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

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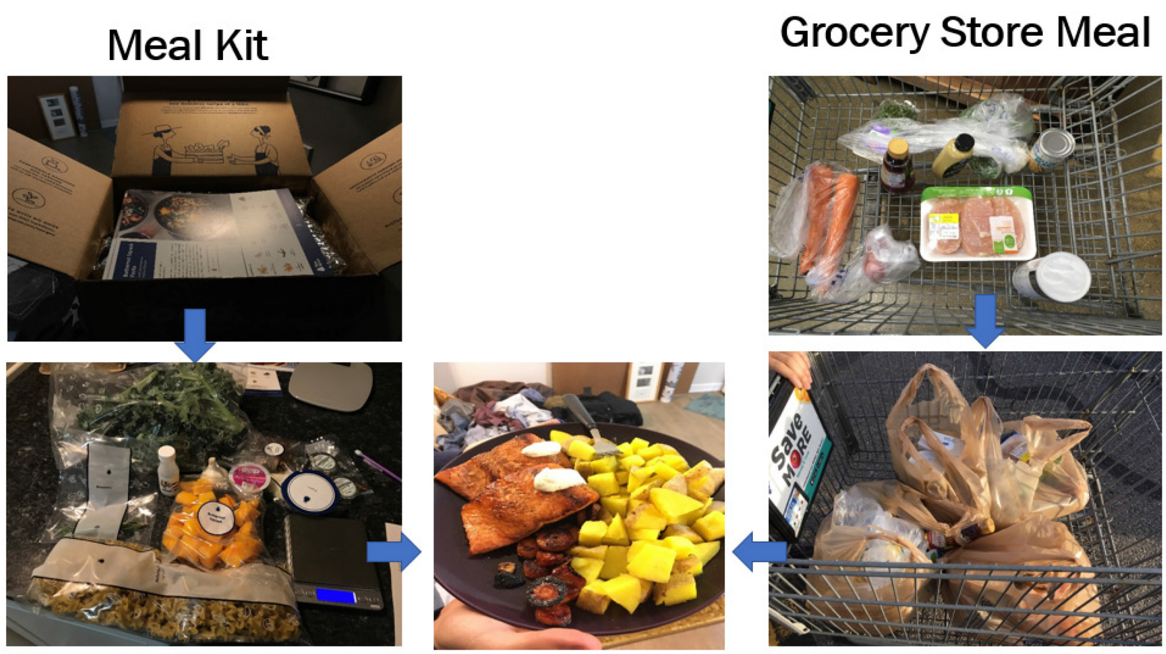
Abstract

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.

Highlights

- Meal kits are an emerging food product with understudied environmental impacts
- Meal kits have lower average greenhouse gas emissions than grocery store meals
- Grocery meals are not pre-portioned, resulting in higher food loss and waste
- Meal kits typically have higher packaging impacts than grocery meals
- Grocery store meals have higher last-mile transportation emissions than meal kits

Graphical Abstract



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).

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.

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 are tested, they are representative of the product and supply chain 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 Supporting Information 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 Supporting Information 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 1.

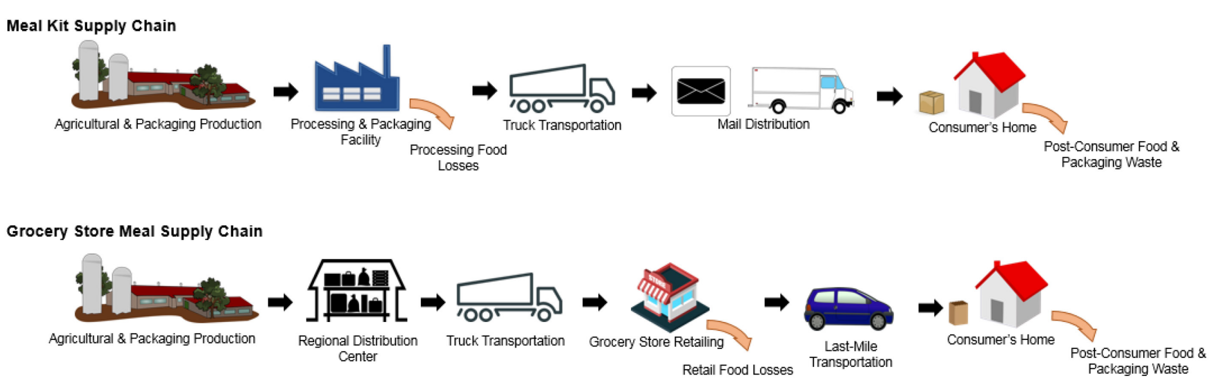


Figure 1: Visual depiction of the meal kit and grocery meal supply chains examined.

