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Life Cycle Assessment of Food Packaging and Waste

Phase 2: Case Study Results

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Contents

1. Summary

Food packaging has long served a role in protecting and preserving both perishable and shelf-stable foods, but sustainability efforts aimed at reducing the environmental impact of packaging typically do not address this critical role directly. There is growing concern, from both an environmental and social perspective, with wasted food, and this wasted food often represents a significant contribution to the overall environmental footprint of food products. This project uses life cycle assessment of complete food product chains to explore the environmental trade-offs between food packaging and food waste. Through case studies, we identify examples where increased or improved packaging configurations result in lower retail-level food waste and reduced full-system environmental impacts.

Building on a thorough review of the literature presented in our Phase 1 report, and augmented in this Phase 2 report, we developed a life cycle model capable of evaluating the cradle-to-grave impacts of particular foods. The scope of the life cycle model includes agricultural production, processing, packaging, transport to retail, retail energy use, transport to home, and home refrigeration. It also accounts for food and packaging waste and disposal at retail and consumer levels. The model was used to investigate three cases: beef, romaine lettuce, and ground turkey. Multiple packaging configurations are compared in each case. Retail-level waste rates were gathered from a retail partner. Global warming potential (greenhouse gas emissions) and cumulative energy use are the focal environmental impact categories, although blue water use is also evaluated in one case.

Results vary across the cases examined. We present three scenarios (beef case 1a, 1c & turkey case 3) where the use of optimized packaging correlates with lower retail-level food waste rates. Two of the three offer situations where, when a packaging change leads to reduced food waste, the reduction in GHGE due to lower waste is sufficient to offset the increase in emissions due to changes in packaging, but this type of "break-even" point is NOT reached with respect to cumulative energy demand. Other presented scenarios, namely beef 1b and lettuce (case 2), demonstrate that more advanced packaging options do not always lead to lower waste rates, although it could be argued that these cases compare products with different qualities to the consumer.

2. Introduction

While the modern food industry has concerned itself with maintaining food safety and quality, the moral imperative of feeding a rapidly growing population, combined with a maturing recognition of the bio-physical planetary limits within which this food must be supplied, has brought acute focus to the problem of food waste. In response, on September 16, 2015, USDA and EPA announced the first ever national food waste reduction goal, calling for a 50% reduction by 2030 (USDA 2015). Food packaging has long served a role in protecting and preserving both perishable and shelf-stable foods, but sustainability efforts aimed at reducing the environmental impact of packaging often overlook this critical role. Life cycle assessment (LCA) of food products typically indicate that the contribution to important environmental indicators from the manufacturing and disposing of packaging materials is often overshadowed by the impacts of producing the food itself. In addition, wasted food – that which is produced but not eaten – can represent a significant fraction of the overall system environmental burden. This presents an important research question: can investments in resources and associated emissions due to increased or improved packaging technologies be justified from an environmental standpoint if they contribute to reductions in food waste? Where do the trade-offs in this relationship occur, and what are the determining parameters? Can such trade-offs be demonstrated with existing food-packaging systems, and what do they teach us about the future role of packaging in further deterring food waste?

These are the questions underlying this research project titled "Life Cycle Assessment of Food Packaging and Waste." In the preceding Phase 1 report, we set the stage for the project with a literature review and an outlining of methodological approaches. In this Phase 2 report, we detail the methods, data and results of three case studies (beef, romaine lettuce, and ground turkey) and draw conclusions on the lessons learned in this project.

3. Additions to Literature Review

Our Phase 1 report provided an academic foundation for the project by highlighting LCA efforts to quantify the environmental impacts of food production, detailing the case for concern with food waste, examining LCA studies of packaging materials as well as emerging sustainability efforts in food packaging, and summarizing the knowledge to date of the environmental trade-off between food waste and food packaging. The remainder of this section introduces relevant literature that has either been published or discovered by our research team since publishing our Phase 1 report (April 8, 2015).

Food waste

A recent meta-analysis of waste characterization studies offers a new estimate of food waste disposal (i.e., through MSW channels) in the U.S. (Thyberg et al. 2015). They found that the proportion of food waste in MSW has increased with statistical significance from 1995 to 2013, and is significantly higher in the West region than in the East or Central region. The mean proportion of food waste in MSW was 14.7%, with a per-capita rate of 0.615 lbs/capita/day (102 kg/capita/year), compared to the USEPA reported values of 17.6% and 0.548 lbs/capita/day (90.7 kg/capita/year), respectively.

A study calculating the total and avoidable food waste of European Union consumers found that food waste averages 123 kg/capita/year, or 16% of all food reaching consumers; 97 kg/capita/year (12% of food reaching consumers) is avoidable food waste (Vanham et al. 2015). The study also estimated the water and nitrogen resources associated with avoidable food waste.

A study based on interviews with food production, wholesaling and retailing managers in the UK and Spain explores the root causes of food waste at the supplier-retailer interface (Mena et al. 2011). The paper presents interesting "causal maps" that trace cause-effect logic to root causes, and classifies these causes into three groups: *mega-trends* such as increasing demand for fresh products, products out of season, and a move away from products with preservatives; *natural constraints* such as short shelf life of fresh products, seasonality of supply and demand, weather fluctuations, and longer lead-times for imported products; and *management root causes* of which many examples are identified.

A working paper from the Institute for International Political Economy Berlin (Adam 2015) examines (in an EU context) the influence of retailers on food date labels and quality standards, both of which can drive food waste across the food supply chain. The argument in the paper is that while consumers are the single largest driver of food waste, food retailers carry power and influence over a number of factors that can have large effect on food waste.

Packaging technologies

A recent review details the influence of modified atmosphere packaging and active/smart packaging on microbial growth and quality characteristics of red meat and poultry (Arvanitoyannis and Stratakos 2012). Responsive food packaging is the subject of another review (Brockgreitens and Abbas 2016). "Responsive packaging" is defined in the review as "any package that elicits a curative or informative response as a result of a specific trigger or change occurring in the food product, food package headspace, or the outside environment." This triggering is an important differentiation from active packaging (such as systems that release antimicrobials or antifungal compounds into food during storage) as active packaging will operate whether or not a change is present in the food. The review discusses recent advances in bio-responsive and stimuli-responsive materials and anticipates steady growth of responsive packaging in the food industry, impacting spoilage, food waste, food recalls, and foodborne illness outbreaks.

Consumer food waste and consumer behavior

Consumer-level food waste represents a dominant portion of the waste across the food system, but is also poorly understood due to the challenges of tracking, monitoring or otherwise recording consumer behaviors. This remains an area of great scholarly interest. Much of what we know today about consumer food waste stems from the work of William Rathje and the Garbage Project of the University of Arizona (see, e.g., (Harrison et al. 1975)). An anthropologist, Rathje turned the science of his trade to studying the garbage of modern society and learned that previous interview-based estimates of food waste were unreliable. The Garbage Project team established a baseline understanding of the percentage of different food items that were disposed of through MSW.

Current work often focuses on understanding the drivers of consumer food waste in order to better target reduction strategies. A recently published study from the Center for a Livable Future at Johns Hopkins University (Neff et al. 2015) represents the first nationally representative US-based study of consumers' awareness, attitudes and behaviors toward wasted food. The study found that three-quarters of respondents perceive that they discard less food than the average American, and that the leading motivations for reducing food waste were saving money and setting an example for children, with environmental concerns ranked last. A literature review of consumer-related food waste studies (Aschemann-Witzel et al. 2015a; Aschemann-Witzel et al. 2015b) concludes that psychographic factors play a much greater role in explaining food waste than do socio-demographic factors. These psychographic factors include: consumers' motivation to avoid food waste; factors related to awareness, knowledge and capabilities that determine how and to what extent consumers can manage food provisioning and handling; and how consumers handle trade-offs and priorities in the presence of conflicting goals. Studies published this year further explore these consumer food waste behaviors and their determinants in Denmark (Stancu et al. 2016) and across EU-27 countries (Secondi et al. 2015).

Another focal point relating to food waste and consumer (as well as retail) behaviors is the application and perceptions of date labeling of food, summarized in a very informative recent review (Newsome et al. 2014). It is well known through surveys and other means (e.g., (Kosa et al. 2007)) that there is substantial misunderstanding by industry and consumers regarding the meanings and proper applications of date labeling terms; this leads to significant unnecessary food loss and waste, misapplication of limited resources, unnecessary financial burden, and potential food safety risk. Newsome, et al. issue a "call to action" to move toward uniformity in date labeling, a focus of regulatory efforts on labeling concerns that carry health and safety risks rather than those of food quality, increased consumer education (supported by uniformity in date labeling), and further research and investment in indicator technologies that could help inform stakeholders when food products no longer meet quality or safety-related criteria.

<u>Food packaging/ food waste trade-off</u>

In a new book on the *Environmental Footprints of Packaging*, a chapter dedicated to life cycle assessment of food-packaging systems (Vignali 2016) conducts a literature review of the space and acknowledges the evolution within the topic toward consideration of the amount of food waste generated. Without offering greater detail, the review acknowledges that the avoided impacts of reduced food waste can be considerably greater than the implementation of new packaging technologies (such as, e.g., MAP or active packaging).

Recent articles further demonstrate this evolution. Zhang et al. (Zhang et al. 2015) demonstrate the food waste/packaging trade-off through a case study of fresh beef in active MAP packaging containing thymol/carvacrol essential oils as an antimicrobial. The paper acknowledges that it is "preliminary LCA modeling" as the active MAP in question is still in development. Further, it isn't completely clear in reading the methods description where the "food loss savings" data for the active packaging originates: they appear to be hypothetical scenarios rather than empirical waste rates. Still, the authors demonstrate that the small reductions in food waste compensate for the additional impacts of the "active packaging" technology, resulting in reduced net impacts, including global warming, fossil energy demand, acidification potential and eutrophication potential.

Another very recent paper highlights the indirect effects of food loss on the environmental performance of a food/packaging system by simulating a case of cheese in various packaging systems (Conte et al. 2015). Here, the authors propose three different empirical equations – first order kinetic, a sigmoid and a straight line – to relate shelf life to food loss probability, fitting kinetic constants with only one (questionable) data point (plus the obvious point that food loss probability goes to unity when shelf life = 0). Using these proposed relations, production data for sheep's milk cheese, and shelf life data in four packaging films and a variety of headspace conditions, an LCA was conducted. Only normalized, weighted eco-indicator scores using CML2001 impact assessment method were reported. The authors conclude that without considering the indirect effects of food losses, LCA shows that the thinner, recyclable packaging materials are more sustainable. However, when food loss is accounted, the packaging able to guarantee a longer shelf life becomes more sustainable.

A more thorough and complete demonstration of the food packaging/waste balance has been recently reported by the Austrian environmental consulting firm, Denkstatt (Denkstatt GmbH 2014). An online slide presentation summarizes six case studies developed in partnership with retailers, packaging producers, polymer producers, industry organizations and research institutes. The cases show reduced retail-level food waste due to changes in packaging for: sirloin steak, "Bergbaron" cheese, plaited yeast bun, garden cress, and cucumber. In all cases except the cucumber, the studies show reduced overall greenhouse gas emissions. An additional example focuses on consumer-level food waste with chicken meat, but relies on an assumed food waste reduction.

4. LCA Model Overview

At the core of this research project was development of a life cycle assessment model capable of evaluating the full life cycle of a food product, with particular focus on food waste and food packaging elements. This section details the development of that model, providing modeling approaches and data sources for the main life cycle stages.

4.1. Goal and Scope

4.1.1. The goals of the LCA study were to explore the trade-off in environmental impact between food waste and food packaging, and to demonstrate the role of packaging in controlling food waste. The results will be used to build awareness both within the food packaging industry as well as with the general public. The findings of the study will be communicated externally via peer-reviewed literature and professional conferences. Benefits are anticipated to be used for marketing purposes to promote light-weight packaging as a preventer of food waste and a sustainable solution.

4.1.2. Scope

4.1.2.1. Product system and function

The products to be studied in this project will be the combined food and packaging unit responsible for delivering safe and fresh food for consumption. While numerous products will be studied, the "function" of all is providing safe, nutritious sustenance to the end consumer. Thus, the system under investigation includes not only the life cycle of the food but also the particular packaging configuration utilized, with special attention to its role in effecting food waste.

4.1.2.2. Functional unit

The functional unit forms the comparative basis of LCA studies and the denominator of presented results, and therefore can influence conclusions drawn from study results. Given the focus on food waste in this project, the functional unit should reflect food actually *consumed*, therefore accounting for waste at all stages. Throughout this study a functional unit of 1 kg of food *consumed* is maintained. Note that, similar to most food LCAs, this mass-based functional unit does not capture a "performance" measurement of the food system. Quantifying the function or performance of foods is a perennial challenge in food LCAs (see (Heller et al. 2013)); assuming there are not significant nutritional differences arising between packaging configurations, a mass-based functional unit presents little problem in making comparisons between scenarios of the same food. Given nutritional differences between foods, however, caution must be exercised in comparing LCA results of different foods.

4.2. System boundaries

A generic system diagram below outlines the stages and processes to be considered in this study.

