekong Delta	0.29	0.37	0.78	0.43
Education Level = 2	-0.07	0.17	-0.41	0.68
Education Level = 2	-0.30	0.57	-0.52	0.61
Ethnic Minority Indicator	-0.82	0.20	-4.16	0.00
Clean Water for Cooking Indicator	-0.35	0.17	-2.00	0.05

Table B.8: Vegetables GAMLSS ZAGA Regression Output

	Estimate	Std. Error	t value	Pr(> | t|)
***μ* coefficients**				
(Intercept)	3.37	0.03	118.86	0.00
Year = 2006	0.02	0.02	0.91	0.36
Year = 2008	0.26	0.02	15.88	0.00
Year = 2010	1.25	0.02	67.68	0.00
Year = 2012	1.14	0.02	59.05	0.00
Year = 2014	1.17	0.02	62.63	0.00
Refrigerator Ownership Indicator	-0.01	0.01	-0.95	0.34
Per Capita Expenditure (2014 USD)	0.00	0.00	5.00	0.00
Urban Indicator	0.07	0.01	5.92	0.00
Household Size = 3	-0.37	0.02	-19.80	0.00
Household Size = 4	-0.57	0.02	-33.76	0.00
Household Size = 5	-0.77	0.02	-41.96	0.00
Household Size = 6	-1.02	0.02	-53.37	0.00
Area = Midlands and Northern Mountainous Areas	0.37	0.02	19.68	0.00
Area = Northern and Coastal Central Region	0.05	0.02	3.00	0.00
Area = Central Highlands	0.46	0.02	19.52	0.00
Area = Southeastern Area	0.41	0.02	22.11	0.00
Area = Mekong Delta	0.33	0.02	20.48	0.00

Education Level = 2	-0.03	0.01	-2.48	0.01
Education Level = 2	-0.03	0.03	-1.11	0.27
Ethnic Minority Indicator	0.08	0.02	4.38	0.00
Clean Water for Cooking Indicator	0.03	0.01	2.90	0.00
***ν* coefficients**				
(Intercept)	-0.02	0.07	-0.25	0.81
Year = 2006	0.09	0.04	2.05	0.04
Year = 2008	-0.18	0.05	-3.73	0.00
Year = 2010	1.33	0.04	30.85	0.00
Year = 2012	1.58	0.04	36.24	0.00
Year = 2014	1.40	0.04	31.79	0.00
Refrigerator Ownership Indicator	-0.29	0.04	-8.20	0.00
Per Capita Expenditure (2014 USD)	0.00	0.00	-21.21	0.00
Urban Indicator	-0.32	0.03	-9.28	0.00
Household Size = 3	-0.33	0.04	-8.41	0.00
Household Size = 4	-0.64	0.04	-17.61	0.00
Household Size = 5	-0.70	0.04	-17.05	0.00
Household Size = 6	-0.81	0.04	-18.56	0.00
Area = Midlands and Northern Mountainous Areas	0.41	0.04	9.78	0.00
Area = Northern and Coastal Central Region	0.20	0.04	5.43	0.00
Area = Central Highlands	-0.04	0.06	-0.80	0.43

Area = Southeastern Area	-0.20	0.05	-4.05	0.00
Area = Mekong Delta	-0.52	0.04	-12.64	0.00
Education Level = 2	-0.02	0.03	-0.68	0.50
Education Level = 2	-0.16	0.08	-2.00	0.05
Ethnic Minority Indicator	-0.56	0.04	-15.61	0.00
Clean Water for Cooking Indicator	-0.19	0.03	-7.18	0.00

Table B.9: Fruit GAMLSS ZAGA Regression Output

	Estimate	Std. Error	t value	Pr(> | t|)
***μ* coefficients**				
(Intercept)	2.90	0.04	80.78	0.00
Year = 2006	0.08	0.02	3.68	0.00
Year = 2008	-0.02	0.02	-0.76	0.45
Year = 2010	0.61	0.02	27.51	0.00
Year = 2012	0.50	0.02	22.48	0.00
Year = 2014	0.53	0.02	24.81	0.00
Refrigerator Ownership Indicator	0.15	0.01	10.53	0.00
Per Capita Expenditure (2014 USD)	0.00	0.00	132.58	0.00
Urban Indicator	0.18	0.01	12.79	0.00
Household Size = 3	-0.14	0.02	-5.83	0.00
Household Size = 4	-0.19	0.02	-8.74	0.00
Household Size = 5	-0.21	0.02	-9.01	0.00
Household Size = 6	-0.32	0.02	-13.34	0.00
Area = Midlands and Northern Mountainous Areas	-0.03	0.02	-1.52	0.13
Area = Northern and Coastal Central Region	0.21	0.02	11.32	0.00
Area = Central Highlands	0.23	0.03	8.66	0.00
Area = Southeastern Area	0.47	0.02	22.34	0.00
Area = Mekong Delta	0.36	0.02	18.49	0.00

Education Level = 2	0.03	0.01	2.21	0.03
Education Level = 2	0.17	0.03	6.37	0.00
Ethnic Minority Indicator	0.21	0.02	9.29	0.00
Clean Water for Cooking Indicator	-0.03	0.01	-1.88	0.06
***ν* coefficients**				
(Intercept)	2.38	0.06	42.32	0.00
Year = 2006	-0.04	0.03	-1.32	0.19
Year = 2008	-0.35	0.03	-10.25	0.00
Year = 2010	0.39	0.04	10.90	0.00
Year = 2012	0.29	0.04	7.89	0.00
Year = 2014	0.16	0.04	4.29	0.00
Refrigerator Ownership Indicator	-0.50	0.03	-18.53	0.00
Per Capita Expenditure (2014 USD)	0.00	0.00	-21.71	0.00
Urban Indicator	-0.34	0.03	-13.14	0.00
Household Size = 3	-0.59	0.04	-16.62	0.00
Household Size = 4	-1.03	0.03	-31.90	0.00
Household Size = 5	-1.22	0.04	-34.09	0.00
Household Size = 6	-1.40	0.04	-37.44	0.00
Area = Midlands and Northern Mountainous Areas	-0.07	0.04	-1.90	0.06
Area = Northern and Coastal Central Region	-0.34	0.03	-10.81	0.00
Area = Central Highlands	-0.51	0.05	-11.06	0.00