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 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. 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. 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. 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:

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

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. 4

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

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. 5

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

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

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

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 Supporting Information 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. 7

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

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. 8

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

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. 9

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

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 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

		Retail fish and seafood losses: 8% Consumer fish and seafood waste: 31% Retail eggs losses: 7% Consumer eggs waste: 21%		select spices and common non-perishables, see Supporting Information 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 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 Supporting Information 5.

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 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.

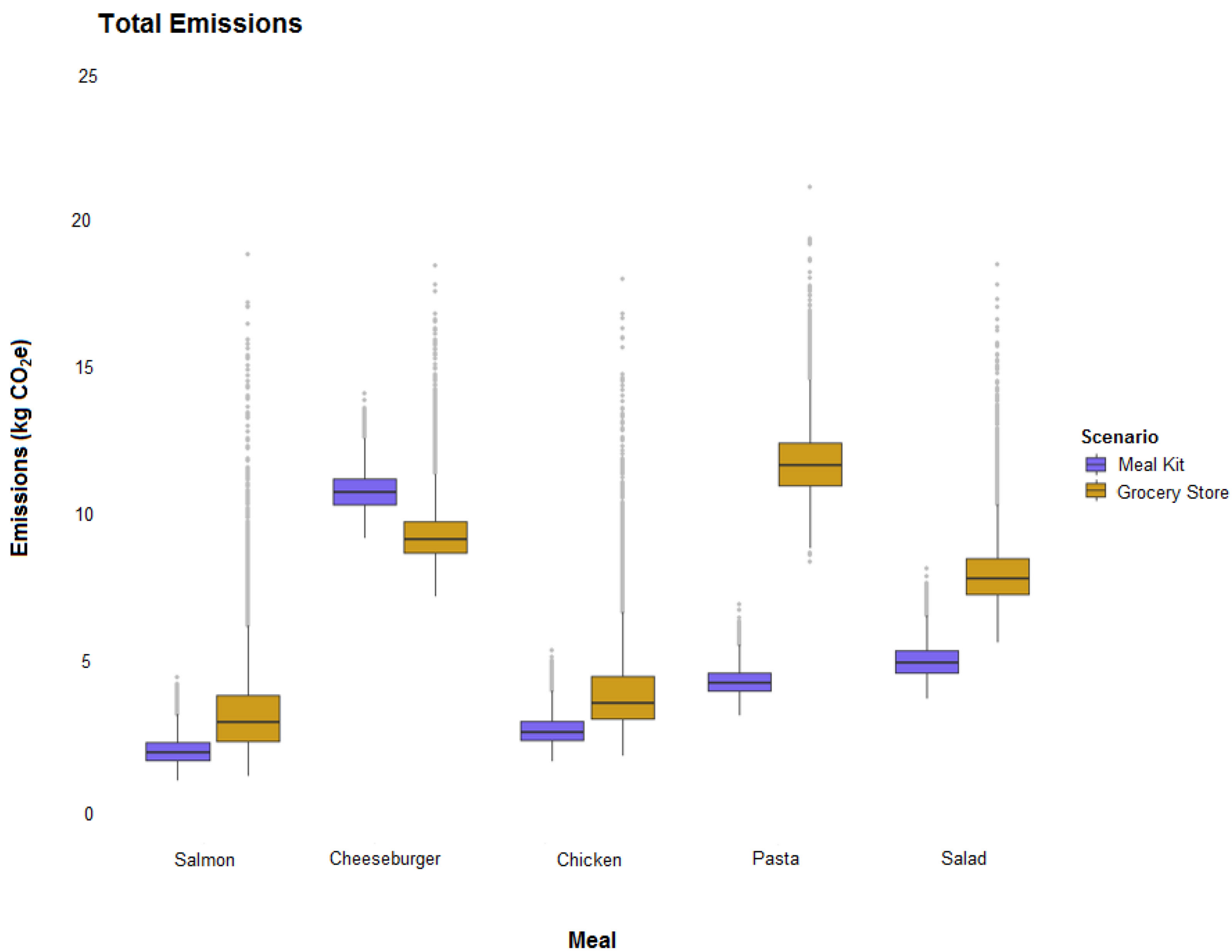
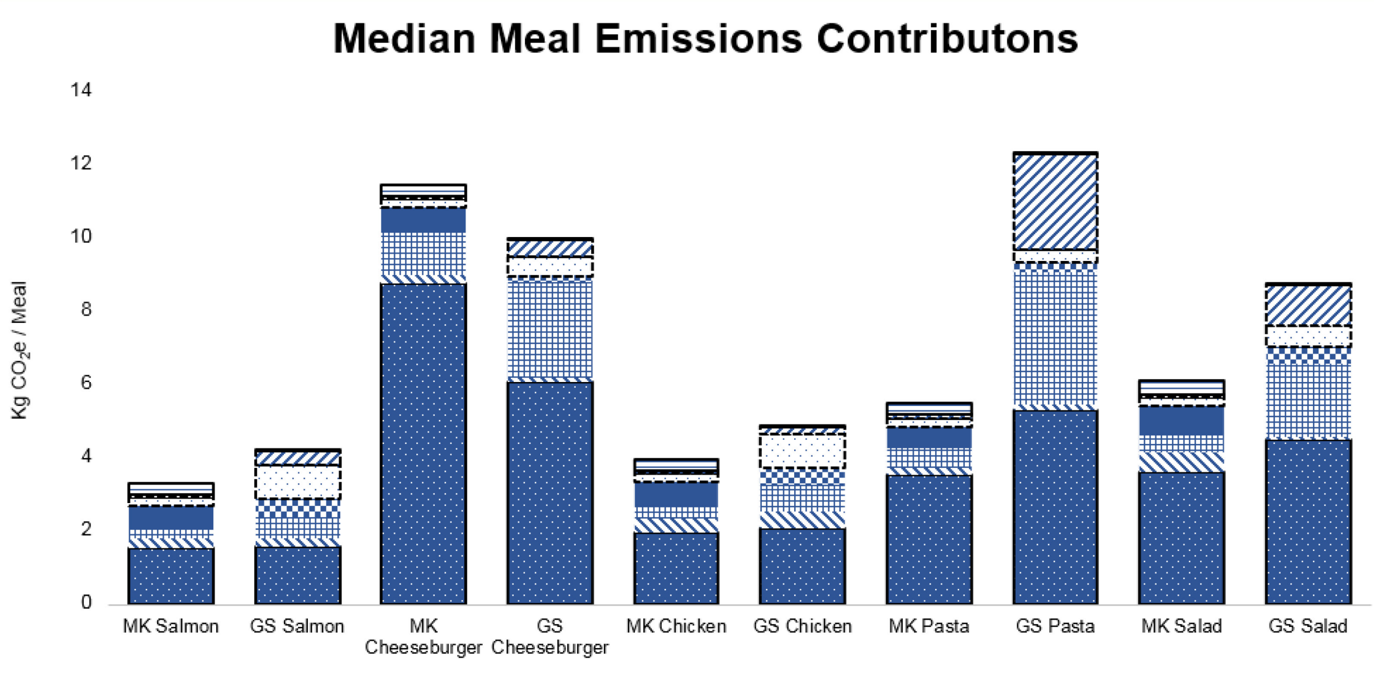