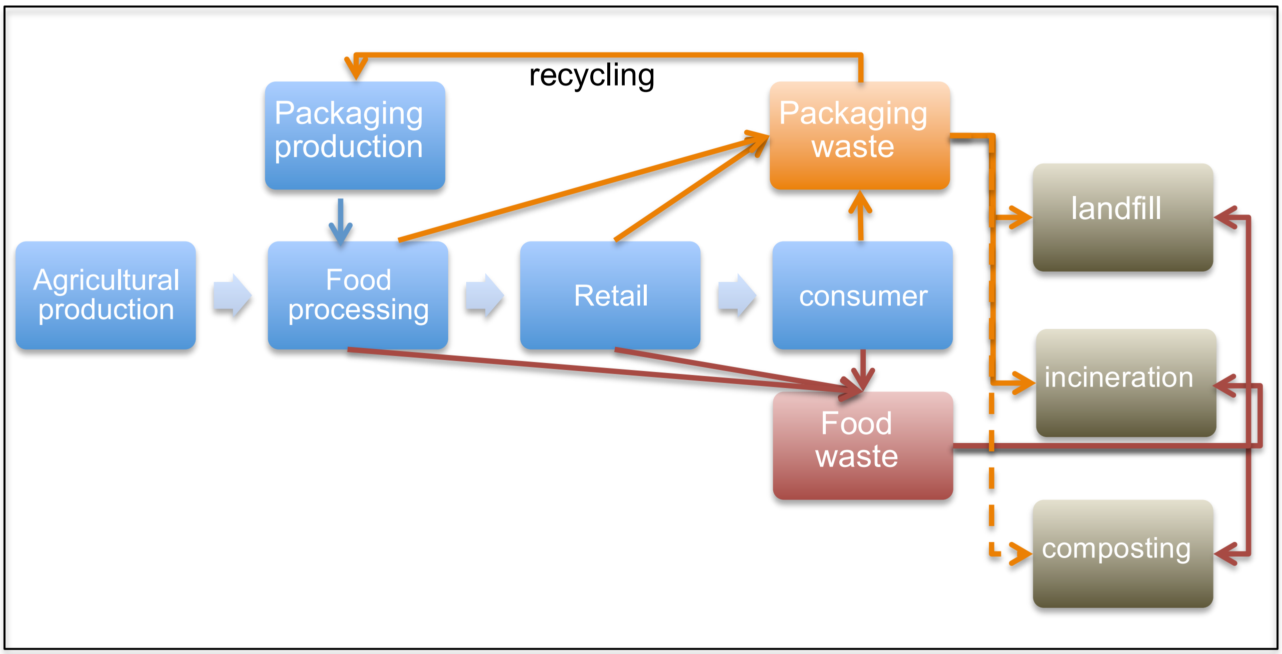

Figure 1. System diagram indicating the life cycle stages to be included in this study. Thick blue arrows represent stages where transport is included

All stages of the food life cycle will be considered. Assessment of agricultural production and food processing will come from existing LCA studies of the food in question; i.e., we will not be collecting primary data for these stages. Given the intended focus of the project, food losses/waste at the agricultural production stage will not be explicitly considered. The study will instead focus on food loss/waste during retail and consumption stages. As shown in Figure 1, the environmental impacts from final disposal of food waste will be considered. Similarly, the impacts of recycling and/or disposing of packaging waste will also be included. Transportation will be accounted for between major stages, although generalized assumptions have been made to reasonably represent U.S. National average transportation distances.

4.3. Impact Categories

The study focuses on global climate change (greenhouse gas emissions) and cumulative energy demand. Inclusion of other impact categories is limited by the availability of food production and processing data, and the fact that the EPA WARM model, used for end-of-life disposal, only includes energy and GHGE. For the purposes of further demonstrating the potential trade-off between food waste and food packaging impacts, we have included water use as an additional impact category for the romaine lettuce case study.

4.4. Life cycle inventory and data sources

In this section, we describe generic modeling and inventory approaches, as well as data sources that are common among case studies. Parameters and data sources unique to individual cases are detailed in their respective sections. "Default" allocation was chosen throughout for datasets drawn from Ecoinvent 3.

Packaging production: Inventory data for the production of packaging materials as well as the transformation of materials into packaging forms were taken from the Ecoinvent 3 database. Specific processes and the dataset origin are shown in Table 1. Note that transport of packaging materials is not included in our assessment.

Table 1. Data sources for packaging material production and transformation

process	Dataset origin
General purpose polystyrene	USLCI
High density polyethylene resin	USLCI
Low density polyethylene resin	USLCI
Linear low density polyethylene resin	USLCI
Polypropylene resin	USLCI
Polyvinyl chloride resin	USLCI
Ethylvinylacetate foil (proxy for Ethylene vinyl alcohol)	Ecoinvent 3
Ethylene vinyl acetate copolymer	Ecoinvent 3
Polyvinylidenechloride, granulate	Ecoinvent 3
Recycled postconsumer PET flake	USLCI
Corrugated board box	Ecoinvent 3
Kraft paper, bleached (used for all other paper beyond corrugated)	Ecoinvent 3
Rough green lumber, softwood, at sawmill (used for palletwood)	USLCI
Blow moulding	Ecoinvent 3
Calendaring, rigid sheets	Ecoinvent 3
Extrusion, plastic film	Ecoinvent 3
Injection moulding	Ecoinvent 3
Polymer foaming	Ecoinvent 3
Thermoforming, with calendering	Ecoinvent 3

Gases used in Modified Atmosphere Packaging (MAP) were modeled using datasets for liquid oxygen and carbon dioxide, applying appropriate densities and expansion ratios. While liquefied gases are likely not the origin for MAP packaging, the impacts based on this modeling approach are negligible, and non-liquified gas sources are anticipated to have even smaller impacts.

Transport: processor to retail: Transportation from processing to retail distribution was modeled using a generic freight trucking process from Ecoinvent 3 which is based on a tonne-km unit. Since many fresh products require refrigerated trucking (and Ecoinvent does not offer a process for refrigerated shipping), the trucking process was modified to account for "reefer" operation by the following:

The majority of medium to large vehicles use self-contained refrigeration units that utilize a self-contained diesel engine. Various sources estimate the fuel consumption of these compressor engines to be 1-5 L per hour (Tassou et al. 2012) (Roibás et al. 2014); we chose a value of 2 L per hour diesel consumption. Assuming an average operating truck speed of 56.3 miles per hour (Statista 2015) and 6 hours of idling per day (Gaines et al. 2006), or 6 hours every 1013 miles, we estimate a diesel consumption of 0.0295 L per km. In addition, a refrigerant leakage of 0.0052 g R134a/km (Roibás et al. 2014) was also assumed.

Transport distance from unspecified processors to retail outlets across the country is extremely difficult to determine accurately. Where no additional information was available, transport distance was based on "average miles per shipment" in Table 24: "Shipment Characteristics of Temperature Controlled Shipments by Three-Digit Commodity for the United States: 2012" in the 2012 Commodity Flow Survey (U.S. Department of Transportation 2015).

Retail Energy Use: Energy use (and associated emissions) at retail are divided into two pieces: refrigeration, and all other energy uses, including space heating and cooling, ventilation, water heating, lighting, cooking, and office equipment and computers. Non-refrigeration energy use (considered overhead in this analysis) is taken from the 2003 U.S. EIA Commercial Buildings Energy Consumption Survey (U.S. Energy Information Administration 2006) (note that while release of the 2012 Survey has begun, the necessary tables are not yet available). Table E1A from the 2003 Survey provides major fuel consumption for all buildings by end use (heating, cooling, lighting, etc) for different sectors: we utilize data from the "food sales" sector. This energy use is then allocated to product categories on an economic basis: total annual national sales at retail for the food in question (e.g., beef) is divided by total supermarket sales ($475,317 million in 2013 according to Progressive Grocer's Annual Consumer Expenditures Study (Progressive Grocer 2014)). This ratio is multiplied into the energy use numbers and then divided by total annual kg of food commodity sold at retail to arrive at an energy use per kg. It was assumed that space heating, water heating and cooking utilize natural gas, whereas all other end uses utilize electricity (U.S. national grid average).

While refrigeration energy is available through the above source, it is desirable to consider refrigeration as an operating "cost" and allocate it on a more physical (rather than economic) basis to individual food products. We estimate energy use for specific commercial refrigeration equipment via the U.S. Department of Energy equipment standards (U.S. Department of Energy 2014). This document provides maximum daily energy consumption (kWh/day) for various equipment categories, e.g.: for "vertical open equipment" with "remote condensing" operating at "medium temperature (38°F)", the standard energy level is given by

$$0.66 \times TDA + 3.05$$

where TDA = total display area of the case, in ft^2.
Appropriate equipment types and sizes are chosen for each food type, then the energy use per day is allocated to an individual product with the ratio of consumer facing area per kg for the product in question to TDA. This value is then averaged annually and nationally by multiplying by 365 and by total number of retail stores (37716 in 2014, according to (FMI 2014)) and divided by the kg of food commodity sold annually at retail.

Refrigerant leakages also contribute to global warming. EPA estimates annual U.S. supermarket refrigeration leakage to be 875 lbs/year, and assumes R-404A to be the typical commercial refrigerant used (U.S. EPA 2011). To estimate the refrigerant leakage per kWh refrigeration energy used, this value is divided by the total annual refrigeration energy for food sales (U.S. Energy Information Administration 2006). This leakage per kWh is then multiplied by the refrigeration energy consumption as calculated above to allocate a portion of the leakage to a given product.

<u>Transport: retail to home</u>: The 2009 National Household Transportation Survey (Santos et al. 2011) reports that the average vehicle trip length for shopping is 6.4 miles. We use this distance as a proxy for average grocery trips, and utilizing a process for "transport in passenger car with internal combustion engine" from Ecoinvent 3, allocate this transportation burden to the individual product in question on an economic basis (total annual sales of product in question / total annual supermarket sales).

<u>Home refrigeration</u>: the 2009 Residential Energy Consumption Survey (U.S. Energy Information Administration 2013) reports that the annual energy consumption per household by refrigerators is 1259.9 kWh, and the average refrigerator volume is 22 ft^3. The annual energy use is divided by 365 to provide a daily energy use, and allocated to the food product in question based on a volume fraction (volume per kg of food-package in question / 22 ft^3). A default of 4 days in home refrigeration is assumed.

<u>Food waste rates</u>: The rate of food wastage at retail and consumer stages is central to the trade-off explored in this study. They are also extremely difficult to quantify. Consumer-level food waste at the individual product level is, for all practical purposes, unavailable. Gathering such data would require extensive (and expensive) surveying, and is outside of the scope of this project. In this study, we rely on the consumer-level waste rates from USDA's Loss Adjusted Food Availability (LAFA) dataset (USDA ERS 2013) as a placeholder for product-specific waste rates. The LAFA waste rates are presented at the food commodity level, and represent the best estimate for food loss at the consumer level, considered broadly as a national average. Differences between comparative packaging systems will not be evaluated at the consumer level.

Comparative differences in retail-level food waste rates were gathered from the sales records of a retail partner (to remain anonymous), as well as other sources. These represent corporate-wide sales (circa 200 storefronts) and "throwaways" for specific UPC IDs compiled over two years.

End-of-life disposal of food and packaging: Modeling of end-of-life disposal of food and packaging follows EPA's Waste Reduction Model (WARM) (US EPA 2015). The WARM model uses a life cycle approach to estimate energy use (or credit) and greenhouse gas emissions associated with recycling, combustion, composting and landfilling of different materials. This model was used as the basis for food waste disposal as well as various packaging materials. One exception to the WARM model was made: it includes in recycling of paper products (corrugated cardboard and other papers) a large carbon sequestration component associated with living forest that goes uncut due to the recycling. While perhaps appropriate for the WARM model's intended purpose (demonstrating the impact of waste reduction) this represents an inappropriate credit in our modeling scenario and has been omitted.

US EPA Municipal Solid Waste data (US EPA 2014) were used to establish the default fractions distributed to recycling (or composting), landfill, and combustion pathways. These fractions are based on US national averages. The fractions used in the model are shown in Table 2.

Table 2. Modeled fractions of disposal pathways for various materials

Material	Recycled[a]	Landfilled[c]	Combusted[c]
food	4.8%[b]	78.1%	17.1%
PET	24.2%	62.2%	13.6%
HDPE	16%	68.9%	15.1%
PVC	0	82%	18%
LDPE	11.5%	72.6%	15.9%
PP	2.1%	80.3%	17.6%
PS	3.8%	78.9%	17.3%
PLA	0[b]	82%	18%
Steel	72.2%	22.8%	5.0%
Aluminum can	54.6%	37.2%	8.2%
Aluminum foil	0	82%	18%
Glass	34.1%	54.0%	11.9%
Corrugated cardboard	90.9%	7.4%	1.6%
Other paper	24.7%	61.7%	13.6%
wood	25.1%	61.4%	13.5%

[a] from US EPA MSW data tables, 2012 (US EPA 2014)
[b] represents percentage composted
[c] derived by subtracting recycling fraction and distributing remaining by national average MSW disposal ratio: 82% landfill, 18% incineration.

4.5. Impact assessment methods

Global warming potential was calculated using the IPCC 2013 GWP 100a method (IPCC 2013). Cumulative energy demand was calculated using the method published by Ecoinvent version 2.0 (Frischknecht and Jungbluth 2003).
Blue water use is evaluated in the lettuce case using the midpoint "water depletion" indicator of the ReCiPe impact assessment method (http://www.lcia-recipe.net/). This

indicator is essentially a summation of the volume of surface or ground water (blue water) used in various processes. While it is often desirable to apply a water stress type impact indicator, this requires region-specific characterization factors in order to be meaningful, and given the mostly generic nature of the modeling scenarios (i.e., nationally representative retail and consumer stages), such specific characterizations are not practical.

Note on Appendices: Data presented in figures throughout the remainder of this report are tabulated in Appendix A. Appendix B provides a sensitivity assessment of each case against consumer level waste rates.

5. Case 1: Beef

Beef represents a sensible case for this study: beef production carries a high environmental impact, and because of its high value and perishability, there is strong interest in applying alternative packaging technologies to extend shelf life. One particular challenge in packaging meat is overcoming consumer perception of quality: packaging meat under vacuum (in the absence of oxygen) greatly extends shelf life, but gives the meat a (reversible) purplish hue, often perceived as undesirable by the American consumer. Ironically, a large majority of beef is distributed in such vacuum packaging, and exposed to air prior to retail display to allow the bright red "bloom" of color expected by the consumer.

Despite this opportunity, we have found it quite difficult to identify directly comparable products offered in different packaging configurations for which we can access empirical data on retail-level food waste.

The beef case is divided into three sub-cases in the description below:

- case 1a is built around shrink (waste) target rates provided by Busch's Fresh Food Market (Ann Arbor, MI area).
- Case 1b is built around actual sales and throwaway data from our retail partner.
- Case 1c is an example presented by the Austrian environmental consulting firm, Denkstatt. (Denkstatt GmbH 2014), adapted here to our modeling structure.

5.1. System Descriptions

Case 1a.