Area = Southeastern Area	-0.46	0.04	-11.99	0.00
Area = Mekong Delta	-0.32	0.03	-10.01	0.00
Education Level = 2	-0.09	0.02	-3.83	0.00
Education Level = 2	-0.59	0.06	-9.51	0.00
Ethnic Minority Indicator	-0.63	0.03	-19.10	0.00
Clean Water for Cooking Indicator	-0.08	0.02	-3.55	0.00

Table B.10: Dairy GAMLSS ZAGA Regression Output

Appendix B.4

Average Consumption of Food Types by Year

All values in the following table are in kcal/day/adult-equivalent.

Average Per-Capita kcal Consumption	2004	2006	2008	2010	2012	2014
Starchy Staple Foods	2261.8	2205.03	1875.8	2042.04	1964.2	1903
Nuts and Seeds	42.09	42.52	36.38	46.19	36.76	40.8
Pulses	2.13	2.02	1.78	2.19	1.46	1.57
Flesh Foods	349	381.11	323.13	443.81	449.95	482.2
Eggs	8.61	8.81	9.18	18.82	13.37	14.73
Vegetables	87.37	87.33	84.20	120.8	112.14	112.3
Fruit	19.70	20.24	27.67	59.86	50.32	56.3
Dairy	17.91	21.10	23.14	38.17	37.24	42.6
Other	506.3	507.8	439.28	850.43	939.7	1003.5
Total Calories	3294.9	3275.9	2820.5	3622.3	3605.1	3657

Table B.11: Average kcal/day/adult equivalent in VHLSS Data (2004-2014)

Appendix C

Supporting Information for Chapter 5

Model parameter details are described in as follows in Table C.1

Model Element	Distribution Details	Source	Notes
Retail Loss Rate	Trianglular Distribution. Modes listed for each food type Fresh Broccoli:10% Frozen Broccoli: 6% Fresh Chicken: 4% Frozen Chicken: 4% Apples: 12%	(Buzby et al., 2014)	Mode is loss rate for corresponding food categories. Distribution bounded by maximum and minimum percentage loss rates recorded in study

	Fresh Fish: 8% Frozen Fish: 8% Milk: 12%		
Processing Loss Rate	Trianglular Distribution. Modes listed for each food type Fresh Broccoli: 2% Frozen Broccoli: 2% Fresh Chicken: 5% Frozen Chicken: 5% Apples: 2% Fresh Fish: 6% Frozen Fish: 6%	(Gustavsson et al., 2011)	Mode is processing and packaging losses for corresponding food categories in North America and Oceania. Distribution bounded by the largest and smallest recorded processing loss rates for foods in this region.

	Milk: 1.2%		
Electricity Emissions Factor	Trianglular Distribution. Min. = 0.017 kg CO2e/kWh, Mode = 0.522 kg CO2e/kWh, Max. = 1.014 kg CO2e/kWh	(International Energy Agency, 2012)	CO_2 emissions per kWh from electricity generation listed. Mode is for the United Sates, bounded by the highest and lowest OCED values listed.
Food & Packaging Production	Fresh & Frozen Broccoli Food Production: 0.405 kg CO_2e/kg Packaging (LDPE): 2.79 kg CO_2e/kg Fresh & Frozen Chicken Food Production: 2.52 kg CO_2e/kg Packaging (LDPE): 2.79 kg CO_2e/kg	Broccoli, Chicken, Apples, Milk, and LDPE from (ecoinvent 3.4, n.d.) database. Fish from (Nielsen PH, Nielsen AM, Weidema BP, Dalgaard R, 2003), Tetra-pack from (Hospido et al., 2003).	

	Apples Food Production: 0.456 kg CO_2e/kg (assuming no packaging) Fish Food Production (assuming cod): 1.18 kg CO_2e/kg Packaging (LDPE): 2.79 kg CO_2e/kg Milk Production: 1.28 kg CO_2e/kg Packaging (Tetra- pack): 0.15 kg CO_2e total		

Processing Energy	Triangular Distribution. Fresh Broccoli Processing Electricity (mode of the U.K. value, bounded by two additional estimates provided for Spanish production): Min. = 0.0355 kWh/kg, Mode = 0.0363 kWh/kg, Max. = 0.0461 kWh/kg Frozen Broccoli Processing Modes by Energy Source (bounded +/- 25%):	Broccoli: (Canals et al., 2008) Chicken: (González-García et al., 2014) Apples: (Blanke and Burdick, 2005) Fish: (Svanes et al., 2011) Milk: (Hospido et al., 2003)	

	Electricity: 0.1326 kWh/kg Natural Gas: 0.0327 kWh/kg Diesel: 0.0002 litres/kg Fresh and Frozen Chicken Processing Modes by Energy Source (bounded +/- 25%): Electricity: 0.08 kWh/kg Fuel Oil (Diesel): 0.02 litres/kg Apples Initial Cooling Electricity Mode (bounded +/- 25%): 0.02 kWh/kg		

	Fresh & Frozen Fish Processing Electricity (bounded +/- 25%): 0.36 kWh/kg Milk Processing Electricity (bounds provided by study): Min. = 0.034 kWh/kg, Mode = 0.045 kWh/kg, Max. = 0.056 kWh/kg		
Transportation to Regional Distribution Center	Triangular Distribution. Min. = 100 km, Mode = 135 km, Max. = 170 km	Expert Judgment	(Petrovskis, personal communication, June 11, 2019). Based on researcher conversation with industry contact