Figure 2: Total estimated emissions (kg CO_2e) for the five meals studied supplied as a meal kit or via a grocery store. Black lines indicate median emissions for each meal by type, and boxes indicate emissions within the 25th and 75th percentiles of model runs. Grey dots indicate values falling outside 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)



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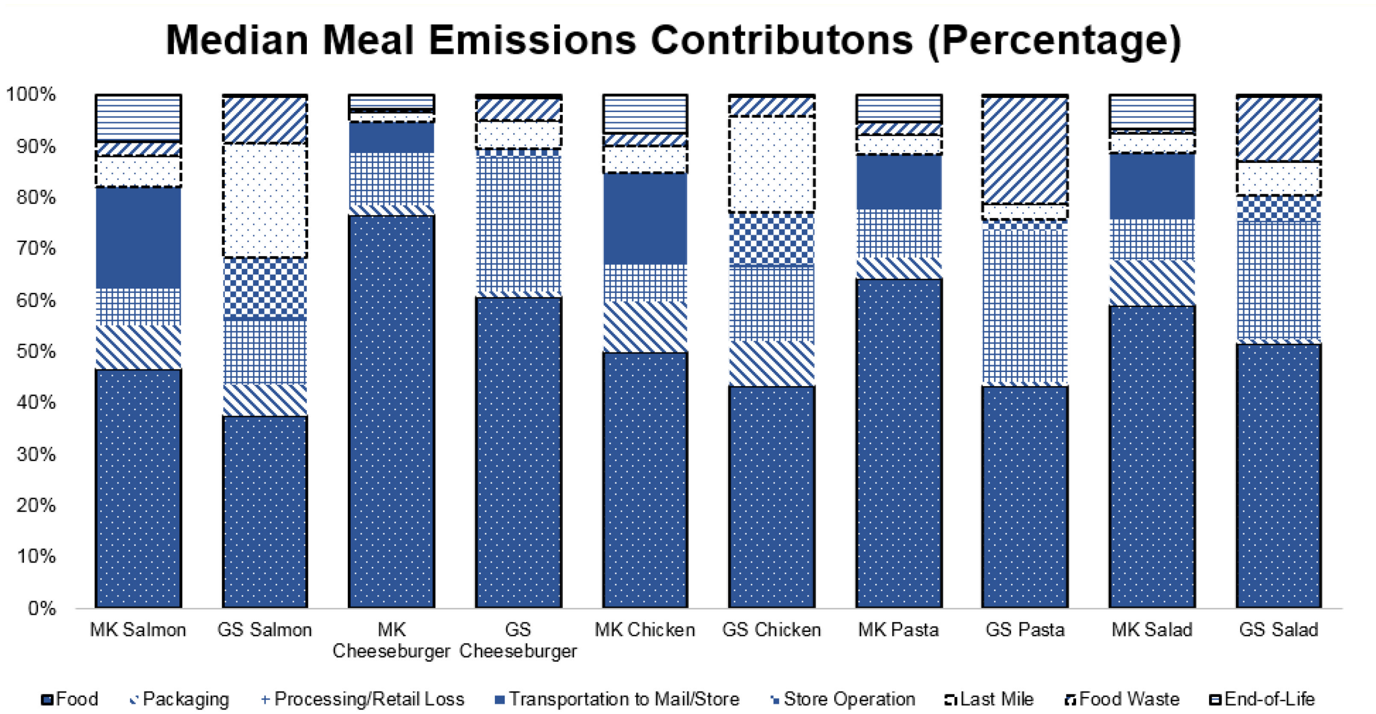

Figure 3: Median emissions (kg CO_2e) for each contributing element to meal emissions by meal type. MK indicates meal kit and GS indicates grocery store meals. Solid lines surround portions of the supply chain more-directly within a consumers' control. Emissions and contributions are displayed in absolute 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 Supporting Information 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 Supporting Information 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 Supporting Information 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 3 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 3 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.

