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

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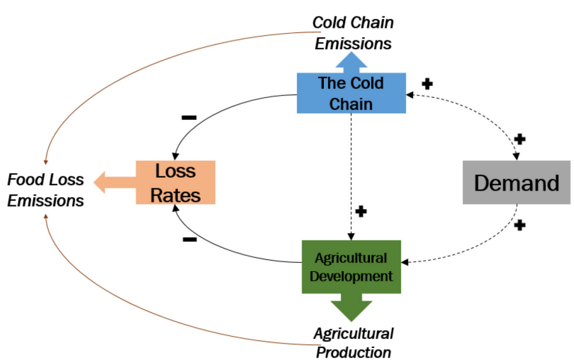
Abstract

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 creating environmental impacts to do so. 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. Modeling these changes indicates the cold chain may increase emissions to supply food to retail by 10% or decrease them by 15%, depending on the scenario.

Visual Abstract



Cold Chain Introduction and the Food Supply Chain

This study explores the inherent tradeoff of reducing food loss and the associated embodied GHG emissions by deploying refrigeration, a technology that increases GHG emissions through energy consumption and refrigerant emissions. The analysis first examines only the direct tradeoffs between increased energy and refrigerant emissions compared to the GHG savings of reduced food loss. The study then takes a broader systems-level examination of the potential impacts of introduced refrigeration, including anticipated impacts on the upstream supply chain 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.[1,2] Refrigeration increases access to perishable foods, extends the shelf-life of food, and has the potential to reduce food losses.[3,4] Access to refrigeration is associated with improved health outcomes, including reduced risk of foodborne illness[3] and improved capacity to store antibiotics and vaccines.[5] 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.[6]

Despite these benefits, refrigeration is energy-intensive and often uses refrigerants with high global warming potentials.[7] When accounting only for direct energy use and refrigerant leakage, refrigeration is responsible for approximately 1% of the world's total greenhouse gas (GHG) emissions,[8] and can represent 3-3.5% of GHG emissions in developed economies such as the UK.[9]

In addition to energy use and emissions, refrigeration facilitates increased consumption of more-perishable foods, which tend to be more environmentally-intensive.[9] 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.[10–13] Additionally, food losses that occur further along the supply chain are more carbon-intense due to additional embodied energy.[14] Approximately one-third of all food produced for human consumption is lost or wasted,[15] and reducing food losses and waste has been identified as a key goal in improving food security.[10–12,16–18] The cold chain has been identified as a key means for reducing food loss and waste, along with its related GHG emissions.[4,13,19,20] Therefore, it becomes crucial to develop a better understanding of whether the emissions savings from reduced food loss are offset by increased emissions of the cold chain.

The cold chain has critical connections to the Sustainable Development Goals (SDG), with target 12.3 seeking a reduction in food loss and waste along the food supply chain,[22] and Goal 2 seeking to improve food security and nutrition.[23]

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.[7] 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.[7,24] 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.[21] Garnett describes cold chain technologies as ubiquitous for a modern food system, embedded in every stage of a product's life cycle.[9] It has also been noted that supply chains for several goods are now based on the ability to supply chilled or frozen products.[25] As such, cold chain introduction is fundamental to food system development.

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.[7] James and James 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.[26] 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.[3]

This study first examines a fundamental trade-off of refrigeration: the ability to reduce food losses which carry embodied emissions, but adding 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 tradeoffs 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, 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.,[15] 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.[15,21] The boundary of this study is the upstream, or pre-consumer, 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 1.

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,[15] 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, which may be 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 [27,28] (see Supporting Information 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.