The meat and seafood category manager for Busch's Fresh Food Market indicated that the *target* shrink rate – what they aim to achieve, or stay below – is different for regularly packaged (tray with overwrap) and modified atmosphere packaging (MAP): 7% and 5%, respectively. Here, we build a case using these waste rates comparing typical tray with overwrap beef packaging with a high-oxygen MAP alternative.

Case 1b.

Our retail partner carries a full array of beef cuts and products in their stores. However, with the exception of ground beef, there are not good comparisons of the *same* cut being offered in different packaging systems. Thus, interpretation of the results in this case need to account for potential differences in value offered to the consumer. Further, we were able to easily retrieve waste rates for products that carry a UPC ID. This does *not* include meats coming out of the full service counter. Therefore, comparisons could not be made between products from the full service counter and those packaged in the display case. As a

Table 3. Products considered in Case 1b: beef products carried by retail partner

Scenario ID		Meat cut	package	Quantity of sales over 2 years (lbs)	Waste rate (averaged over 2 years)	Price/lb (averaged over 2 years)
b1		80/20 fine ground beef	chub	243000	1.07%	$3.39
b2		80/20 CAB ground chuck	Tray / overwrap. Processed at store	6,050,000	1.00%	$3.70
b3		80/20 case-ready ground beef	Tray / overwrap. Case ready	1,093,000	1.95%	$4.42
b4		Beef shank	Sealed tray; assuming hi O_2 MAP	224,000	4.96%	$5.24
b5		CAB chuck shoulder ranch steak	Tray / overwrap	132,000	11.85%	$5.76
b6		CAB top sirloin filet	Tray / overwrap	1,352,000	1.32%	$7.05
B7		CAB bone-in ribeye steak	Tray / overwrap	220,000	11.19%	$10.94

compromise, we have gathered an array of products to consider here, summarized in Table 3. Most do not conform to the anticipated trend of higher technology packaging resulting in reduced food waste, further emphasizing the complex interplay between shelf life, product popularity, product turnover rate, and marketing efforts that contributes to waste rates.
Case 1c.
In a study aimed at demonstrating how packaging contributes to food waste prevention, Denkstatt (Denkstatt GmbH 2014) presents a case of sirloin steak packaged in an EPS top seal tray (in combination with a vacuum bag used to age the meat prior to retail display) with a 34% retail waste rate. This is compared with the same steak in a "Darfresh" skin packaging (cut can be aged in final retail packaging) with only 18% retail waste. According to Denkstatt, the skin packaging extends shelf life from 6 days to 16 days, and no separate aging packaging is needed. Personal communication with the researchers of the study confirmed that these waste rates included only retail-level waste, that they were actually measured rates based on product specific data from one or more months, and that they are indeed high compared to the average fresh meat sector, but reflect a high price, high quality, low throughput product.

5.2. Data Sources

Beef production (used throughout)
Beef production has been studied extensively with LCA, and emission factors range widely, from 8-50 kg CO_2 eq/kg (Heller and Keoleian 2014). However, the National Cattlemen's Beef Association recently sponsored an LCA of US beef production, conducted by BASF, that serves as a reasonable reference point for the US beef industry (Battagliese et al. 2013). While the study is a true cradle-to-grave LCA, taking the beef product through to consumption, we extract energy use and GHGE factors up through beef harvest (i.e., prior to packaging and distribution) for use in this study. These results, converted from the "consumed" functional unit of the report to a "boneless, post-harvest" functional unit, are shown in Table 4.

Table 4. Emission factors and energy use for beef production, as taken from (Battagliese et al. 2013).

	GHGE (kg CO2 eq/ kg edible beef at slaughterhouse)	Energy use (MJ / kg edible beef at slaughterhouse)
feed	5.59	44*
Cattle	26.1	13.5
harvest	0.34	8.48
total	32	66

*note that the energy use value in the BASF study includes the gross bioenergy represented by crops and pasture, which is not appropriate to include in the comparisons made here, where the focus is on fossil energy. While it is difficult to extract, it appears that the non-biobased portion of feed production is ~57 MJ/kg consumed beef, which, after accounting for loss factors along the product chain, translates into ~44 MJ /kg harvested beef.

Additional modeling parameters and their sources for the 3 sub-cases are shown in Table 5, Table 6 and Table 7.

Table 5. Modeling parameters used in Case 1a

	1 lb. beef in PS tray w/ overwrap		1 lb. beef in hi O_2 MAP tray	
	value	source	value	source
Weight of primary packaging (kg / kg food)	0.0268	#2 PS tray = 5.7g, 21g wrap, 0.08 g paper label	0.054	SealedAir contacts
Primary packaging composition	21.3% PS 78.4% LDPE 0.3% paper foaming & thermoforming incl. for PS; film extrusion for LDPE	#2 PS tray = 5.7g, 21g wrap, 0.08 g paper label	96% PP 4% EVOH thermoforming incl. for PP, film extrusion for EVOH	SealedAir
Distribution packaging (3°) (kg/ kg food)	0.093	(Battagliese et al. 2013)	0.093	(Battagliese et al. 2013)
Distribution packaging composition	98.68% corrugated cardboard 1.32% wood (pallet)	(Battagliese et al. 2013)	98.68% corrugated cardboard 1.32% wood (pallet)	(Battagliese et al. 2013)
Consumer-level food waste	20%	USDA LAFA	20%	USDA LAFA
Retail-level food waste	7%	Busch's target waste rate	5%	Busch's target waste rate
Product volume (ft^3/kg)	0.055	# 2 tray dimensions ~ 5.5"x8"0.75"	0.0803	Tray dimensions: 8 15/16" x 6 13/16" x 1 7/8"
Consumer-facing area (ft^2/kg)	0.964	5.5"x8"	0.964	8 15/16" x 6 13/16"
Average retail price per kg	$9.64	(210 Analytics LLC 2014)	$9.64	(210 Analytics LLC 2014)
Annual kg sold at retail	2.22e9	Total 2013 beef retail sales(210 Analytics LLC 2014)	2.22e9	Total 2013 beef retail sales(210 Analytics LLC 2014)
Transport distance to retail (km)	290	(U.S. Department of Transportation 2015), Table 24, SCTG code 051	290	(U.S. Department of Transportation 2015), Table 24, SCTG code 051
MAP ratio	-		80% O_2, 20% CO_2	
Assumed retail refrigerator unit	Horizontal open, remote condenser, medium temp (38F), 36 ft^2 total display area		Horizontal open, remote condenser, medium temp (38F), 36 ft^2 total display area	

Many of the scenarios considered in Case 1b follow the same parameters in Table 5: scenarios b2, b3, b5, b6 & b7 all follow the parameters for "1 lb. beef in PS tray with overwrap," whereas b4 follows the "1lb. beef in hi O_2 tray" parameters.

Table 6. Modeling parameters for Case 1b1 scenario (beef in chub)

	1 lb. beef in chub (scenario b1)	
	value	source
Weight of primary packaging (kg / kg food)	0.011	1 lb chub packaging weighs ~5g
Primary packaging composition	80% LDPE 10% EVA 10% PVdC (film extrusion included)*	
Distribution packaging (3°) (kg/ kg food)	0.093	(Battagliese et al. 2013)
Distribution packaging composition	98.68% corrugated cardboard 1.32% wood (pallet)	(Battagliese et al. 2013)
Consumer-level food waste	20%	USDA LAFA
Retail-level food waste	1.07%	Retail partner data
Product volume (ft^3/kg)	0.0375	Cylinder with 2.5" diameter, 6" length
Consumer-facing area (ft^2/kg)	0.229	Cylinder with 2.5" diameter, 6" length
Average retail price per kg	$9.64	(210 Analytics LLC 2014)
Annual kg sold at retail	2.22e9	Total 2013 beef retail sales(210 Analytics LLC 2014)
Transport distance to retail (km)	290	(U.S. Department of Transportation 2015), Table 24, SCTG code 051
Assumed retail refrigerator unit	Horizontal open, remote condenser, medium temp (38F), 36 ft^2 total display area	

*because of the mixed components of this film, the LDPE recycling rate has been set to zero for this scenario.

Table 7. Modeling Parameters for Case 1c: Denkstatt sirloin steak example

	358g sirloin steak in EPS tray w sealed top film		300 g sirloin steak in "Darfresh" skin packaging	
	value	source	value	source
Weight of primary packaging (kg / kg food)	0.0419	20 g vacuum bag per 6 kg meat for aging, 11g EPS tray, 4 g top film (Denkstatt GmbH 2014)	0.0633	19 g skin packaging
Primary packaging composition	2.22% PVdC 10.82% LDPE 2.59% EVA 67.91% EPS 8.23% EVOH 8.23% PA (modeled as Nylon 6-6)	Personal communication with Denkstatt	62% PS 26% EVA 12% LDPE	Simplified summary of two complex multilayer components. Personal communication with Denkstatt
Distribution packaging (3°) (kg/ kg food)	0.093	Assumed same as previous beef examples (Battagliese et al. 2013)	0.093	Assumed same as previous beef examples (Battagliese et al. 2013)
Distribution packaging composition	98.68% corrugated cardboard 1.32% wood (pallet)	(Battagliese et al. 2013)	98.68% corrugated cardboard 1.32% wood (pallet)	(Battagliese et al. 2013)
Consumer-level food waste	20%	USDA LAFA	20%	USDA LAFA
Retail-level food waste	34%	(Denkstatt GmbH 2014)	18%	(Denkstatt GmbH 2014)
Product volume (ft^3/kg)	0.0368	Assumed based on meat density	0.0368	Assumed based on meat density
Consumer-facing area (ft^2/kg)	0.441	Assumed based on above volume and 1" thickness	0.441	Assumed based on above volume and 1" thickness
Average retail price per kg	$9.64	(210 Analytics LLC 2014)	$9.64	(210 Analytics LLC 2014)
Annual kg sold at retail	2.22e9	Total 2013 beef retail sales(210 Analytics LLC 2014)	2.22e9	Total 2013 beef retail sales(210 Analytics LLC 2014)
Transport distance to retail (km)	290	(U.S. Department of Transportation 2015), Table 24, SCTG code 051	290	(U.S. Department of Transportation 2015), Table 24, SCTG code 051
Assumed retail refrigerator unit	Horizontal open, remote condenser, medium temp (38F), 36 ft^2 total display area		Horizontal open, remote condenser, medium temp (38F), 36 ft^2 total display area	

5.3. Results

Case 1a: typical tray vs. MAP

Figure 2 shows the greenhouse gas emissions associated with the two scenarios in case 1a, a comparison of typical PS tray with overwrap retail packaging and a high O_2 MAP. Here, beef production and processing dominate, representing 96% of the total life cycle emissions. A move from the tray/ overwrap packaging to high O_2 MAP packaging represents a doubling in packaging mass and a nearly 40% increase in the GHGE associated with packaging production and disposal. Yet, the small decrease in food waste (7% to 5% retail waste) is sufficient to offset this increase, resulting in a net system decrease. The break-even point (assuming all other wastes the same) is a 6.4% retail waste for the hi O2 MAP.

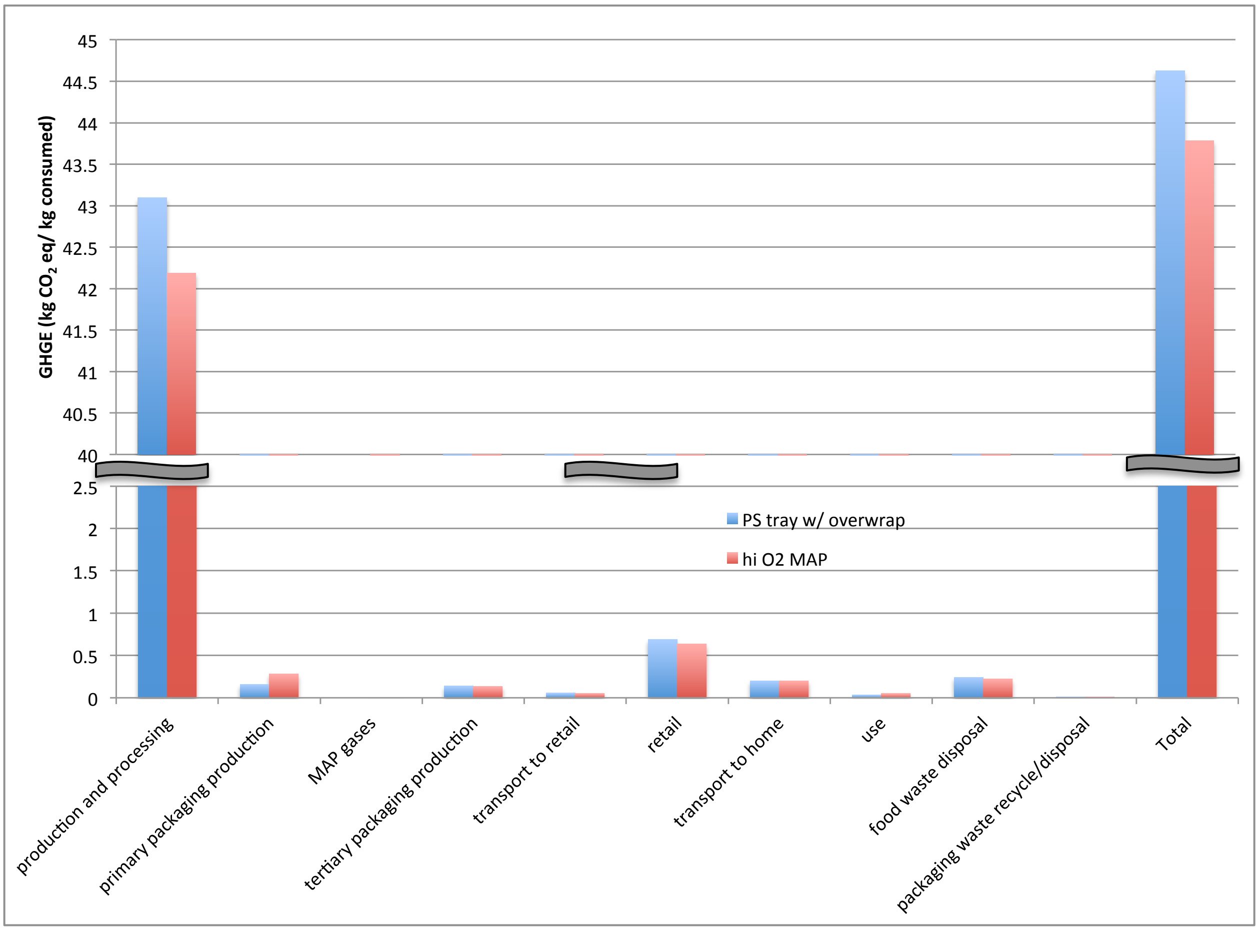

Figure 2. Distribution of greenhouse gas emissions across the life cycle for Case 1a: comparing tray with overwrap and high oxygen MAP packaging. Note the break in the y-axis in order to show details of the small contributions from most life cycle stages. Total values are PS tray: 44.56 kg CO_2 eq/kg beef consumed; high O_2 MAP: 43.78 kg CO_2 eq/kg beef consumed.