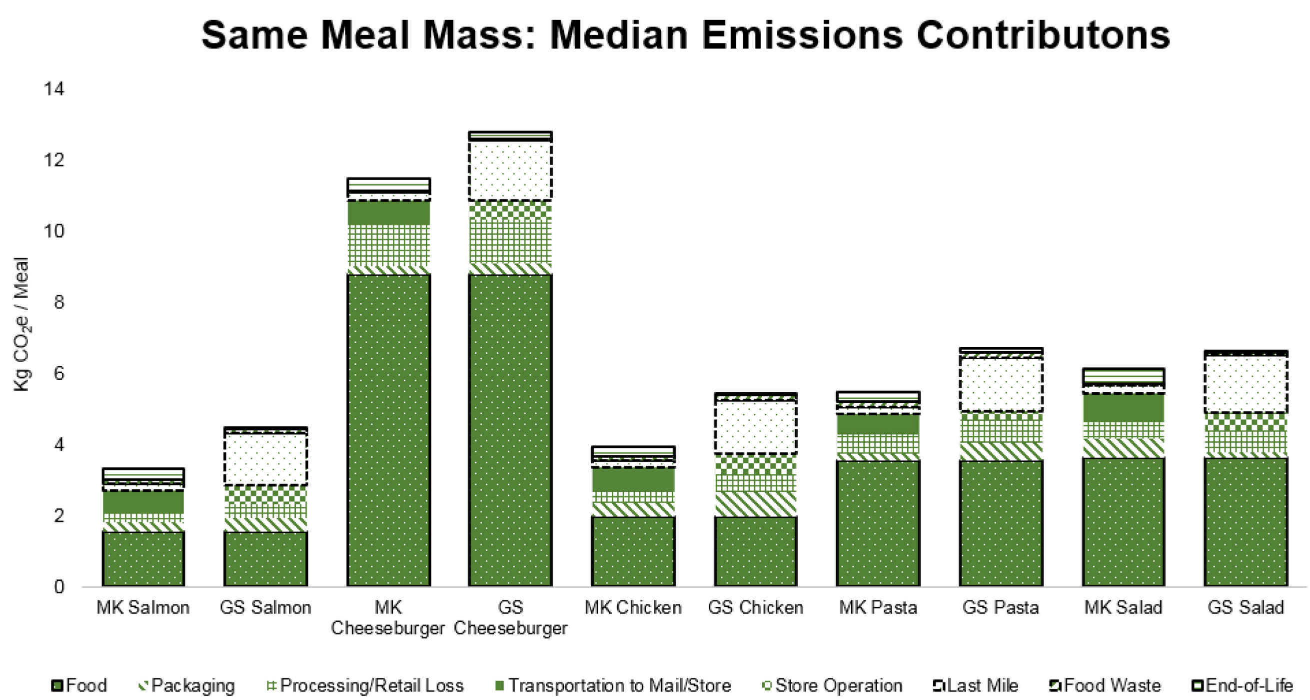

Figure 4: Median emissions (kg CO_2e) for contributing elements to meal emissions by meal type if grocery meal ingredients have identical mass to meal kit ingredients. MK indicates meal kit and GS indicates grocery store meals. Solid lines surround portions of the supply chain more-directly within a 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.

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.

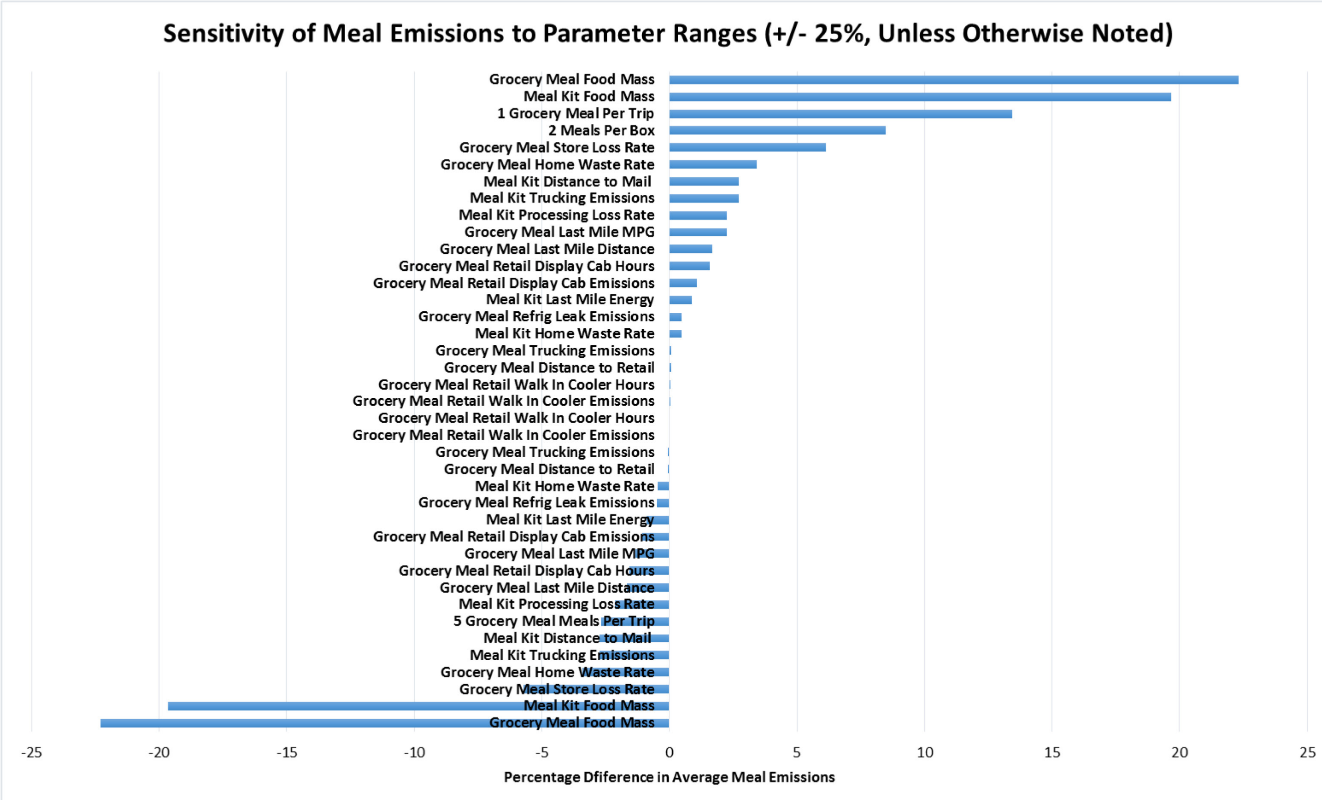

Figure 5: Percentage difference between emissions (kg CO_2e) for an average meal kit or grocery store meal calculated when each parameter of interest is fixed to 25% greater or less than its median value (or as otherwise noted) and other parameters held at their median values.

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).

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.

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References

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. in press, 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