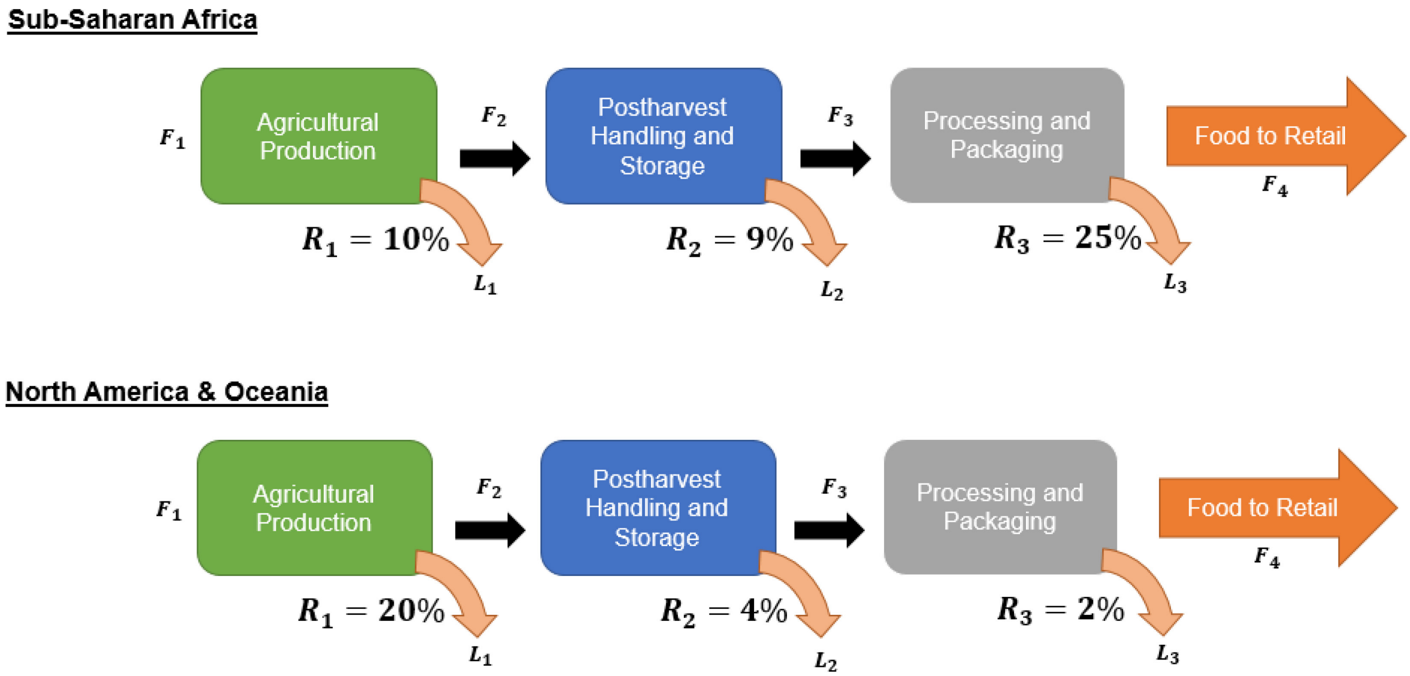


Figure 1: Visual representations of mass flows, loss rates, and losses in the upstream food supply chain. R values are loss rates in each FSC stage for fruits and vegetables for Sub-Saharan Africa (top) and North America & Oceania (bottom) from Gustavsson et al.[15] Each food type has unique food loss rates at each stage; the values for fruits and vegetables are shown here as an example. F and L values indicate food and loss flows at each FSC stage (numbered sequentially as subscripts), respectively. Further description of these terms is available in Methods.

As seen in the comparison of fruit and vegetable loss rates between Sub-Saharan Africa and North America & Oceania in Figure 1, a greater quantity of food successfully makes it to retail in the latter region, attributable to more-developed food supply chains. Agricultural losses are higher in North America & Oceania due to increased grading from higher quality standards set by retailers.[15] These 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.[15]

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 Supporting Information 2. Monte Carlo Analysis (MCA) is conducted to create probability distributions for each parameter for each of the seven food types for each region. MCA repeatedly and randomly draws values from probability distributions to better-capture the variance and uncertainty associated with data for each parameter within the model.[29] Distribution choices and parameter values are detailed in Supporting Information 3, and sensitivity analysis for these parameters is detailed in Supporting Information 4.