On the other hand, the reduction in food waste is not sufficient to reach the break-even point with respect to life cycle energy demand, as shown in Figure 3. While the life cycle is also dominated by beef production, the energy demand for the MAP packaging (production

& disposal) is twice that of the tray/ overwrap. The retail food waste rate would need to decrease to 2.6% in order to reach the break-even point when shifting from tray/ overwrap to MAP packaging.

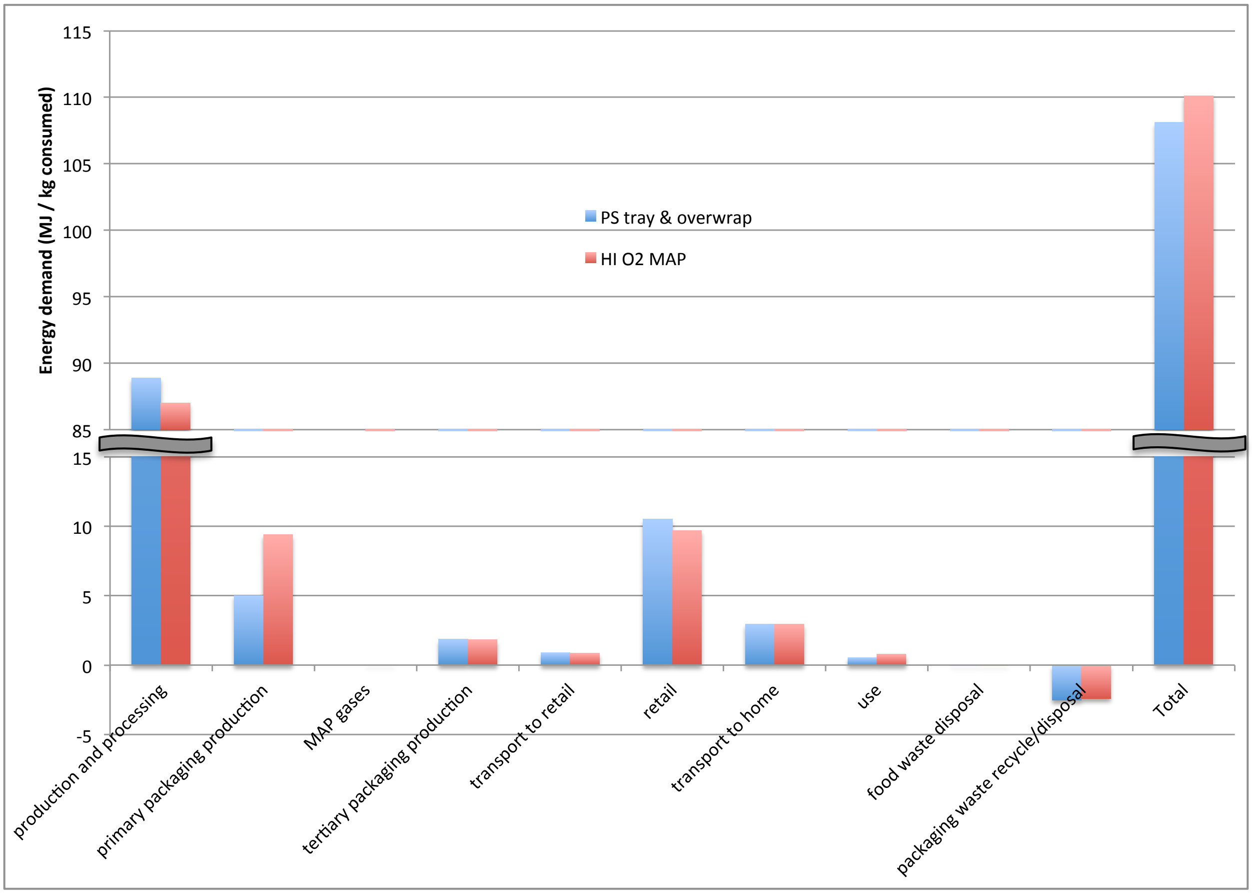

Figure 3. Distribution of cumulative energy demand per kg of consumed beef for Case 1a: comparing tray with overwrap and high oxygen MAP packaging. Note the break in the y axis in order to show detail of life cycle stages with small contributions. Total values are PS tray: 108.1 MJ /kg beef consumed; high O2 MAP: 110.1 MJ /kg beef consumed.

Exploring consumer level food waste reduction

The WRAP study, "Reducing Food Waste by Extending Product Life," (Lee et al. 2015) presents an approach for estimating the possible reduction in food waste that could result from offering the consumer greater shelf life (i.e., more days before the "use by" date). This method borrows heavily on an earlier survey-based study (Brook Lyndhurst 2011) that offers a probability "distribution" of when products are disposed relative to on-package date labels. The WRAP method presumes that extending the time on date labels pushes actual disposal times further into the probability curve (assumed to be a normal distribution), thereby reducing the amount of food wasted.

We utilize this method to offer a glimpse of the potential for packaging to reduce food waste at the consumer level.

Studies on beef packaging options show typical shelf lives for different packaging configurations. A white paper on beef shelf life (Delmore 2009) shows the expected shelf life for whole muscle beef to be:

- air-permeable overwrap: 5-7 days
- high oxygen MAP: 12-16 days

  increase = 7-9 days

Using a 7 day increase in shelf life to be conservative, and assuming that half of this extended shelf life is passed on to the consumer, we utilize the method presented by WRAP to estimate a reduction in waste from an additional 3.5 days of "shelf life" available to the consumer.

Based on the disposal distribution for "cooked meat" (which admittedly is not a perfect fit, but the closest available from the WRAP studies), the additional 3.5 days of available life may result in a 32% reduction in consumer food waste. From a baseline of 20% consumer waste, this reduction results in a consumer waste level of 13.6%.

Thus, the high O_2 MAP scenario, with a consumer level waste=13.6% and retail waste=5%, results in a total GHGE of 40.4 kg CO_2 eq/kg and energy use of 102 MJ/kg consumed. This scenario, with reductions in retail *and* consumer food waste with the MAP (relative to the tray baseline), passes the break-even point for both GHGE and energy use, when compared to the PS tray scenario (see Figures 2 and 3).

Case 1b: Retail partner scenarios

The collection of beef scenarios described in Table 3 demonstrate the challenges of attributing differences in even retail-level food waste to packaging configurations: clearly, many attributes play into the degree of waste for a particular product, including consumer preference, product turnaround, and in-store marketing aspects. Results for the ground beef scenarios are shown in Table 8. The modeling of scenarios b2 & b3 differ only in retail waste rate, whereas b1 is modeled with a different primary packaging, product volume, and product area.

Table 8. Summary of results for ground beef scenarios.

Scenario ID	description	Retail waste rate	Total GHGE (kg CO_2 eq / kg consumed)	Total energy demand (MJ/ kg consumed)
b1	1lb 80/20 ground beef, chub	1.07%	41.8	99.2
b2	1 lb 80/20 in-store ground chuck, tray/overwrap	1.00%	41.9	101.8
b3	1 lb case-ready 80/20 ground beef, tray/overwrap	1.95%	42.3	102.7

Results for the remaining Case 1b scenarios, summarized in Table 9, further demonstrate the opportunity to reduce food waste at the retail level through alternative packaging designed to extend shelf life. In addition to presenting the total system energy demand and GHGEs for each scenario, Table 9 also indicates the additional primary packaging burden that would still allow the system GHGE to "break even" if the retail waste rate could be reduced by one percentage point. For example, with scenario b5 (chuck shoulder ranch steak), if a change in primary packaging (from the current tray/overwrap to an alternative) offered a 1 percentage point reduction in the retail waste rate, GHGE associated with production and disposal of that packaging could increase over 4 times (above the emissions of the tray/overwrap package) and still result in a system net benefit.

Table 9. Summary of results for remaining beef scenarios gathered from retail partner.

Scenario ID	description	Retail waste rate	Total energy demand (MJ / kg consumed)	Total GHGE (kg CO_2 eq / kg consumed)	Primary packaging GHGE (kg CO_2 eq / kg consumed)	% increase in primary packaging GHGE allowable with 1% decrease in retail waste rate
B4	Beef shank; hi O2 MAP	4.96%	110.1	43.8	0.284	276%
B5	Chuck shoulder ranch steak; tray	11.85%	113.9	47.1	0.168	410%
B6	Top sirloin filet; tray	1.32%	102.1	42.0	0.150	367%
B7	Bone-in ribeye; tray	11.19%	113.0	46.8	0.166	461%

<u>Case 1c: Denkstatt example</u>

The beef case presented in the Denkstatt study (Denkstatt GmbH 2014) is a specific example of a high-value, low-throughput beef cut (sirloin steak) marketed through a European retailer. In their example, a modification in packaging, from a sealed tray to a skin pack, results in a notable reduction in food waste. We have borrowed the basic packaging and waste data and assembled a case using our LCA model (retaining the modeling approach for transport, retail, at-home, and disposal stages described in Section 4.4). GHGE results are shown in Figure 4. In this case, the reduction in retail food waste (from 34% to 18%) dominates the differences between the two scenarios, while very little difference in impact of packaging material production is evident. Figure 5 offers results for cumulative energy use. While there is a slight increase in energy use with the skin pack, the food waste reduction more than makes up for this, resulting in a 17% decrease in total system energy use. In fact, a retail waste rate of 32% for the skin pack would break even on energy demand with the sealed tray packaging with retail waste of 34%.

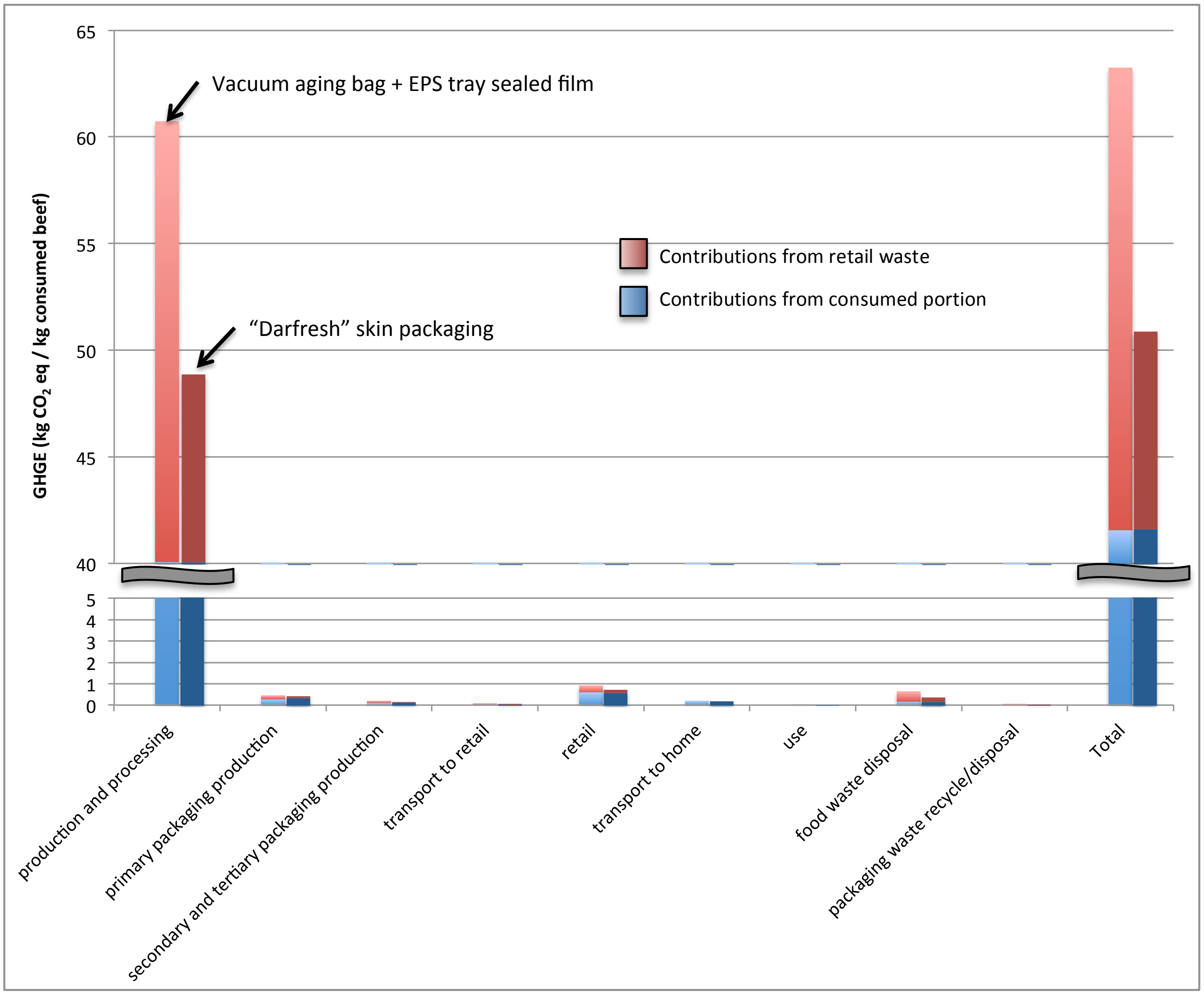

Figure 4. Distribution of greenhouse gas emissions across life cycle stages, comparing sealed tray with skin packaging. Red portions of bars are contributions due to retail waste. Note break in y-axis to show details of lesser contributing stages. Values for life cycle totals: EPS tray: 63.3 kg CO_2 eq/kg consumed; skin pack: 50.9 kg CO_2 eq / kg consumed.