Regional Distribution Center Electricity	Triangular Distribution (bounded +/- 25%): Fresh Broccoli: 0.00417MJ/kg Frozen Broccoli: 0.02528MJ/kg Chicken: 0.000018 kWh/kg-hr (stored for 12 hrs) Apples: 0.225 kWh/kg Fish: 0.245 kWh/kg Milk: 0 kWh/kg (zero hours of RDC storage)	Broccoli: (Canals et al., 2008) Chicken: (Defra, 2008) Apples: (Blanke and Burdick, 2005) Fish: (Svanes et al., 2011) Milk: (Defra, 2008)	

Transportation to Grocery Retail Distance	Trianglular Distribution. Min. = 10 km, Mode = 60 km, Max. = 110 km	Expert Judgment	
Truck Transportation Emissions (Excluding Refrigerant Leakage)	Triangular Distribution. Fresh (chilled): Min. = 0.059 kg CO_2e/pallet-km, Mode = 0.0802 kg CO_2e/pallet-km, Max. = 0.109 kg CO_2e/pallet-km) Frozen: Min. = 0.061 kg CO_2e/pallet-km, Mode = 0.085 kg CO_2e/pallet-km,	(Defra, 2008)	Modes are average of values for chilled or frozen food distribution (respectively), bounded by the extreme reported values

	Max. = 0.115 kg CO_2e/pallet-km)		
Food per Pallet	Fresh & Frozen Broccoli: 540 kg/pallet Fresh & Frozen Chicken: 840 kg/pallet Apples: 142.88 kg/pallet Fresh & Frozen Fish: 370 kg/pallet Milk: 750 kg/pallet	Broccoli: (Homifreez, 2017) Chicken:(Eurogourmet, n.d.) Apples: (Stemilt Growers, 2010) Fish: (Ranheim Paper & Board, n.d.) Milk: (Defra, 2008)	
Walk-In Refrigerated Storage	Frozen Broccoli, Chicken, and Fish Electricity: 0.00056	(Defra, 2008)	No hours of walk-in storage reported for fresh produce

	kWh/kg-hr Direct Emissions: 0.00017 kg CO_2e/kg-hr (for 24 hrs). Fresh Chicken Electricity: 0.00026 kWh/kg-hr Direct Emissions: 0.00015 kg CO_2e/kg-hr (for 24 hrs). Milk Electricity: 0.00015 kWh/kg-hr Direct Emissions: 0.00009 kg CO_2e/kg-hr (for 12 hrs).		

Retailing in Display Cabinet	Triangular Distribution (bounded +/- 25%): Fresh Broccoli and Apples Electricity: 0.021 kWh/kg-h Direct Emissions: 0.0121 kg CO_2e/kg-hr (for 36 hrs) Frozen Broccoli, Chicken, Fish Electricity: 0.011 kWh/kg-h Direct Emissions: 0.0033 kg CO_2e/kg-hr (for 96 hrs) Fresh Chicken, Fish	(Defra, 2008)	Frozen modal values are the average of the three different display case values reported

	Electricity: 0.0155 kWh/kg-h Direct Emissions: 0.0089 kg CO_2e/kg-hr (for 24 hrs) Milk Electricity 0.0028 kWh/kg-h Direct Emissions: 0.00162 kg CO_2e/kg-hr (for 12 hrs)		

Table C.1: Supply Chain Model Baseline Values

Appendix C References

Blanke, M.M., Burdick, B., 2005. Food (miles) for Thought: Energy Balance for Locally-Grown versus Imported Apple Fruit. Environ. Sci. Pollut. Res. 12, 125–127. doi:http://dx.doi.org/10.1065/espr2005.05.252

Buzby, J.C., Farah-Wells, H., Hyman, J., 2014. The Estimated Amount, Value, and Calories of Postharvest Food Losses at the Retail and Consumer Levels in the United States, Economic Information Bulletin. doi:10.2139/ssrn.2501659

Canals, L.M.I., Muñoz, I., Hospido, A., Plassmann, K., McLaren, S., 2008. Life Cycle Assessment (LCA) of domestic vs. imported vegetables. Case studies on broccoli, salad crops and green beans (No. 01/08), Centre for Environmental Strategy Working Paper. doi:1464-8083

Defra, 2008. Greenhouse Gas Impacts of Food Retailing (No. Defra Project code FO405).

ecoinvent, n.d. ecoinvent.

Eurogourmet, n.d. Eurogourmet Halal Chicken [WWW Document]. URL eurochoice.nl/products/categories/meat/dutch-meat.../euro-gourmet-chicken-turkey%0A

González-García, S., Gomez-Fernández, Z., Dias, A.C., Feijoo, G., Moreira, M.T., Arroja, L., 2014. Life Cycle Assessment of broiler chicken production: a Portuguese case study. J. Clean. Prod. 74, 125–134.

Gustavsson, J., Cederberg, C., Sonesson, U., 2011. Global Food Losses and Food Waste: Extent, Causes and Prevention, Food and Agriculture Organization of the United Nations (FAO).

Homifreez, 2017. Broccoli [WWW Document]. URL http://www.homifreez.com/en/broccoli-35.htm

Hospido, A., Moreira, M.T., Feijoo, G., 2003. Simplified life cycle assessment of galician milk production. Int. Dairy J. 13, 783–796. doi:10.1016/S0958-6946(03)00100-6

International Energy Agency, 2012. CO2 Emissions From Fuel Combustion Highlights.

Nielsen PH, Nielsen AM, Weidema BP, Dalgaard R, H.N., 2003. LCA Food DK.