Methods

The changes in food supplied and the emissions associated with cold chain introduction are determined by adjusting four parameters: loss rates (R_n), demand (F_n), agricultural emissions factors (E_A), and cold chain emissions factors (E_c). Emissions factors characterize food (and food losses) which enter a stage and are subject to its emissions-contributing processes. These parameters are drawn from the Monte Carlo distribution types described, with specific parameters are values described in Supporting Information 3. Parameter distributions are assumed to be independent and 10,000 Monte Carlo simulations are run to produce this study's results.

There are five stages of the food supply chain corresponding to Gustavsson et al.[15]: 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." 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: 1. Cereals, 2. Roots and Tubers, 3. Fruits, 4. Vegetables, 5. Meat, 6. Fish and Seafood, and 7. Milk.

The food types each parameter corresponds to are indicated for summations with index T which ranges from 1-7, for each of the food types. Parameters are also defined for the regions examined as superscripts, with Sub-Saharan African values indicated as B ("Baseline") and the North American or European values are denoted as D ("Developed").

Between each stage of the FSC is a loss rate:

$$R = \{R_1, R_2, R_3, R_4\}$$

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 in each region. Loss rates calculated by Gustavsson et al.[15] are used to define triangular Monte Carlo distributions for this parameter for each food type and region.

The cold chain co-develops and is integrated with related post-harvest storage and transportation infrastructure and spoilage-reducing supply chain properties.[7,9,21,30] As such, some changes in loss rates observed are not directly due to refrigeration, but cannot be distinguished or separated from those which are in the data.

The food present at each section of the supply chain prior to losses can be represented similarly:

$$F = \{F_1, F_2, F_3, F_4, F_5\}$$

Where F_n represents mass (kg) of each food type at each stage of the region's FSC. 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,[31] capturing the food available for human consumption in each region within a given year.

The food loss for each type and region in each stage (L_n, in kg) is calculated as:

Eqn. 1

$$L_n = F_n * R_n$$

The food available at each upstream FSC stage can be computed by:

Eqn. 2

$$F_{n-1} = \frac{F_n}{(1 - R_{n-1})}$$

Such that

Eqn 3.

$$F_5 = [\{[F_1 * (1 - R_1)] * (1 - R_2)\} * (1 - R_3)] * (1 - R_4)$$

To model per-capita demand shifts occurring with development, per-demand is calculated for each region as:

Eqn. 4

$$C^D = {F_5^D}/{P^D}$$

Where

C^D is the per-capita food consumption for the developed region (North America or Europe)

F_5^D is the “food” from the 2013 FAOSTAT Food Balance Sheets for the developed region (North America or Europe)

P^D is the population for the developed region (North America or Europe)

And

Eqn. 5

$$C^B = {F_5^B}/{P^B}$$

Where

C^B is the per-capita food consumption for the baseline region (Sub-Saharan Africa)

F_5^B is the “food” from the 2013 FAOSTAT Food Balance Sheets for Sub-Saharan Africa

P^B is the population for the Sub-Saharan Africa

The developed diet is then calculated as

Eqn. 6

$$F_5^D = F_5^B * (\frac{C^D}{C^B})$$

An important trade-off analyzed through this research is the addition of direct cold chain emissions to reduce emissions from food losses in the cold chain. Eqn. 7 computes GHG emissions added through cold chain operation, Eqn. 8 calculates the difference in food losses (characterized into their corresponding GHG emissions from production), and Eqn. 9 takes the difference between these two values.

Eqn. 7

$$\mathrm{E}_{\Delta C} = E_C\left(\frac{F_4^D + L_2^D + L_3^D}{F_4^D}\right)$$

Where $\mathrm{E}_{\Delta C}$ is the change in GHG emissions (kg CO_2e/kg) added to the upstream FSC from cold chain operation.

Since the baseline models a food system without robust cold chain infrastructure, cold chain emissions are assumed to be zero for the Sub-Saharan African region.

E_C values encompass post-farm transportation, processing, storage at regional distribution centers, and transportation to retail. These 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[16] which contained sufficient post-farm gate data on emissions from the cold chain.