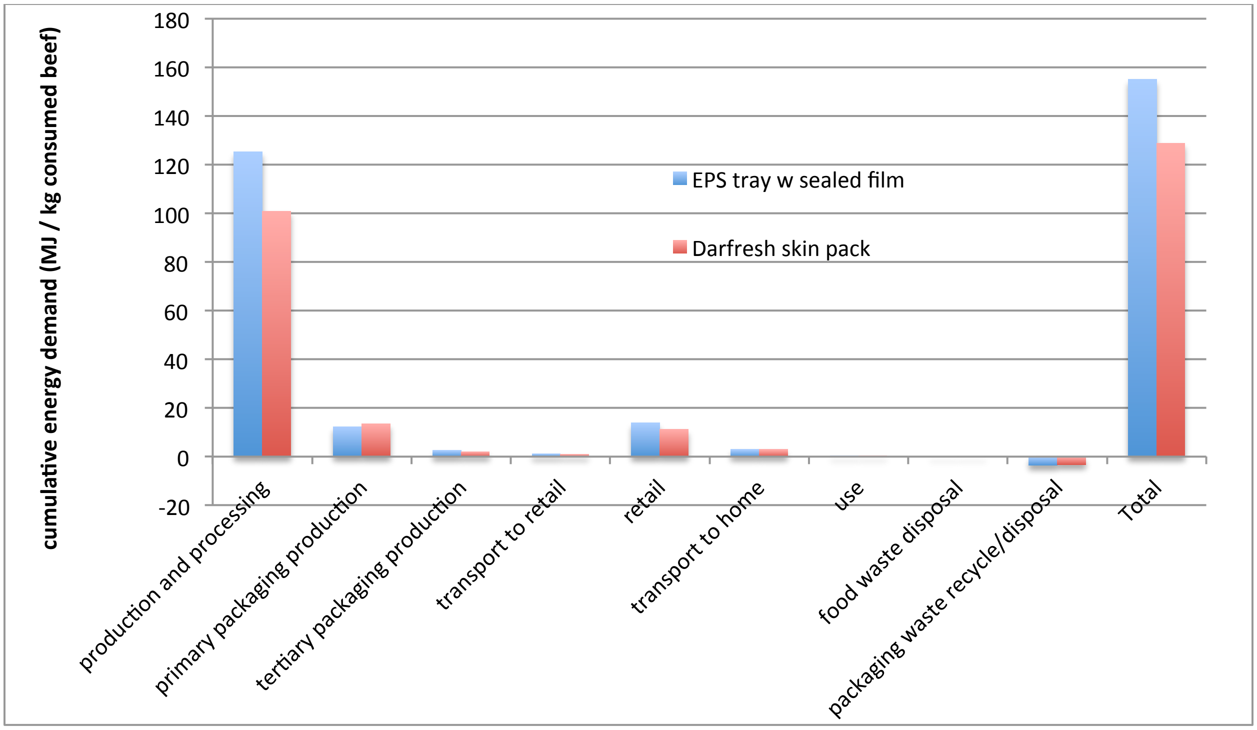

Figure 5. Distribution across life cycle stages of cumulative energy demand, comparing sirloin steak packaged in sealed EPS tray with Darfresh skin pack. Life cycle totals: EPS tray: 155 MJ/ kg consumed beef; skin pack: 129 MJ/ kg consumed beef.

5.4. Discussion and conclusions

The array of beef cases presented here offers a glimpse into the environmental trade-off between food packaging and food waste where the food product carries a large production burden. Beef ranks at or near the top of commonly consumed foods in nearly all environmental indicator categories. Thus, efforts to reduce food waste through advanced packaging typically will pay off in terms of reduced system environmental burden. As the somewhat conjectural scenario in case 1a demonstrate, this isn't always the case, and different indicators may demonstrate incongruous trends.

The generic scenario in case 1a provides an interesting starting point for considering the interplay between food waste and food packaging as it demonstrates that, even for beef, there can be instances where a waste reduction is not significant enough to balance greater impacts of packaging alternatives (in this case, in terms of cumulative energy demand). The European case, (case 1c) on the other hand, represents a scenario with exceptionally high retail waste rates. Here, a nearly 50% reduction in retail level waste rates through the adoption of an alternative packaging (skin pack) results in significant net system benefits, both in terms of GHGE and energy use. Case 1b, the scenarios drawn from our retail partner, offers little in terms of strong comparative conclusions. It does, however, offer reminders that numerous factors (beyond packaging configuration and shelf life) play into retail-level waste rates, and that there appears to be significant opportunity to reduce retail waste rates through packaging alternatives.

One general observation arising out of efforts to establish beef cases is that it appears, in the U.S. marketplace at least, that packaging choices prioritize a number of other criteria (appearance, consumer preference, familiarity, cost, etc.) above food waste reduction. Whereas anecdotal evidence suggests that packaging formats aimed at reducing food waste are available, if not common, in Western Europe, such options are still rare in the U.S. marketplace. This speaks to the opportunity for packaging to contribute significantly to food waste reduction. However, it also suggests that the predominant barrier to this happening is consumer education and perception, as well as perceptions throughout the food chain (producers, marketers, retailers, etc.).

6. Case 2: Romaine Lettuce

6.1. System Descriptions

Romaine lettuce is one of a number of fresh produce products that has seen a significant market shift to minimally processed, ready-to-eat forms, often offered side-by-side on grocery shelves with raw, unprocessed lettuce heads. While consumer choice between these reasonably similar products may be based on numerous factors including convenience, it is interesting to consider how additional packaging influences retail performance (waste rates) as well as overall system environmental performance.

The photos above show the scenarios considered in this case. On the left is a whole romaine head, which, in the case of the product carried by our retail partner, is supplied with a minimally protective sleeve (primarily for product identification/ UPC ID). On the right is a common brand of cut and ready-to-eat romaine fully enclosed in a sealed bag. It is important to note that the cut and ready-to-eat lettuce offers an additional service to the consumer (convenience) that may be considered an inexact comparison with raw head lettuce. Our initial hypothesis for this case was that the bagged lettuce would have greater shelf life and therefore reduced waste at retail, but that this waste savings might not be sufficient to offset the environmental "cost" of the bag, given the low environmental impact of lettuce production. To further explore the nuances of the food waste/ packaging trade-off, we aspired to include in this case an estimate of water use throughout the product life cycle.

6.2. Data Sources

Lettuce production and processing: No known LCA study of lettuce production in the US exists. We use a study that considers production in a number of geographic regions and production methods, averaging emission factors and energy use for production in open fields in the UK and Spain (i Canals et al. 2008), shown below.

	UK open field	Spain open field	Average (value used in model)
GHGE (kg CO_2 eq/ kg)	0.17	0.106	0.138
Energy use (MJ / kg)	8.33	12	10.2

Since 71% of the US lettuce production occurs in California, and the majority of California lettuce production occurs in Salinas Valley, we have chosen to model water demand and transport distances for lettuce grown in Salinas Valley. Irrigation demands were estimated via a model specific for lettuce crop growth and water use (Gallardo et al. 1996), utilizing evapotranspiration data from California Irrigation Management Information System (CIMIS) for Salinas, averaged over 10 years (2004-2014). Irrigation needs for 3 growing seasons were weighted by season length to arrive at an annual average. This resulted in an estimated irrigation need of 88.2 L / kg lettuce produced, which compares well with a value of 93.4 L /kg romaine lettuce produced in Salinas reported in a Chiquita sponsored water footprint study (LimnoTech 2012).

(i Canals et al. 2008) report an average processing electricity demand – primarily associated with initial cooling – of 0.0562 kWh/kg lettuce. We include this as an estimate of processing energy needs. The Chiquita study (LimnoTech 2012) indicates a processing water demand of 4.45 L/kg for bagged salad. We assume this value accounts for added washes needed for ready-to-eat salad and use it only in connection with the bagged salad. While it is likely that there is some wash water used at the harvest/processing stage with head lettuce, it is not included in our estimates. Further, due to lack of data, there is no additional energy demand included for cutting, sorting, and otherwise handling the bagged lettuce.

Additional modeling comments

The modeling parameters used for the two romaine lettuce scenarios are shown in Table 10. The bagged lettuce requires significantly greater primary and tertiary packaging per unit of lettuce mass delivered. Note also that the head lettuce contains a fraction of its total weight (estimated at 9.8% based on our own measurements) that is not consumed (stem/core, outer leaves) and is therefore counted as 'inedible waste'. For the head lettuce, this waste is applied at the consumer level, and therefore carries the distribution and storage burdens of the consumed lettuce. On the other hand, the bagged lettuce is processed shortly after harvest, removing the inedible portion at that stage. Due to a lack of

Table 10. Modeling Parameters for Romaine Lettuce Case

	9 oz. raw head romaine		9 oz. bagged, ready-to-eat romaine	
	value	source	value	source
Weight of primary packaging (kg / kg food)	0.007	1 HDPE produce bag included for every 9 oz. head (sleeve in photo above not included). Bag weighed.	0.0274	Bag weighed.
Primary packaging composition	100% HDPE (film extrusion included)	Assumed typical produce bag	65.7% LDPE 34.3% PP (film extrusion included)	Film 15µm PP, 30-µm LDPE. Weight ratio determined by this thickness and density of each material.
Distribution packaging (3°) (kg/ kg food)	0.055	Based on weighed produce boxes.*	0.197	6 bags packed in 40x30x17 cm box, weighing 0.302 kg
Distribution packaging composition	100% corrugated cardboard*	assumed	100% corrugated cardboard	
Retail-level food waste	0.22%	Retail partner data. Averaged over 3 years in this case, based on 224,980 units sold.	2.51%	Retail partner data. Averaged over 3 years in this case, based on 5,324,533 units sold.
Consumer-level food waste	24%	USDA LAFA	24%	USDA LAFA
Inedible waste	9.8%, applied at point of consumption	Average of 3 measured samples	9.8%, applied at point of processing	Assumed same as measured samples
At-home wash water	7 L/ kg consumed lettuce	Average of 3 measurements	-	Ready-to-eat. Assumed no washing at home
Product volume (ft^3/kg)	0.257	Assumed based on volume of right cone with height=12", diameter=6"	0.363	Based on bag dimensions and contained product weight
Consumer-facing area (ft^2/kg)	0.98	Assumed based on cross-sectional area of above cone	2.17	Based on bag dimensions and contained product weight
Average retail price per kg	$3.73	2014 average for romaine lettuce, (Bureau of Labor Statistics 2015)	$3.73	2014 average for romaine lettuce, (Bureau of Labor Statistics 2015)
Annual kg sold at retail	4.40e8	(The Packer Produce Universe 2014)	4.40e8	(The Packer Produce Universe 2014)
Transport distance to retail (km)	3343	Population weighted average distance from Salinas, CA to the population center of each continental state, as calculated by GIS	3343	Population weighted average distance from Salinas, CA to the population center of each continental state, as calculated by GIS
Assumed retail refrigerator unit	Semi-vertical open, remote condenser, medium temp (38F), 60 ft^2 total display area		Semi-vertical open, remote condenser, medium temp (38F), 60 ft^2 total display area	

*Produce boxes are typically waxed or coated with plastic film to avoid moisture absorption. LCI data was not available for waxed boxes or wax, but corrugated recycling was to zero (from 90.9%) to reflect the fact that waxed boxes typically are not recyclable.

reliable data on inedible waste in processing bagged, ready-to-eat lettuce, we have assumed the same inedible rate as in our 'at home' measurements.

We have assumed that lettuce production occurs in the Salinas Valley of California and is distributed nationwide. To estimate transportation distances to retail outlets, we have calculated (via GIS) a transport distance from Salinas, CA to the population center of each of the 48 continental states (reported in Table 10). A population-weighted average of these distances was then calculated.

Blue water use, defined here as surface or ground water (i.e., excluding rainwater) evaporated or incorporated into a product, is evaluated in the lettuce case using the midpoint "water depletion" indicator of the ReCiPe impact assessment method (http://www.lcia-recipe.net/). This indicator is essentially a summation of the volume of surface or ground water (blue water) used in various processes. While it is often desirable to apply a water stress type impact indicator, this requires region-specific characterization factors to be meaningful, and given the mostly generic nature of the modeling scenarios (i.e., nationally representative retail and consumer stages), such specific characterizations are not practical.

6.3. Results

As can be seen in Table 10, the retail level waste rates as experienced by our retail partner did not agree with our initial hypothesis: that is, the waste rate for the bagged lettuce is an order of magnitude greater than that for the raw romaine head. This is despite the fact that more than 20 times the number of units were sold (waste rate typically decreases with increasing sales volume). Again, it must be emphasized that comparisons of cut, ready-to-eat lettuce with raw, unprocessed heads do not represent a direct, "apples-to-apples" comparison as there are differences in the "convenience" function offered to the consumer. Interpretations of these results need to account for this difference.

Figure 6 shows the distribution of GHGE across life cycles for the two romaine lettuce scenarios. Despite a factor 10 difference in retail level waste rates, there is no significant difference in food production and processing GHGE, due to the low emissions per kg of producing lettuce, as well as the relatively small retail waste levels. The primary difference between the two scenarios is driven by impacts of producing packaging. Also noticeable in the figure are the additional impacts due to transporting and refrigerating the 9.8% of inedible waste in the case of the whole lettuce head. Packaging disposal is higher for the lettuce head because it was assumed that the waxed cardboard used for distribution could not be recycled.