Ranheim Paper & Board, n.d. Packaging for Frozen Salmon/Trout [WWW Document]. URL https://ranheim-pb.com/produkter/emballasje-for-frossen-laksorret/

Stemilt Growers, 2010. Common Apple Carton Specifications [WWW Document]. URL http://www.stemilt.com/assets/pdfs/Cartons_Apples.pdf

Svanes, E., Vold, M., Hanssen, O.J., 2011. Environmental assessment of cod (Gadus morhua) from autoline fisheries. Int. J. Life Cycle Assess. 16, 611–624. doi:10.1007/s11367-011-0298-2

Appendix D

Supporting Information for Chapter 6

Appendix D.1

Ingredient	**Food Eaten (g)**	**Food Unused (g)**	**Plastic (g)**	**Cardboard (g)**	**Styrofoam (g)**	**Paper (g)**	**Glass (g)**	**Metal (g)**
Salmon Meal								
Salmon	274.03	0	58.8	0	0	0	0	0
Garlic	6.7	27.55	0	0	0	0	0	0
Carrots	170	48.98	4.46	0	0	0	0	0
Potato	340.2	114.1	3.84	0	0	0	0	0
Honey	19.9	0	0	3.9	0	0	0	0
Greek Yogurt	117.05	0	0	0	0	0	0	0
Aleppo Pepper	4.26	0	0	0	0	0	0	0
Cumin	1.55	0	0.99	0	0	0	0	0
Mint	5.22	0	6.51	0	0	0	0	0
Cheeseburger Meal								
Ground Beef	289.25	0	7.62	0	0	0	0	0
Potato Buns	109.52	0	3.78	0	0	0	0	0

Chioggia Beet	178.11	0	0	0	0	0	0	0
Garlic	4.73	31.57	0	0	0	0	0	0
Russet Potato	305.63	0	0	0	0	0	0	0
Sugar	8.87	0	0.96	0	0	0	0	0
Red Wine Vinegar	14.63	0	7.35	0	0	0	0	0
Provolone Cheese	45.3	0	3.19	0	0	0	0	0
<u>Chicken Meal</u>								
Chicken Breasts	334.19	0	12.21	0	0	0	0	0
Cannellini Beans	304.56	134.44	0	0	0	0	0	65.41
Carrots	184.8	0	4.46	0	0	0	0	0
Garlic	6.7	27.55	0	0	0	0	0	0
Kale	128.33	0	12.05	0	0	0	0	0
Thyme	2.15	0	1.79	0	0	0	0	0
Dijon Mustard	26.55	0	4.12	0	0	0	0	0
Shallot	23.34	0	0	0	0	0	0	0
Red Wine Vinegar	14.63	0	7.35	0	0	0	0	0
Panko Breadcrumbs	18.77	0	1.9	0	0	0	0	0
<u>Pasta Meal</u>								

Mafalda Pasta	255	0	4	0	0	0	0	0
Garlic	4.86	30.91	0	0	0	0	0	0
Kale	49.9	79.23	10.87	0	0	0	0	0
Butternut Squash	228.35	0	3.01	0	0	0	0	0
Rosemary	3.24	0	2.36	0	0	0	0	0
Butter	57.37	0	0	0	0	0	0	2.31
Parmesan Cheese	11.86	0	7.5	0	0	0	0	0
Crème Fraîche	34.43	0	1.4	0	0	0	0	0
Roasted Walnuts	26.46	0	1.41	0	0	0	0	0
Verjus Blanc	24.33	0	3.52	0	0	0	0	0
Crushed Red Pepper Flakes	1.2	0.45	4.88	0	0	0	0	0
Capers	17.78	0	1.56	0	0	0	0	0
Salad Meal								
Semi-Pearled Farro	112.3	0	1.81	0	0	0	0	0
Eggs	124.49	0	0	49.35	8.29	0	0	0
Apple	162.43	0	0	0	0	0	0	0
Purple Top Turnip	102.75	0	0	0	0	0	0	0
Carrots	107.16	0	5.57	0	0	0	0	0
Yellow Onion	120.57	0	0	0	0	0	0	0

Garlic	3.84	0	0	0	0	0	0	0
Sage	2.14	31.93	2.03	0	0	0	0	0
Apple Cider Vinegar	13.58	0	7.67	0	0	0	484.77	0
Butter	31.57	0	0	0	0	0	0	1.13
Dried Shiitake Mushrooms	17.07	12.01	2.46	0	0	0	0	0
Lamb Chopper Cheese	39.2	0	1.58	0	0	0	0	0

Table D.1: Meal Kit Ingredients and Food-Specific Packaging Masses

Ingredient	Food Eaten (g)	Food Unused (g)	Plastic (g)	Cardboard (g)	Styrofoam (g)	Paper (g)	Glass (g)	Metal (g)
Salmon Meal								
Salmon	417.3	0	0	0	14.81	0	0	0
Garlic	14.83	40.38	1.85	0	0	0	0	0
Carrots	168	125.3	1.85	0	0	0	0	0
Potato	340.19	219.25	8.62	0	0	0	0	0
Honey	14.66	325.34	25.82	0	0	0	0	0
Greek Yogurt	114.39	0	9.28	0	0	0	0	0
Aleppo Pepper	0.43	113.62	58.62	0	0	0	0	0
Cumin	0.71	44.31	29.31	0	0	0	0	0
Mint	9	9	20.47	0	0	0	0	0
Cheeseburger Meal								
Ground Beef	291	0	0	12.885	0	12.885	0	0
Potato Buns	42	126	9.4	0	0	0	0	0
Chioggia Beet	62.5	0	51.64	0	0	0	0	0
Garlic	7.42	35.63	1.85	0	0	0	0	0
Russet Potato	316.3	0	1.85	0	0	0	0	0
Sugar	4.48	902.52	0	65	0	0	0	0