Eqn. 8

$$\mathrm{E}_{\Delta A} = E_A(\left(\frac{F_4^B + L_2^B + L_3^B}{F_4^B}\right) - \left(\frac{F_4^D + L_2^D + L_3^D}{F_4^D}\right))$$

Where $\mathrm{E}_{\Delta A}$ is the change in GHG emissions (kg CO_2e/kg) from changes in food loss with cold chain introduction.

The E_A values 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.[16] These values include any environmental burdens prior to food leaving its place of agricultural production. The comparison calculated in Eqn. 8 is bounded to examine losses and food in the postharvest FSC. As such, it excludes agricultural losses L_1^B.

Eqn. 9

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

E_D is the per-unit difference between the cold chain emissions added in the developed case and the difference in loss emissions avoided between these cases.

Whether the cold chain adds a greater total quantity of emissions than it saves through loss rate changes is determined by multiplying E_D for each food type by the quantity of food supplied in (F_4) and summing these emissions differences. The median differences are reported as a percentage of the baseline emissions by dividing these medians by the median baseline emissions (for SSA).

Changes in emissions are also examined when incorporating the indirect effects of the cold chain. This is done changing by L_1 from its baseline values to median estimated developed scenario values, changing E_A from its baseline values to median developed values to model changes in agricultural emissions, and changing F_5 from its baseline to median developed scenario values for demand shifts. Food supplied to retail is normalized to one representative kilogram, where each fraction corresponds to the fraction of each food type in the diet examined. Food supply emissions are calculated in Equation 10:

Eqn. 10

$$E_P = E_A\left(\frac{F_2 + L_1}{\sum_{T=1}^{7} F_{4_T}}\right) + E_C\left(\frac{F_4 + L_2 + L_3}{\sum_{T=1}^{7} F_{4_T}}\right)$$

where E_P provides emissions normalized to ~~a functional unit of~~ 1 kg of representative food delivered to retail (kg CO_2e/representative kg) for each food type T. Respective differences between the developed scenarios and baseline are reported by taking the percentage difference between the median E_P values for the developed scenarios and the baseline (SSA).

Results

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. The SSA postharvest handling and storage (R_2, see Methods), processing and packaging (R_3), and cold chain emissions (E_C) parameters are changed to their North American and European values, holding all other model parameters constant. The loss rates for agricultural production (R_1) remains unchanged, as agricultural losses are not directly influenced by the presence of the cold chain. This calculation evaluates a scenario where refrigeration is introduced into the postharvest FSC, creating emissions and reducing spoilage, but all other aspects of the system including agricultural production and consumption patterns are unchanged. The emissions trade-off can be calculated from the difference between added cold chain emissions and avoided food loss emissions (Figures 2 and 3).

In total, the cold chain is found to add more emissions than it saves through avoided food losses. Adding 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 losses 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.

Comparison of Added Cold Chain Emissions and Avoided Food Loss Emissions

Sub-Saharan Africa —> North America

	Cereals	Roots and Tubers	Fruits	Vegetables	Meat	Fish and Seafood	Milk
Added Cold Chain Emissions	▲ 0.007	▲ 0.212	▲ 0.372	▲ 0.436	▲ 1.103	▲ 1.654	▲ 0.205
Avoided Food Loss Emissions	▲ 0.037	▼ 0.040	▼ 0.156	▼ 0.557	▲ 0.030	▼ 0.645	▼ 0.323
Difference	▲ 0.044	▲ 0.172	▲ 0.216	▼ 0.121	▲ 1.133	▲ 1.009	▼ 0.118

Sub-Saharan Africa —> Europe

	Cereals	Roots and Tubers	Fruits	Vegetables	Meat	Fish and Seafood	Milk
Added Cold Chain Emissions	▲ 0.150	▲ 0.028	▲ 0.037	▲ 0.137	▲ 0.231	▲ 2.055	▲ 0.132
Avoided Food Loss Emissions	▲ 0.045	▼ 0.043	▼ 0.154	▼ 0.551	▲ 0.014	▼ 0.645	▼ 0.323
Difference	▲ 0.195	▼ 0.015	▼ 0.117	▼ 0.414	▲ 0.245	▲ 1.410	▼ 0.191