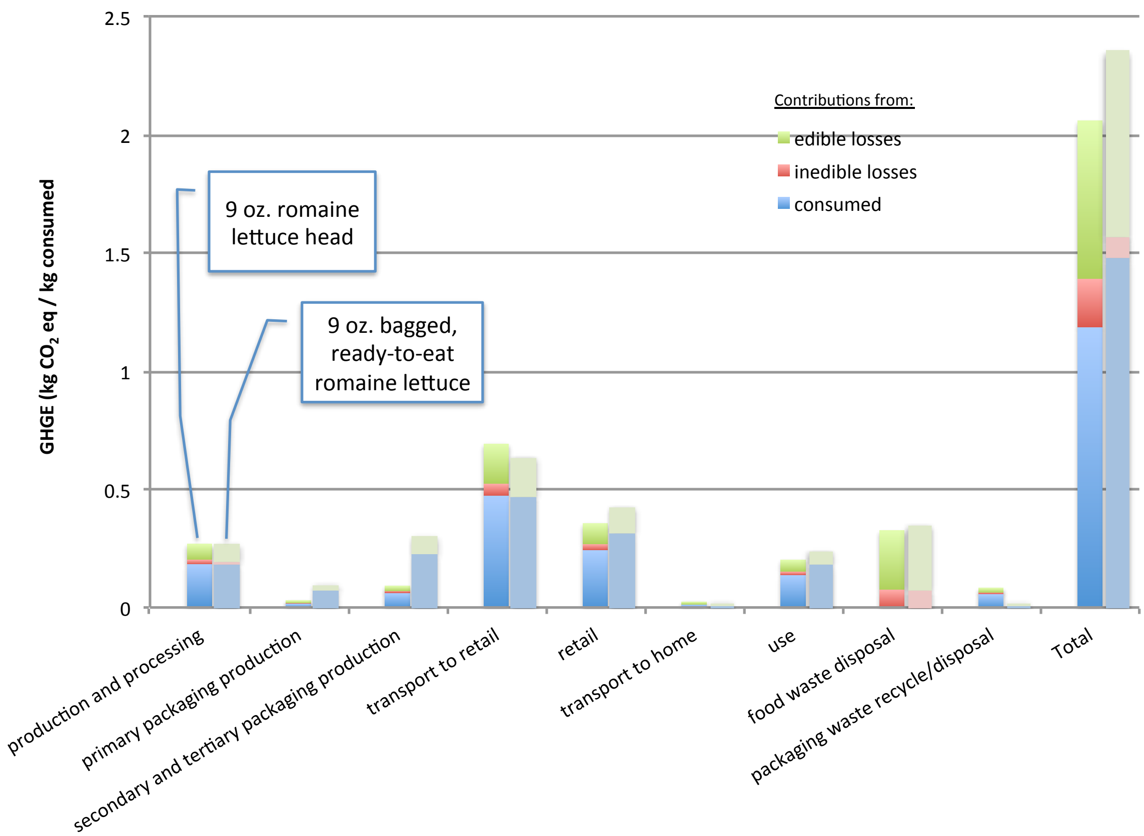

Figure 6. Distribution of GHGE per kg of consumed product across life cycle stages. The figure compares the romaine lettuce head scenario (darkened bars) with bagged, ready-to-eat romaine lettuce (lighter bars). Also shown are the contributions due to consumed product, edible losses, and inedible losses.

Figure 7 demonstrates that cumulative energy demand follows a similar trend to GHGE when comparing the two romaine scenarios. Impacts from food and packaging production are greater for the bagged lettuce case; a significant credit for recycling of corrugated cardboard in the bagged lettuce case brings the total system difference a bit closer (recall that no cardboard recycling was permitted in the head lettuce scenario).

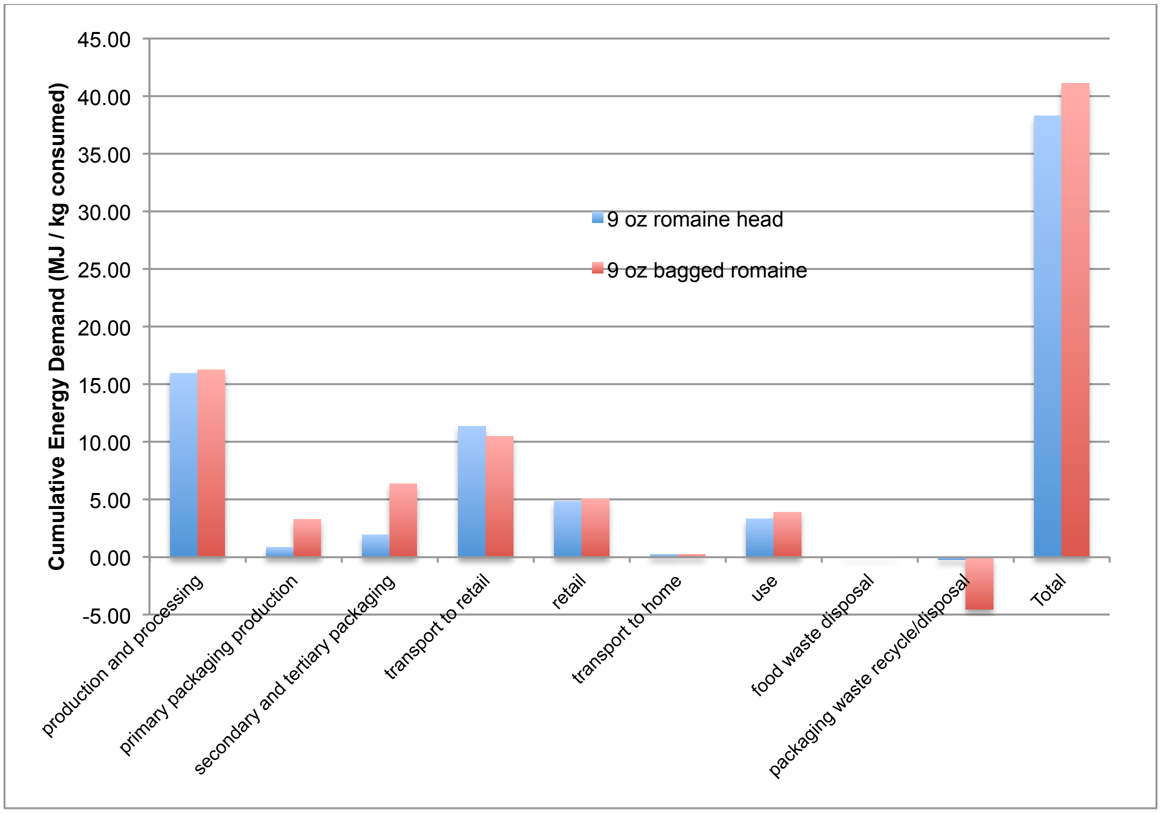

Figure 7. Distribution of life cycle energy demand for the romaine lettuce scenarios.

On the other hand, blue water use, summarized in Figure 8, shows a different trend. Based on the data used in this model, there is significantly more wash water used at home in washing the lettuce head than is used in processing the bagged lettuce. Such a claim must be confirmed with additional data collection, but the preliminary conclusion is that bagged, ready-to-eat lettuce may offer water savings due to more efficient washing in the processing stage than may be typical in homes. Thus, the packaging system that allows distribution of ready-to-eat salad indirectly contributes to this water savings, albeit not through a reduction in food waste, in this case.

Table 11. Results of romaine lettuce case study, by life cycle stage and contributions from consumed food and wasted food.

	9 oz. romaine head		9 oz. bagged romaine	
	GHGE kg CO_2 eq/ kg consumed	CED MJ / kg consumed	GHGE kg CO_2 eq/ kg consumed	CED MJ / kg consumed
lettuce production				
Consumed food	0.183	10.9	0.183	10.9
Wasted food	0.0847	5.05	0.0844	5.32
Primary packaging production				
Consumed food	0.0168	0.586	0.0732	2.44
Wasted food	0.00774	0.271	0.0256	0.85
Secondary packaging production				
Consumed food	0.0624	1.32	0.224	4.74
Wasted food	0.0288	0.611	0.0782	1.66
Transport to retail				
Consumed food	0.474	7.78	0.474	7.78
Wasted food	0.219	3.59	0.166	2.72
retail				
Consumed food	0.243	3.32	0.317	3.75
Wasted food	0.112	1.53	0.111	1.31
Transport to home				
Consumed food	0.0122	0.187	0.0122	0.187
Wasted food	0.00558	0.086	0.00384	0.0592
Home refrigeration (use)				
Consumed food	0.138	2.28	0.184	2.98
Wasted food	0.0632	1.04	0.0582	0.94
Food waste disposal	0.325	-0.034	0.349	-0.036
Packaging disposal				
Consumed food	0.0570	-0.154	0.00322	-3.34
Wasted food	0.0263	-0.071	0.00162	-1.17
TOTAL				
Consumed food	1.19	26.2	1.48	29.5
Wasted food	0.873	12.1	0.879	11.7
SUM	2.06	38.3	2.36	41.1

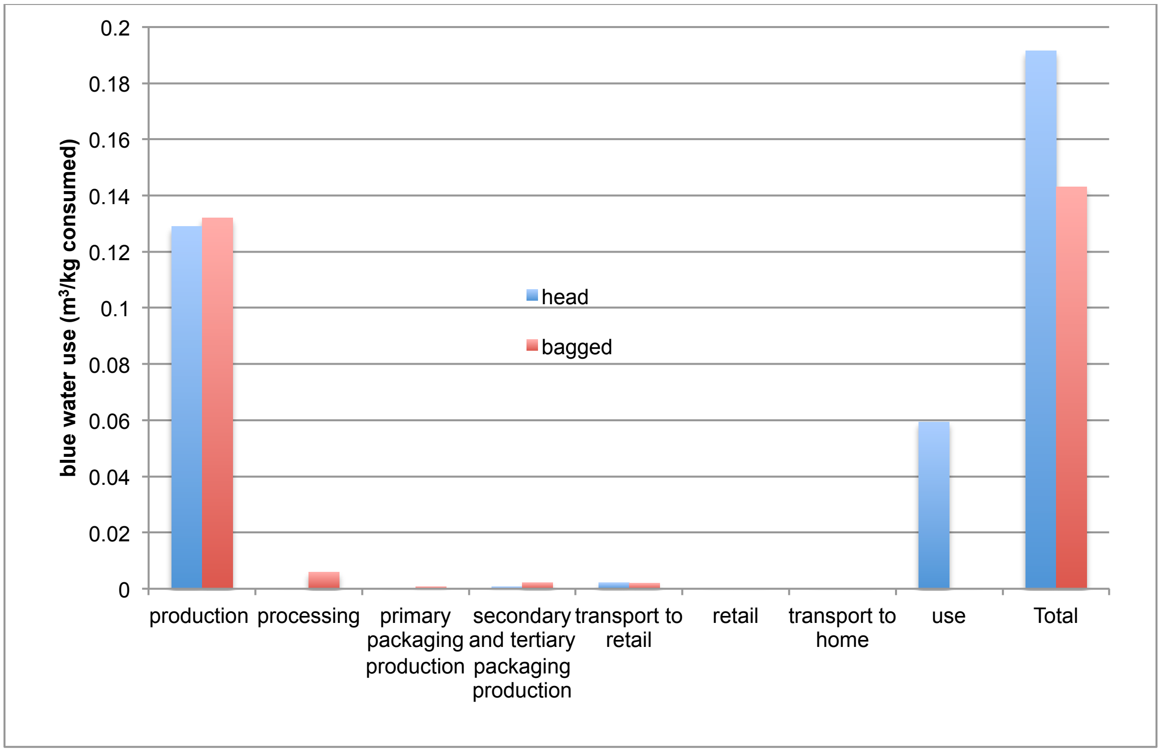

Figure 8. Distribution of blue water use across the life cycle for the romaine lettuce scenarios. Here, blue water use is evaluated based on the ReCiPe impact assessment method's midpoint indicator. Food and packaging disposal stages are not shown because the model does not contain water use estimates for these stages.

6.4. Discussion and conclusions

Based on the waste rates gathered from our retail partner, the initial hypothesis that bagged lettuce would have less retail-level food waste did not prove true. There are a few potential explanations for this. First, bagged lettuce may simply have poorer shelf life performance. It is well known that cutting lettuce leaves compromises their shelf stability: careful attention to packaging conditions must occur in order to assure sufficient shelf life for distribution, sale and consumption. We were unable to find reliable shelf life estimates for bagged lettuce. However, it may be that the packaging technology employed does *not* offer greater shelf life than the raw, unprocessed lettuce head. Thus, adding additional "convenience" for the consumer may come at the expense of reduced shelf life. The other potential explanation has to do with determining when a product is unsalable. Bagged lettuce carries a "use-by" date that retailers use to manage their inventory. It may be that this date is conservative and bagged lettuce is being disposed before it is truly unsalable. On the other hand, whole lettuce heads do not carry a sell-by or use-by date, and it is up to the discretion of the retailer when they are no longer salable.

Given the very low retail food waste rate observed for the raw head lettuce, a breakeven point cannot be achieved with a lower retail food waste rate for the bagged lettuce (i.e., even with retail waste = 0%, total GHGE/kg is greater with bagged lettuce). However, lowering consumer level food waste from the assumed 24% to 16% (with other wastes kept constant) results in the bagged lettuce case having lower GHGE than the raw head. These conclusions also hold true for cumulative energy demand. While such difference in consumer-level food waste seems anecdotally possible, we have no empirical evidence to suggest it.

7. Case 3: Ground Turkey

7.1. System Descriptions

The Jennie-O brand of turkey products offers lean ground turkey in two packaging configurations, shown side-by-side in the photo below.

The product on the right is a 3 pound “chub” or tube of lean ground turkey (90% lean, 10% fat). The product on the left is 3 pounds of lean ground turkey (93% lean, 7% fat) in a PP tray with a sealed lidding material. For the purposes of this comparison, we are assuming that the slight difference in fat content is not significant and that these are equivalent products in alternative packaging formats. Our retail partner carries both products.

Our initial hypothesis upon encountering this example was that the sealed tray product was a modified atmosphere package (MAP) designed to extend the shelf-life of the product. A phone conversation with an R&D employee at Jennie-O confirmed that the tray packaging contains a modified atmosphere, and indicated that it was a high oxygen formulation. Surprisingly, this conversation also revealed that the MAP product has a shorter expected shelf-life than the chub packaging and that the additional packaging was motivated by marketing factors (customer appeal, etc.) Still, waste rate data from our retail partner demonstrates lower waste with the MAP packaging (1% vs. 3.1%); we present this case as an additional example of the complexities of packaging’s role in affecting food waste – in this case, apparently by influencing the appeal of a product.