Red Wine Vinegar	7.93	435.64	39.6	0	0	0	0	0
Provolone Cheese	44.22	120.52	3.47	0	0	0	0	0
<u>Chicken Meal</u>								
Chicken Breasts	601.21	0	0	0	20.81	0	0	0
Cannellini Beans	292.24	146.76	0	0	0	0	0	50
Carrots	212.82	0	1.85	0	0	0	0	0
Garlic	14.83	0	1.85	0	0	0	0	0
Kale	31.09	0	1.85	0	0	0	0	0
Thyme	18.16	0	18.16	0	0	0	0	0
Dijon Mustard	23.1	316.55	48.51	0	0	0	0	0
Shallot	72.41	0	1.85	0	0	0	0	0
Red Wine Vinegar	7.93	435.64	39.6	0	0	0	0	0
Panko Breadcrumbs	14.29	211.89	0	0	0	0	0	78.38
<u>Pasta Meal</u>								
Mafalda Pasta	226	211.49	0	34.51	0	0	0	0
Garlic	7.52	33.3	1.87	0	0	0	0	0
Kale	59.31	173.99	0	0	0	0	0	0
Butternut Squash	245.2	958.8	1.88	0	0	0	0	0
Rosemary	11.13	23.54	14.9	0	0	0	0	0

Butter	56.64	396.48	0	12.66	0	0	0	0
Parmesan Cheese	32.35	132.7	18.06	0	0	0	0	0
Crème Fraîche	37.81	188.5	23.5	0	0	0	0	0
Roasted Walnuts	28.21	33.5	4.28	0	0	0	0	0
Verjus Blanc	21	414.66	0	0	0	0	309.9	0
Crushed Red Pepper Flakes	0.97	41.35	0	0	0	0	0	29.25
Capers	14.31	84.42	0	0	0	0	112.51	0
<u>Salad Meal</u>								
Semi-Pearled Farro	119.62	515.88	7.37	0	0	0	0	0
Eggs	115.72	220.1	0	0	0	0	0	0
Apple	158.97	0	1.87	0	0	0	0	0
Purple Top Turnip	200.82	0	0	0	0	0	0	0
Carrots	130.59	0	0	0	0	0	0	0
Yellow Onion	297.07	0	1.87	0	0	0	0	0
Garlic	7.17	33.65	0	0	0	0	0	0
Sage	3.27	9.54	15.24	0	0	0	0	0

Apple Cider Vinegar	11.92	892.2	0	0	0	0	0	0
Butter	28.75	38.79	1.91	0	0	0	0	0
Dried Shiitake Mushrooms	14.31	424.99	0	12.66	0	0	0	0
Lamb Chopper Cheese	28	85.43	41.8	0	0	0	0	0

Table D.2: Grocery Meal Ingredients and Food-Specific Packaging Masses

Appendix D.2

Values not from the literature were accessed from the databases listed in SimaPro Classroom 8.5.2.0.

Items	**kg CO2-eq/g**	**Notes, Source**
Salmon	0.00237	From literature (Silverman, 2009)
Garlic	0.000407	Substituted Onion {GLO} 855 production Alloc Def, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Carrots	0.000119	LCA Food DK database (Carrot, conventional, washed and packed, from field)
Lemon	0.02637	From literature (Beccali et al., 2009)
Potato	0.000142	LCA Food DK database (Potatoes from farm)
Saffron	0.0031711	Substituted Lettuce {GLO} | 360 + 361 production, Alloc Def, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Honey	4.75E-05	Substituted Molasses from sugar beet {CH} Alloc Def, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Greek Yogurt	0.00169	Assuming yogurt, from cow milk (CA-QC) [production] Alloc Def, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Aleppo Pepper	1.09E-05	Substituted Green bell pepper production alloc Def, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist

Cumin	0.000766	Substituted Sunflower Seed, Swiss integrated production {CH} Alloc Def, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Mint	0.0031711	Substituted Lettuce {GLO} | 360 + 361 production, Alloc Def, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Boneless, Skinless Chicken Breasts	0.00171	Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Cannellini Beans	0.000548	Substitued Cannellini Beans: Fava Bean, Swiss integrated production [GLO] (Market For) Alloc Def, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Kale	0.0031711	Substituted Lettuce {GLO} | 360 + 361 production, Alloc Def, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Thyme	0.0031711	Substituted Lettuce {GLO} | 360 + 361 production, Alloc Def, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Dijon Mustard	0.003	From literature (Khatri et al., 2017)
Shallot	0.000407	Substituted Onion {GLO} 855 production Alloc Def, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Red Wine Vinegar	0.00171	Value for "condiments" (which includes vinegar) (Masset et al., 2014)

Panko Breadcrumbs	0.00117	From literature (Vázquez-Rowe et al., 2013)
Mafalda Pasta	0.00101	From literature (Hoolohan et al., 2013)
Butternut Squash	0.00409	Substitued Aubergine {GLO} market for, Alloc Def, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Rosemary	0.0031711	Substituted Lettuce {GLO} | 360 + 361 production, Alloc Def, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Capers	0.000766	Substituted Sunflower Seed, Swiss integrated production {CH}, Alloc Def, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Butter	0.00924	Butter, from cow milk {GLO} production, Alloc Def, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Crème Fraîche	0.00233	Substituted Cream, from cow milk {CA-QC} yogurt production, from cow milk, Alloc Def , Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Verjus Blanc	0.00171	Substituting value used for vinegar (Masset et al., 2014)
Parmesan Cheese	0.072	Cheese from cheese production, at plant (NL Mass), Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Roasted Walnuts	0.000261	Groundnuts, with shell, at farm / US Mass, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist

Crushed Red Pepper Flakes	1.09E-05	Assumed Green bell pepper production, Alloc Def, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Lamb Chopper Cheese	0.072	Assumed Cheese from cheese production, at plant (NL Mass), Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Semi-Pearled Farro	0.000529	Substituted Barley grain {DE} barley production, Alloc Def, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Cage-Free Farm Eggs	0.00184	LCAFoodDK (Egg)
Apple	0.000248	Apple {GLO} production, Alloc Def,Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Purple Top Turnip	0.000142	Substituted Potato, LCAFoodDK
Yellow Onion	0.000373	Onion {GLO}	855 production, Alloc Def, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Sage	0.0031711	Substitued Lettuce {GLO}	360 + 361 production, Alloc Def, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Apple Cider Vinegar	0.00171	Value for "condiments" (which includes vinegar) (Masset et al., 2014)

Dried Shiitake Mushrooms	0.002147	From literature (Gunady et al., 2012)
Ground Beef	0.0163	Beef meat, fresh, from beef cattle, at slaughterhouse (IE Mass), Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Potato Buns	0.000816	Substituted rolls, conventional, fresh, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Chioggia Beet	3.53E-05	Substituted Sugar beet at farm, UK mass, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Sugar	0.00026	Sugar, from sugarcane, at sugar refinery, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Provolone Cheese	0.072	Cheese from cheese production, at plant (NL Mass), Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Plastic	0.002277564	Packing film, low density polyethylene, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Metal	0.002934586	Aluminum sheet, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Styrofoam	0.003839393	Substituted polystyrene, general purpose, GPPS, at plant, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Glass	0.000629559	Packaging glass, white, at plant, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist

Paper	0.001730403	Kraft paper, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Cardboard	0.000498333	Folding Boxboard/Chipboard, market for, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Polylactide	0.003178402	Polylactide, granulate, at plant/GLO, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Water to user	3.25167E-07	Tap water, at user/RER, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Ethylene Glycol	0.00173	Ethylene Glycol, at plant/RER, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Insulating Sheet/Blanket	0.00695	Average of aluminum and PET film, to reflect observed composition, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Polyethylene Landfilling	0.000147723	Disposal, polyethylene, 0.4% water, to sanitary landfill/CH, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Paper Landfilling	0.001438967	Disposal, packaging paper, 13.7% water, to sanitary landfill/CH, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Glass Landfilling	7.66918E-06	Disposal, glass, 0% water, to inert material landfill/CH, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Cardboard Landfilling	0.001852811	Disposal, packaging cardboard, 19.6% water, to sanitary landfill/CH, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist

Aluminum Landfilling	2.20744E-05	Disposal, aluminium, 0% water, to sanitary landfill/CH, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Polystyrene Landfilling	0.000155008	Disposal, polystyrene, 0.2% water, to sanitary landfill, Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Non-specific Landfilling	4.63395E-06	Process-specific burdens, sanitary landfill. Ecoinvent Database 3.4, default, ReCiPe 2016 v1.1 Hiearchist
Bioplastic End-of-Life	-0.0006	Landfilling of biodegradable waste, ELD LCA database
Plastic Recycling	-0.00097	(Turner et al., 2015)
Paper Recycling	-0.00046	(Turner et al., 2015)
Glass Recycling	-3.14E-04	(Turner et al., 2015)
Cardboard Recycling	-0.00012	(Turner et al., 2015)
Aluminum Recycling	-8.14E-03	(Turner et al., 2015)
Polystyrene Recycling	-0.00102	(Turner et al., 2015)

Table D.3: Food and Packaging Emissions Characterization Values

Appendix D.3

First column is an indicator of whether foods are modeled as refrigerated in retailing (1 if true, 0 if false). Loss and waste rates are assigned as the most-likely values in Monte Carlo distributions (Buzby et al., 2014). Asterisks indicate values assigned to zero by researchers, reflecting extremely low spoilage rates.

Food	**Refrigerated During Retail?**	**Store Loss Rate (%)**	**Home Waste Rate (%)**
Salmon	1	8	31
Garlic	0	8	22
Carrots	1	8	22
Potato	0	8	22
Honey	0	11	0*
Greek Yogurt	1	10	19
Aleppo Pepper	0	8	22
Cumin	0	10	0*
Mint	1	8	22
Ground Beef	1	4	23
Potato Buns	0	12	19
Chioggia Beet	1	8	22
Garlic	0	8	22
Russet Potato	0	8	22
Sugar	0	11	0*
Red Wine Vinegar	0	11	0*

Provolone Cheese	1	10	19
Chicken Breasts	1	4	18
Cannellini Beans	0	8	22
Carrots	1	8	22
Garlic	0	8	22
Kale	1	8	22
Thyme	1	8	22
Dijon Mustard	0	10	0*
Shallot	0	10	22
Red Wine Vinegar	0	10	0*
Panko Breadcrumbs	0	12	19
Mafalda Pasta	0	12	19
Garlic	0	8	22
Kale	1	8	22
Butternut Squash	0	8	22
Rosemary	1	8	22
Butter	1	21	0
Parmesan Cheese	1	10	19
Crème Fraîche	1	10	19
Roasted Walnuts	0	6	9
Verjus Blanc	0	10	0*
Crushed Red Pepper Flakes	0	10	0*

Capers	0	10	0*
Semi-Pearled Farro	0	12	19
Eggs	1	7	21
Apple	0	12	25
Purple Top Turnip	1	8	22
Carrots	1	8	22
Yellow Onion	0	8	22
Garlic	0	8	22
Sage	1	8	22
Apple Cider Vinegar	0	10	0*
Butter	1	21	0*
Dried Shiitake Mushrooms	1	6	18
Lamb Chopper Cheese	1	10	19