▲ Emissions Increase (kg CO_2e/kg)
▼ Emissions Decrease (kg CO_2e/kg)

Figure 2: Comparison of median emissions added from the cold chain introduction and emissions associated with avoided food loss. The calculated values pertain to emissions occurring during the post-harvest and pre-retail supply chain (i.e. L_1, L_2, and L_3 in Figure 1). The calculated difference indicates the direct tradeoff between introduced cold chain emissions and avoided food loss 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 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 greatest loss emissions savings are for 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.[32]

Emissions increases are observed from higher loss rates for cereals and meat in both scenarios. For cereals, losses increase 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.[15] 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 Supporting Information 3). The cause for an increased postharvest meat loss rate in North America is not discussed by Gustavsson et al.,[15] 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[33] 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.[7]

The distribution of differences between added cold chain emissions and avoided loss emissions by food type and in total emissions from Monte Carlo model runs are displayed in Figure 3. With the exceptions of meat and fish/seafood, the median difference between these values is close to zero with small interquartile ranges. Meat and fish/seafood both show larger emissions increases, and also possesslarger variances. The histograms in Figure 3c and 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.

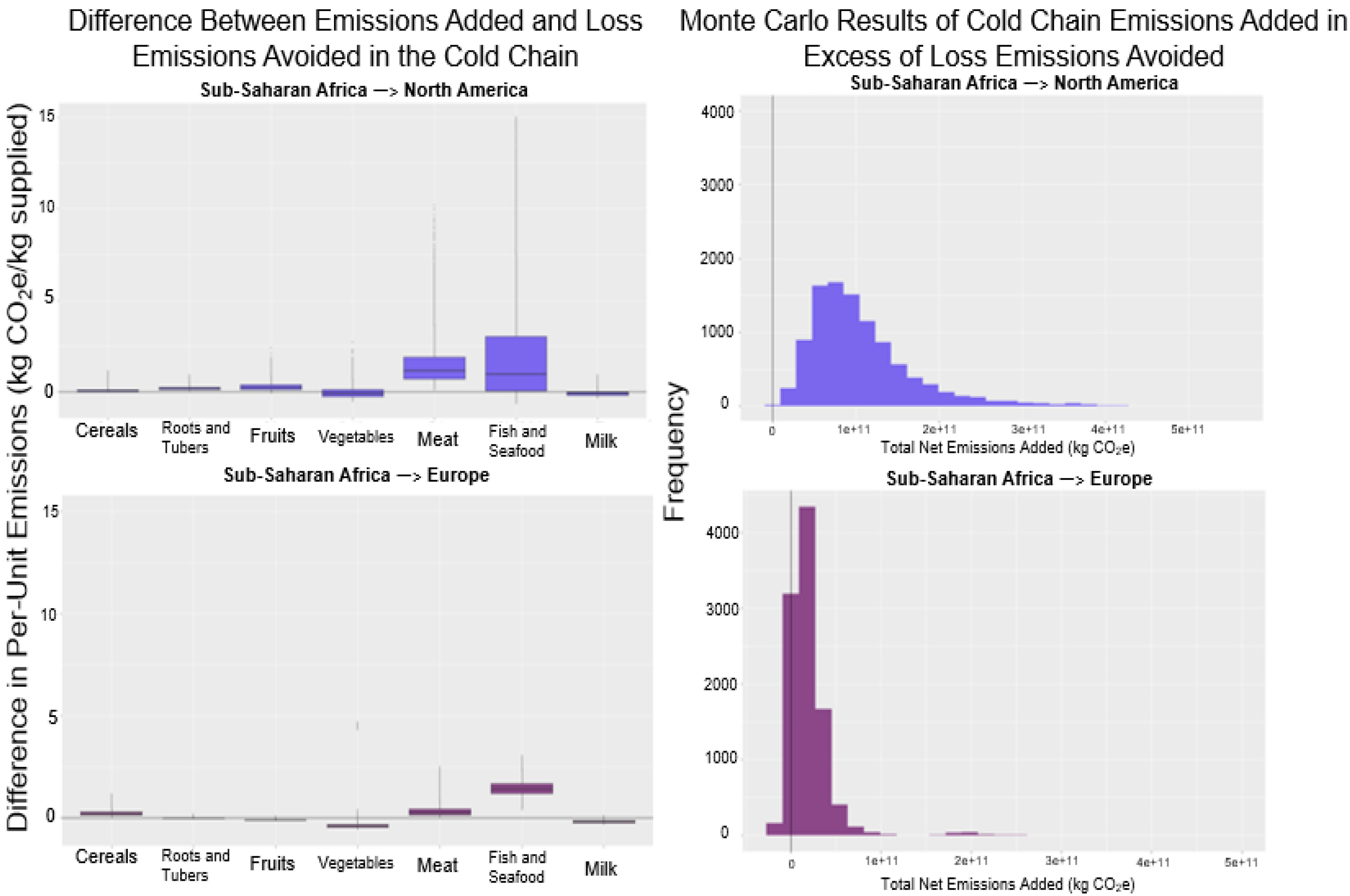


Figure 3: Boxplots and histograms of the difference between added cold chain emissions and avoided loss emissions in the postharvest cold chain for both introduction scenarios. Boxplot results are shown by kg of food delivered to retail, with boxes showing the range of values between the 25th and 75th 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. Histograms show the distributions of total net emissions calculated with each model run, based on a weighted average of food types.

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 an expanded scope, incorporating changes to agricultural production and demand.

Refrigeration enables structural changes in food production systems. For example, cold storage allows agriculture system industrialization, since farms can supply a greater quantity of perishable crops due to lower spoilage rates.[34] The indirect effect of cold chain introduction on agricultural emissions is modeled by changing the parameters for agricultural emissions (E_A) 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 2 and 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,[7] and has been linked with shifts in diet as nations develop.[3,35] The effects of demand changes reflecting a North American or European diet facilated 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 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.