7.2. Data Sources

Turkey production and processing: Limited LCA studies of turkey production exist. We have chosen to use a UK-based study that reports four slightly different production systems (Leinonen et al. 2014). We use the average of these production systems, with global warming potential of 4.29 kg CO_2 eq/ kg live weight (SD=0.22) and primary energy use of 20.16 MJ/ kg live weight (SD=1.19) (note: the SDs here indicate standard deviations across the 4 production scenarios). A dress yield of 79.13% was used to convert from kg live weight to kg carcass (USDA 1992). An additional primary energy consumption of 3.85 MJ/ kg dress carcass was added for processing (poultry, cut up, deboned & chilled, from

Table 12. Modeling parameters for ground turkey case.

	3 lb. chub packaging		3 lb. MAP tray packaging	
	value	source	value	source
Weight of primary packaging (kg / kg food)	0.00852	Packaging material weighed for 1 lb. chub (5 g). Assume packaging weight scales proportionally to surface area of cylinder	0.0359	SealedAir contacts, personal communication. Tray weight = 46.9 kg; proportion of tray to lidding material is 24:1
Primary packaging composition	80% LDPE 10% EVA 10% PVdC (film extrusion included)*	Assumption based on information from patents and other sources	96% PP (thermoforming included) 4% EVOH (film extrusion included)	SealedAir contacts indicated beef high O_2 MAP use EVOH lidding material; assumed same here
Distribution packaging (3°) (kg/ kg food)	0.093	Assumed same as beef case	0.093	Assumed same as beef case
Distribution packaging composition	98.68% corrugated cardboard 1.32% wood (pallet)	Assumed same as beef case	98.68% corrugated cardboard 1.32% wood (pallet)	Assumed same as beef case
Consumer-level food waste	35%	USDA LAFA	35%	USDA LAFA
Retail-level food waste	3.1%	Retail partner data	1%	Retail partner data
Product volume (ft^3/kg)	0.0376	Dimensions of package, assuming cylinder	0.0801	Package dimensions
Consumer-facing area (ft^2/kg)	0.191	Dimensions of package, assuming cylinder	0.383	Package dimensions
Average retail price per kg	$6.39	Average for Jennie-O ground turkey over 2 years for retail partner	$6.39	Average for Jennie-O ground turkey over 2 years for retail partner
Annual kg sold at retail	1.27e8	(Jennie-O 2013)	1.27e8	(Jennie-O 2013)
Transport distance to retail (km)	290	(U.S. Department of Transportation 2015), Table 24, SCTG code 051	290	(U.S. Department of Transportation 2015), Table 24, SCTG code 051
MAP ratio	-		80% O_2, 20% CO_2	assumed
Assumed retail refrigerator unit	Horizontal open, remote condenser, medium temp (38°F), 36 ft^2 total display area		Horizontal open, remote condenser, medium temp (38°F), 36 ft^2 total display area	

*because of the mixed components of this film, the LDPE recycling rate has been set to zero for this scenario.

(Ramirez et al. 2006)). Specific energy demand for grinding, blending, etc. of ground turkey was not available; since both products are equivalent in this regard, the exclusion of a grinding process should not effect the comparative results.

The relevant parameters for the two packaging formats considered in this case are given in Table 12. It should be noted that the tray packaging is a relatively new product offering, and the waste percentage is based on significantly smaller baseline sales (nearly factor 25 greater sales with chub than tray), largely because the tray product was not offered over the full 2 years for which the data are averaged. It is not clear how this is influencing the waste rates used here.

7.3. Results

Figure 9 shows the life cycle GHGE for the two packaging configurations (numerical values shown in Table 13). The GHGE associated with packaging (primary, tertiary and disposal) increases 41% from the chub to the tray packaging. However, because the emissions associated with producing the turkey are so much greater, even the small reduction in retail food waste (3.1% to 1%) is sufficient to result in a net reduction in the overall system GHGE. Note that refrigeration at the retail level is a function of consumer-facing area of the

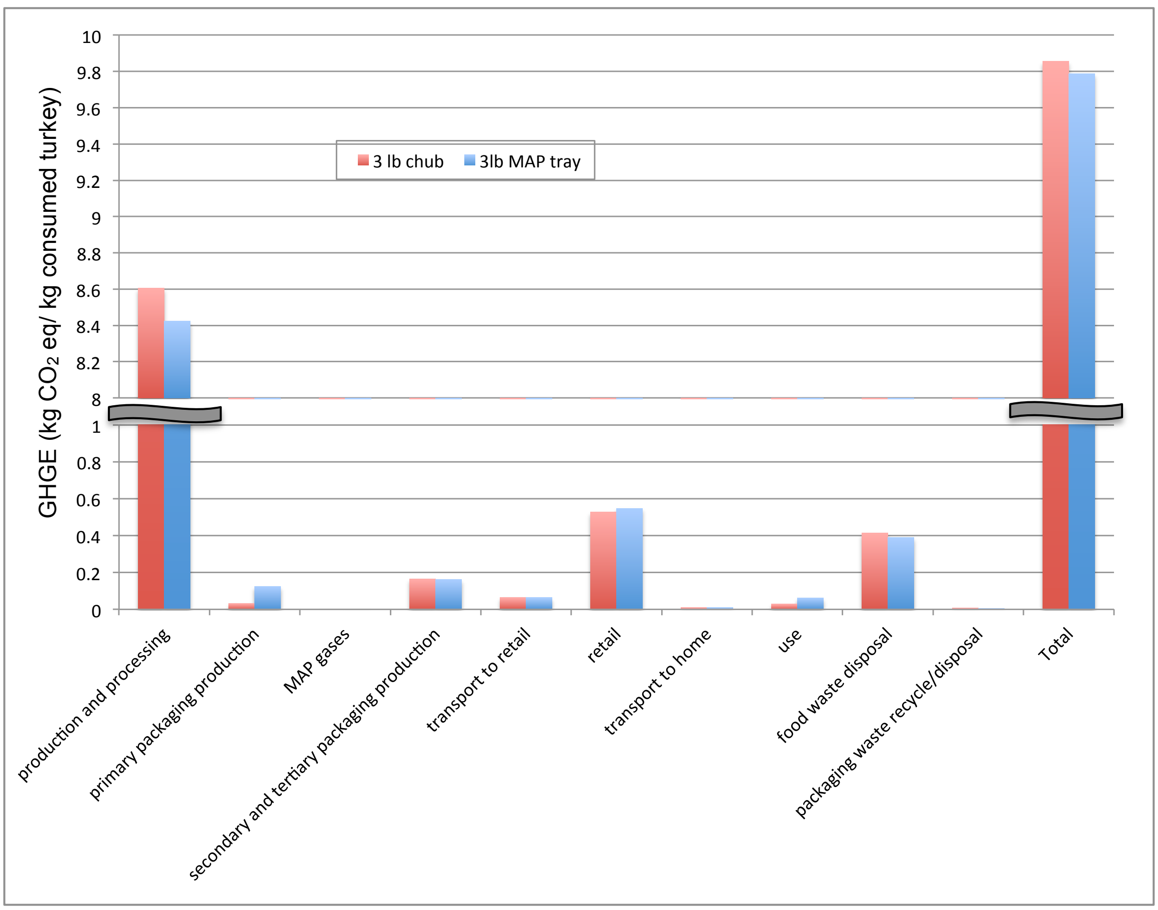

Figure 9. Distribution of greenhouse gas emissions per kg of consumed product, comparing the chub packaging with MAP tray packaging of ground turkey. Note the break in scale in order to show detail of the less contributing life cycle stages.

product, and home refrigeration (use phase) is a function of product volume, which explains the increase in these two stages when going to the MAP tray.

The relative difference between the two packaging systems can be better seen if the contributions due to the food that is actually consumed as well as the consumer level food waste (which is assumed equal in this case) are removed. Figure 10 shows the GHGE of only the retail-level food waste *and* the full impacts of the packaging system. In other words, Figure 10 compares the components of the system that are *different* in the two packaging configurations, leaving out those components that are equivalent.

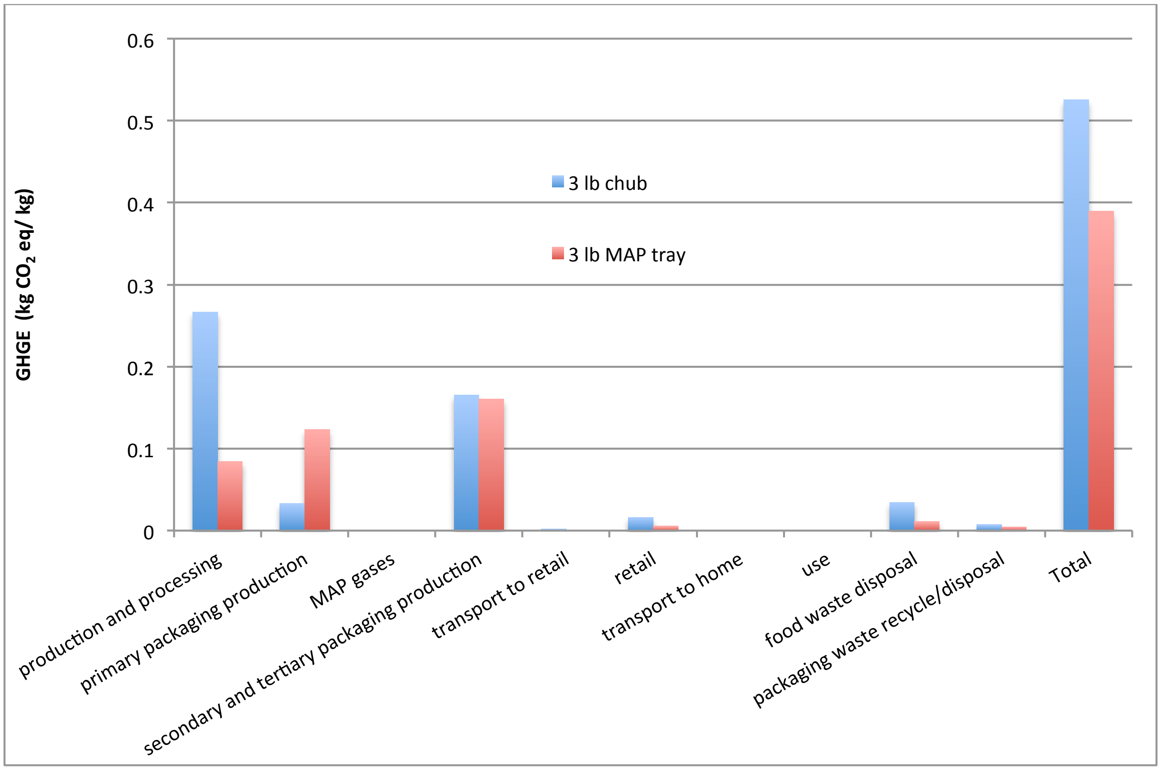

Figure 10. System GHGE showing only the contribution due to wasted food and total packaging (does not include contributions from the 1 kg of consumed turkey that is the functional unit).

Interestingly, while reductions in retail food waste are sufficient to offset the increased GHGE due to additional packaging, this is not the case with cumulative energy demand, as can be seen in Figure 11 (numerical values shown in Table 13). In this case, the energy intensity of packaging production relative to food production results in a net increase in energy use for the system when shifting from chub to MAP tray packaging.

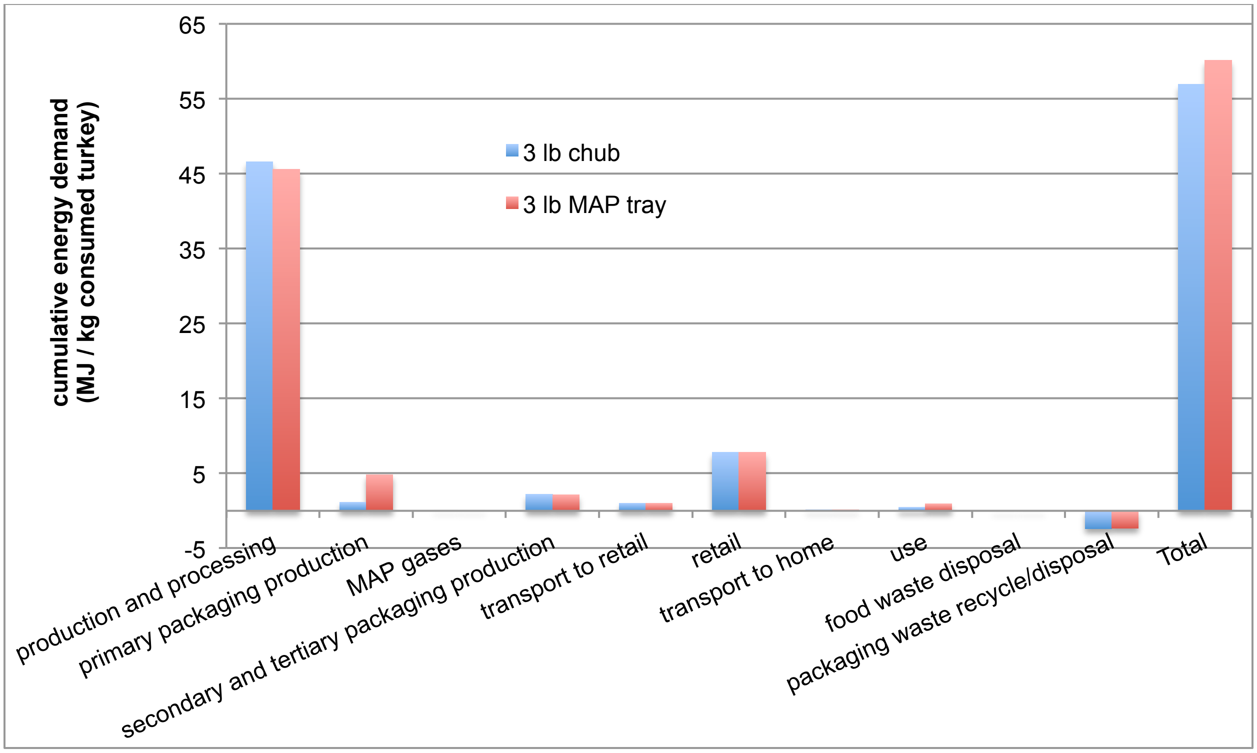

Figure 11. Distribution of cumulative energy demand per kg of consumed product, comparing the two packaging configurations.