Table D.4: Food Loss and Waste Rates, Retail Refrigeration Indicator

Appendix D.4

Meal	Median Meal Kit Emissions (kg CO_2e/average meal)	Median Grocery Store Meal Emissions (kg CO_2e/ average meal)	Percentage of Times Meal Kit Emissions Exceed Grocery Store Meal	Percentage of Times Grocery Store Meal Emissions Exceed Meal Kit
Salmon	3.35	4.30	15%	85%
Cheeseburger	11.61	10.13	90%*	10%
Chicken	4.01	4.94	14%	86%
Pasta	5.56	12.46	0%	100%**
Salad	6.21	8.87	0%	100%**

*Percentage of Model Runs $\geq$ 90%

** Percentage of Model Runs $\geq$ 95%

Table D.5: Monte Carlo Simulation Results

	Food (Percentage of Total)	Food Waste (Percentage of Total)	Packaging (Percentage of Total)	Processing Loss (Percentage of Total)	Transportation to Mail (Percentage of Total)	Last Mile (Percentage of Total)	End-of-Life (Percentage of Total)
Meal Kit Salmon	1.55 (47%)	0.10 (3%)	0.28 (9%)	0.24 (7%)	0.65 (20%)	0.20 (6%)	0.30 (9%)
Meal Kit Cheeseburger	8.81 (77%)	0.06 (1%)	0.20 (2%)	1.17 (10%)	0.70 (6%)	0.23 (2%)	0.32 (3%)
Meal Kit Chicken	1.98 (50%)	0.09 (2%)	0.39 (10%)	0.29 (7%)	0.70 (18%)	0.21 (5%)	0.30 (8%)
Meal Kit Pasta	3.53 (64%)	0.13 (2%)	0.22 (4%)	0.52 (10%)	0.59 (11%)	0.21 (4%)	0.30 (5%)
Meal Kit Salad	3.62 (52%)	0.05 (1%)	0.54 (9%)	0.49 (8%)	0.81 (13%)	0.23 (4%)	0.41 (7%)

Table D.6: Meal Kit Median Emissions Contributions by Process

	Food (Percentage of Total)	Food Waste (Percentage of Total)	Packaging (Percentage of Total)	Retail Loss (Percentage of Total)	Store Operation (Percentage of Total)	Transportation to Store (Percentage of Total)	Last Mile (Percentage of Total)	End-of-Life (Percentage of Total)
Grocery Store Salmon	1.57 (37%)	0.38 (9%)	0.26 (6%)	0.54 (13%)	0.49 (12%)	0.02 (1%)	0.94 (22%)	0.02 (~0%)
Grocery Store Cheeseburger	6.09 (61%)	0.43 (4%)	0.11 (1%)	2.60 (26%)	0.17 (2%)	0.02 (~0%)	0.55 (5%)	0.06 (1%)
Grocery Store Chicken	2.10 (43%)	0.19 (4%)	0.43 (9%)	0.70 (14%)	0.49 (10%)	0.03 (1%)	0.91 (19%)	0.01 (~0%)
Grocery Store Pasta	5.33 (43%)	2.60 (21%)	0.13 (1%)	3.63 (29%)	0.26 (2%)	0.02 (~0%)	0.37 (4%)	0.03 (~0%)
Grocery Store Salad	4.53 (52%)	1.12 (13%)	0.06 (1%)	2.00 (23%)	0.46 (5%)	0.02 (~0%)	0.57 (6%)	0.02 (~0%)

Table D.7: Grocery Meal Median Emissions Contributions by Process

Appendix D.5

Acidification, eutrophication, land use, and water use impacts are estimated for the food and packaging produced for each meal kit and grocery meal. These impacts are estimated for only the production of these elements of each meal, and in the specific aggregations reported, due to data constraints. Acidification and land use estimates are aggregated for both food and packaging, but are separated for eutrophication and water use due to differences in characterization units and their boundaries. Food items are characterized by their best-corresponding factors from (Poore and Nemecek, 2018). Packaging is characterized using the ReCiPe 2016 Midpoint (H) V1.02 method from Ecoinvent Database 3.4, excluding cardboard and paper whose water use is characterized in SimaPro by (Hoekstra et al., 2012) which yield more-realistic values, using the same products as identified in Table D.8.

Acidification (g SO_2e)										
	MK Salmon	GS Salmon	MK Cheeseburger	GS Cheeseburger	MK Chicken	GS Chicken	MK Pasta	GS Pasta	MK Salad	GS Salad
Food	22.71	31.97	102.20	101.87	43.59	70.15	10.05	13.31	19.16	18.02
Meal Kit Processing Loss or Grocery Retail Loss	2.97	5.09	13.01	16.30	5.93	9.93	1.36	8.84	2.47	9.62
Food Waste	0.10	1.13	0.02	3.52	0.50	1.05	0.10	6.26	0.05	7.25
Food Packaging	0.44	0.70	0.14	0.27	1.72	2.34	0.28	0.63	1.22	0.18

Meal Kit Box or Grocery Store Bag	0.81	0.05	0.91	0.02	0.83	0.04	0.83	0.02	0.90	0.03
Sum	27.03	38.94	116.29	121.98	52.57	83.51	12.62	29.07	23.79	35.09

Eutrophication (g PO_4^{3-} eq for food, g P-eq for packaging freshwater, g N-eq for packaging marine)	MK Salmon	GS Salmon	MK Cheeseburger	GS Cheeseburger	MK Chicken	GS Chicken	MK Pasta	GS Pasta	MK Salad	GS Salad
Food	67.53	101.09	93.60	93.53	23.67	36.17	5.15	7.06	11.92	11.61

Meal Kit Processing Loss or Grocery Retail Loss	8.66	12.74	11.92	13.56	3.31	6.83	0.68	4.61	1.53	6.53
Food Waste	0.09	0.83	0.01	2.14	0.43	0.71	0.04	3.36	0.02	5.45
Food Packaging: Freshwater	0.04	0.00	0.00	0.31	0.00	0.00	0.00	0.19	0.62	0.06
Food Packaging: Marine	0.00	0.00	0.00	0.21	0.00	0.00	0.00	1.97	7.10	0.00