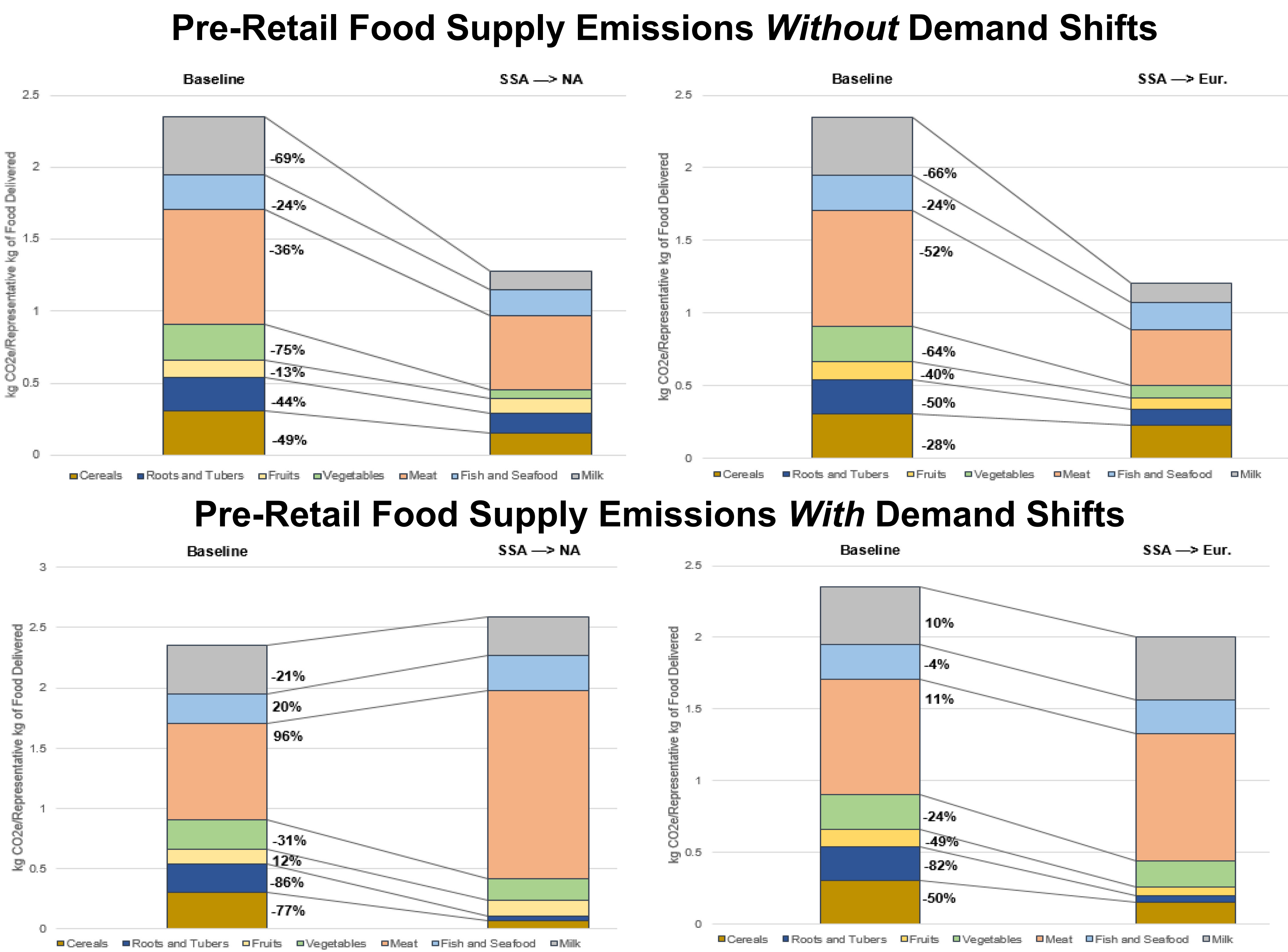


Figure 4: Changes in upstream food supply emissions (kg CO_2e) required to deliver one kg of food, based on a weighted average of each food type within a typical diet (so the composition of the kilogram corresponds to the relative amount of each food type in the diet). Percentage differences in emissions (kg CO_2e/Representative kg of food 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.[14]

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.[36]

The agricultural production loss rate for roots and tubers increases in both development scenarios due to increased grading standards for produced food (see Supporting Information 3.[15] 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.[37,38] However, since fruit and vegetable exposure to refrigeration is typical in their developed supply chains,[39] 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.[40] 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,[41] 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.[42] Increased availability of refrigeration has been connected to increased consumption of perishable food items,[3] which may also improve nutritional outcomes.[43] Pradhan et al. 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.[42] 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.

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.[44] 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.,[45] 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 Supporting Information 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.

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 tradeoffs of the technology in order to identify potential areas for improvement as the cold chain continues to expand globally.

As shown in Figure 3, we find that the emissions from additional energy consumption and refrigerant emissions of cold chain operations 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.[4] 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.[46] 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.[47]

The Kigali Amendment to the Montreal Protocol will have African nations freeze the use of hydrofluorocarbon (HFC) refrigerants in 2024.[48] These refrigerants carry high global warming potential values,[49] with HFC leakage from stationary refrigeration estimated to release 1740,000 tonnes of CO_2e in 2005,[50] and use in the mobile portion of the cold chain comprising 7% of global HFC consumption.[19] 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,[51] 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 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.[52] 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.,[16] 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.[21] 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.[53] Increased emissions from dietary shifts are not a pre-ordained conclusion. 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.[54]

The influence of behavioral choices and diet on food system emissions has been noted in the literature.[46,47] 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.[35] 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 highly limited and uncertain,[21,55,56] presenting distinct challenges in creating informed models. There is similarly-limited data on the cold chain, particularly in the developing world.[30] 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),[57] 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[58] to the efficiency and emissions of cold chain operation.[26]

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.[59] The deployment of renewable and alternative energy technologies such de-centralized solar power in areas of Africa[60,61] 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.[47]

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.

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Supporting Information

Five further-detailed descriptions of methods, nine tables of model parameters, one figure displaying results of sensitivity analysis, and one figure displaying detailed results from modeling the nationally recommended diet scenario.

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