Meal Kit Box or Grocery Store Bag: Freshwater	0.05	0.00	0.05	0.00	0.05	0.00	0.05	0.00	0.05	0.00
Meal Kit Box or Grocery Store Bag: Marine	0.12	0.00	0.13	0.00	0.12	0.00	0.12	0.00	0.13	0.00
Food sum	76.29	114.66	105.53	109.23	27.41	43.71	5.87	15.03	13.46	23.59

Packaging freshwater eutrophication sum	0.09	0.00	0.06	0.31	0.05	0.00	0.05	0.19	0.68	0.06
Packaging marine eutrophication sum	0.12	0.00	0.13	0.21	0.12	0.00	0.12	1.97	7.23	0.00
Land Use (m^2a)										
	MK Salmon	GS Salmon	MK Cheeseburger	GS Cheeseburger	MK Chicken	GS Chicken	MK Pasta	GS Pasta	MK Salad	GS Salad
Food	3.76	4.93	98.80	99.18	9.32	12.33	3.24	4.98	5.07	4.13

Meal Kit Processing Loss or Grocery Retail Loss	0.50	0.73	12.66	11.82	1.46	2.34	0.42	3.39	0.65	2.19
Food Waste	0.02	0.12	0.00	1.84	0.39	0.56	0.01	2.53	0.00	1.79
Food Packaging	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.03	0.09	0.01
Meal Kit Box or Grocery Store Bag	0.19	0.00	0.21	0.00	0.19	0.00	0.19	0.00	0.21	0.00
Sum										

Water Use (L)										
	MK Salmon	GS Salmon	MK Cheeseburger	GS Cheeseburger	MK Chicken	GS Chicken	MK Pasta	GS Pasta	MK Salad	GS Salad
Food	1124.79	1647.78	710.06	696.73	412.81	570.86	371.13	475.04	605.76	560.24
Meal Kit Processing Loss or Grocery Retail Loss	144.33	228.91	90.51	253.21	60.11	138.48	48.40	270.81	77.69	337.89
Food Waste	1.62	28.90	0.17	118.55	11.01	34.57	1.66	198.94	0.80	305.51
Food Packaging	4.53	7.69	1.44	3.21	106.34	134.87	6.00	125.57	394.08	1.89

Meal Kit Box or Grocery Store Bag	40.35	0.61	45.55	0.35	41.69	0.58	41.68	0.27	44.86	0.38
Food freshwater withdrawals sum	1270.74	1905.60	800.73	1068.49	483.93	743.91	421.19	944.79	684.25	1203.63
Packaging water use sum	44.88	8.31	46.99	3.56	148.03	135.45	47.68	125.84	438.93	2.27

Table D.8: Additional Environmental Impact Values for the Production of Food and Packaging

Appendix D References

Beccali, M., Cellura, M., Iudicello, M., Mistretta, M., 2009. Resource Consumption and Environmental Impacts of the Agrofood Sector: Life Cycle Assessment of Italian Citrus-Based Products. Environ. Manage. 43, 707–724. doi:10.1007/s00267-008-9251-y

Buzby, J.C., Farah-Wells, H., Hyman, J., 2014. The Estimated Amount, Value, and Calories of Postharvest Food Losses at the Retail and Consumer Levels in the United States, Economic Information Bulletin. doi:10.2139/ssrn.2501659

Gunady, M.G.A., Biswas, W., Solah, V.A., James, A.P., 2012. Evaluating the global warming potential of the fresh produce supply chain for strawberries, romaine/cos lettuces (Lactuca sativa), and button mushrooms (Agaricus bisporus) in Western Australia using life cycle assessment (LCA). J. Clean. Prod. 28, 81–87. doi:10.1016/j.jclepro.2011.12.031

Hoekstra, A.Y., Mekonnen, M.M., Chapagain, A.K., Mathews, R.E., Richter, B.D., 2012. Global Monthly Water Scarcity: Blue Water Footprints versus Blue Water Availability. PLoS One 7, e32688. doi:10.1371/journal.pone.0032688

Hoolohan, C., Berners-Lee, M., McKinstry-West, J., Hewitt, C.N., 2013. Mitigating the greenhouse gas emissions embodied in food through realistic consumer choices. Energy Policy 63, 1065–1074. doi:10.1016/j.enpol.2013.09.046

Khatri, P., Jain, S., Pandey, S., 2017. A cradle-to-gate assessment of environmental impacts for production of mustard oil using life cycle assessment approach. J. Clean. Prod. 166, 988–997. doi:10.1016/j.jclepro.2017.08.109

Masset, G., Soler, L.G., Vieux, F., Darmon, N., 2014. Identifying sustainable foods: The relationship between environmental impact, nutritional quality, and prices of foods representative of the french diet. J. Acad. Nutr. Diet. 114, 862–869. doi:10.1016/j.jand.2014.02.002

Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science (80). 992, 987–992. doi:10.1126/SCIENCE.AAQ0216

Silverman, H., 2009. Not all Salmon Are Created Equal: Life Cycle Assessment (LCA) of Global Salmon Farming Systems. Environ. Sci. Technol. 43, 1–37.

Turner, D.A., Williams, I.D., Kemp, S., 2015. Greenhouse gas emission factors for recycling of source-segregated waste materials. Resour. Conserv. Recycl. 105, 186–197. doi:10.1016/j.resconrec.2015.10.026

Vázquez-Rowe, I., Villanueva-Rey, P., Mallo, J., De La Cerda, J.J., Moreira, M.T., Feijoo, G., 2013. Carbon footprint of a multi-ingredient seafood product from a business-to-business perspective. J. Clean. Prod. 44, 200–210. doi:10.1016/j.jclepro.2012.11.049