Table 14 gives the results of a sensitivity assessment conducted on the MAP tray case. In order to demonstrate the influence of various modeling parameters on the total system impacts, we varied each parameter independently by ±20%. The results show that, for the majority of modeling parameters, a 20% change in value has less than a 1% effect on the overall system impact, suggesting that estimates used in the model do not carry a strong influence.

Table 13. Results of ground turkey case study, by life cycle stage and contributions from consumed food and wasted food.

	3 lb chub		3 lb MAP tray	
	GHGE kg CO_2 eq/ kg consumed	CED MJ / kg consumed	GHGE kg CO_2 eq/ kg consumed	CED MJ / kg consumed
Turkey production & processing				
Consumed food	5.42	29.4	5.42	29.4
Wasted food	3.19	17.2	3.00	16.3
Packaging production				
Consumed food	0.125	2.11	0.184	4.49
Wasted food	0.0734	1.24	0.102	2.49
Transport to retail				
Consumed food	0.0411	0.656	0.0411	0.656
Wasted food	0.0242	0.385	0.0228	0.363
retail				
Consumed food	0.333	4.92	0.353	5.04
Wasted food	0.196	2.89	0.195	2.79
Transport to home				
Consumed food	0.00601	0.0884	0.00601	0.0884
Wasted food	0.00324	0.0475	0.00324	0.0475
Home refrigeration (use)				
Consumed food	0.0191	0.291	0.0407	0.620
Wasted food	0.0103	0.157	0.0219	0.334
Food waste disposal	0.413	-0.043	0.390	-0.0407
Packaging disposal				
Consumed food	0.00466	-1.50	0.00293	-1.48
Wasted food	0.00274	-0.883	0.00162	-0.822
TOTAL				
Consumed food	5.95	35.9	6.05	38.8
Wasted food	3.91	21.0	3.74	21.4
SUM	9.86	56.9	9.79	60.2

Table 14. Sensitivity assessment of various modeling parameters on the total system environmental impacts. The base case for this assessment is: MAP tray ground turkey, retail waste = 1.0%, consumer waste = 35%.

parameter	% change in total system impacts due to +/- 20% change in parameter			
	GHGE		CED	
	+20%	-20%	+20%	-20%
Weight of primary packaging	0.26%	-0.26%	1.62%	-1.62%
Weight of tertiary packaging	0.35%	-0.34%	-0.046%	0.045%
Product volume per kg	0.13%	-0.13%	0.32%	-0.32%
Customer facing area per kg	0.13%	-0.13%	0.12%	-0.12%
Retail price per kg	1.0%	-1.0%	2.53%	-2.53%
Annual kg sold at retail	-0.086%	0.14%	-0.049%	0.095%
National total grocery sales	-0.84%	1.3%	-2.1%	3.2%
Transport distance to retail	0.13%	-0.13%	0.34%	-0.34%
Total display area of retail refrigeration unit	-0.020%	0.029%	-0.018%	0.026%
Annual home refrigeration energy use	0.13%	-0.13%	0.32%	-0.32%
Average home refrigerator volume	-0.11%	0.16%	-0.26%	0.40%
Days in home refrigerator	0.13%	-0.13%	0.32%	-0.32%
Corrugated cardboard recycling rate	-0.15%*	0.29%	-0.35%*	0.70%
Food composting rate	-0.035%	0.035%	0.007%	-0.007%
PP recycling rate	-0.003%	0.003%	-0.014%	0.014%
Wood recycling rate	-0.003%	0.003%	0.000%	0.000%
Consumer-level food waste rate	12.9%	-10.4%	12.1%	-9.7%
Retail-level food waste rate	0.22%	-0.22%	0.20%	-0.20%
Turkey production	17.2%	-17.2%	13.2%	-13.2%
Turkey processing	-	-	2.0%	-2.0%

*Given the high baseline recycling rate (90.9%), a full 20% increase would place the rate at over 100%. Value capped at 100%

7.4. Discussion and conclusions

This ground turkey case represents one where virtually identical product is supplied in differing packaging formats. While it appears that the driver for introducing the MAP tray packaging may not be increased shelf life, nonetheless, based on the retail waste rate data available, the MAP tray does demonstrate a lower retail-level waste. This reduced waste is sufficient to offset the additional GHGE attributable to more sophisticated packaging, resulting in a net system reduction in GHGE per kg of consumed product when shifting from the chub packaging to the MAP tray packaging. On the other hand, this break-even point is not reached in our assessment of the energy use attributable to the food-packaging systems, meaning that the energy use per kg of consumed product is greater for the MAP tray than the chub packaging.

It should be noted that while the consumer-level waste rate used in this example may seem almost absurdly high, as long as the same consumer waste rate is used in both scenarios, it does not affect the final result as both scenarios scale equally with increased consumer-level waste rate. Of course, if there were reason to assign different consumer waste to the two packaging configurations, this could have significant influence on the results. At this point, we have no evidence to suggest differing waste behaviors at the consumer level with the different packages.

The sensitivity assessment conducted as part of this case gives indication to the influence of modeling parameters used throughout this study. With exception of the parameters that one would anticipate to have large influence on the overall results (waste rates and food production impacts), all other parameters have limited influence, with the vast majority showing less than a 1% effect on overall system impacts due to a 20% change in their value.

8. Project Conclusions

The goals of this project were to explore the trade-off between environmental impact of food waste and food packaging, and to demonstrate the role of packaging in controlling food waste. We have presented three scenarios (beef case 1a, 1c & turkey case 3) where "increased" or optimized packaging correlates with lower retail-level food waste rates. Other presented scenarios, namely beef 1b and lettuce (case 2), demonstrate that more advanced packaging options do not always lead to lowered waste rates.

Further, the cases presented demonstrate the delicate balance between food waste and food packaging when considering a packaging design change. Scenarios 1a & 3 offer situations where, when a packaging change leads to reduced food waste, the break-even point is reached with respect to GHGE (meaning, the reduction in GHGE due to lower waste is sufficient to offset the increase in emissions due to changes in packaging), but that the break-even point is NOT reached with respect to cumulative energy demand.

The cases considered here vary widely in their generic behavior. In the beef and turkey cases, food production, processing and disposal represent 90-97% of the overall system GHGE, with packaging production and disposal constituting only 1-2% of the total. On the other hand, in the romaine lettuce case, packaging production and disposal constitutes 20% of the GHGE total, whereas the lettuce production, processing and disposal represents 25%. As suggested in the literature review presented in our Phase 1 report, this ratio – the environmental impact of the food relative to that of the packaging – is a key indicator of whether reduced food waste from additional packaging will be a net system benefit.

A generalized observation made as part of this study is that packaging design within the US market is currently not optimized to minimize food waste. Clearly, we have not investigated enough cases to make this a definitive conclusion. Yet, based on our observations, it appears that food waste reduction, and overall system environmental impact, are often not the top priority in determining packaging configurations. This is perhaps not surprising, as packaging offers numerous other functions such as product appearance and appeal, retailer and consumer convenience, etc. However, as efforts to reduce food waste intensify, the importance of food waste reduction in packaging design may increase. The turkey case is an excellent example of a change in packaging configuration that has not necessarily been driven by a desire to reduce food waste. Personal communication with R&D at the product supplier suggested that the investment in modified atmosphere packaging was not made to increase shelf life, but instead for marketing purposes. Interestingly, based on the retail waste data collected here, this new MAP product actually demonstrated a lower retail waste rate than its equivalent in simple "chub" packaging. Additional data collection is required to confirm that this trend holds up in other markets and over time. The beef scenarios gathered from our retail partner also suggest large retail waste rates that could potentially be minimized with optimized packaging configurations.

A great deal of effort in this study went in to gathering food waste rate data for specific products, such that comparisons could be made between differing packaging configurations. Much of this effort involved building relationships with grocery retailers and "selling" the project such that retailers found it worth their effort to participate. Far more doors were closed than were opened. Participation by additional retailers would certainly benefit both the selection of possible scenarios as well as the statistics of retail waste rates.

The lack of consumer-level waste rates for specific products is a notable shortfall for this project. While the USDA sourced consumer waste rates used here offer an "place-holding" approximation, they cover broad commodity categories and include wastes (such as, for example, plate scraps) that would ideally not be included in a comparison of this nature, as they are unlikely influenced by packaging design. Appendix B contains a series of sensitivity analyses of the influence of consumer-level waste rates on overall results. The indirect method offered in case 1a offers a coarse approximation of the potential for packaging to effect consumer-level food waste. Establishing this relationship more directly is extremely difficult and would require extensive surveying or, perhaps more desirably, consumer "experiments" in which differing packaging options of the same food product are given to equal fractions of a population. Even with such studies, disentangling the cause of wasted food and assigning waste reduction to packaging is extremely difficult.

A sensitivity study performed as part of the turkey case (Case 3) suggests that the majority of the large number of modeling parameters utilized in this study have minimal influence on the overall result: for most, a 20% change in parameter value has less than a 1% effect on net results. This is to say that while assumptions and estimates were often necessary to approximate missing data, these approximations have a small effect on the final results.

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Appendix A. Data tables for Figures

Data for Figure 2. Distribution of greenhouse gas emissions across the life cycle for Case 1a: comparing tray with overwrap and high oxygen MAP packaging. Note the break in the y-axis in order to show details of the small contributions from most life cycle stages. Total values are PS tray: 44.56 kg CO_2 eq/kg beef consumed; high O_2 MAP: 43.78 kg CO_2 eq/kg beef consumed..

	Tray w/ overwrap	Hi O_2 MAP
production and processing	43.1	42.2
primary packaging production	0.159	0.284
MAP gases		7.33E-05
secondary and tertiary packaging production	0.14	0.137
transport to retail	0.0552	0.0541
retail	0.689	0.635
transport to home	0.2	0.2
use	0.0349	0.051
food waste disposal	0.242	0.222
packaging waste recycle/disposal	0.012	0.0107
Total	44.6	43.8

Data for Figure 3. Distribution of cumulative energy demand per kg of consumed beef for Case 1a: comparing tray with overwrap and high oxygen MAP packaging. Note the break in the y axis in order to show detail of life cycle stages with small contributions. Total values are PS tray: 108.1 MJ /kg beef consumed; high O2 MAP: 110.1 MJ /kg beef consumed.

	tray w/ overwrap	hi O2 MAP
production and processing	88.9	87.0
primary packaging production	5.02	9.41
MAP gases		0.000777
secondary and tertiary packaging production	1.86	1.82
transport to retail	0.881	0.863
retail	10.5	9.70
transport to home	2.94	2.94
use	0.532	0.776
food waste disposal	-0.0253	-0.0232
packaging waste recycle/disposal	-2.52	-2.40
Total	108	110

Data for Figure 4. Distribution of greenhouse gas emissions across life cycle stages, comparing sealed tray with skin packaging. Red portions of bars are contributions due to retail waste. Note break in y-axis to show details of lesser contributing stages. Values for life cycle totals: EPS tray: 63.3 kg CO_2 eq/kg consumed; skin pack: 50.9 kg CO_2 eq / kg consumed.

	EPS tray with sealed film			"Darfresh" skin packaging		
	consumed portion	contribution of retail waste	total	consumed portion	contribution of retail waste	total
production and processing	40.1	20.6	60.7	40.1	8.80	48.9
primary packaging production	0.295	0.152	0.447	0.357	0.0784	0.436
secondary and tertiary packaging production	0.130	0.0671	0.197	0.130	0.0286	0.159
transport to retail	0.0514	0.0265	0.0778	0.0514	0.0113	0.0627
retail	0.600	0.309	0.909	0.600	0.132	0.731
transport to home	0.200	0	0.200	0.200	0	0.200
use	0.0233	0	0.0233	0.0233	0	0.0233
food waste disposal	0.176	0.453	0.629	0.176	0.193	0.369
packaging waste recycle/disposal	0.0181	0.00913	0.0273	0.0224	0.00492	0.0273
Total	41.6	21.7	63.2	41.6	9.25	50.9

Data for Figure 5. Distribution across life cycle stages of cumulative energy demand, comparing sirloin steak packaged in sealed EPS tray with Darfresh skin pack. Life cycle totals: EPS tray: 155 MJ/ kg consumed beef; skin pack: 129 MJ/ kg consumed beef.

	EPS tray w/ sealed film	"Darfresh" skin packaging
production and processing	125	101
primary packaging production	12.3	13.6
tertiary packaging production	2.62	2.11
transport to retail	1.24	0.999
retail	13.9	11.2
transport to home	2.94	2.94
use	0.356	0.356
food waste disposal	-0.0657	-0.0385
packaging waste recycle/disposal	-3.63	-3.25
Total	155	129

Data for Figure 6. Distribution of GHGE per kg of consumed product across life cycle stages. The figure compares the romaine lettuce head scenario (darkened bars) with bagged, ready-to-eat romaine lettuce (lighter bars). Also shown are the contributions due to consumed product, edible losses, and inedible losses.

	9 oz. lettuce head				9 oz. bagged, ready-to-eat lettuce			
	consumed portion	inedible losses	edible losses	total	consumed portion	inedible losses	edible losses	total
production and processing	0.183	0.0199	0.0648	0.268	0.183	0.0150	0.0694	0.268
primary packaging production	0.0168	0.00182	0.00592	0.0245	0.0732	1E-09	0.0256	0.0987
secondary and tertiary packaging production	0.0624	0.00678	0.0221	0.0912	0.224	0	0.0782	0.301708

transport to retail	0.474	0.0515	0.167	0.693	0.474	0	0.166	0.639
retail	0.243	0.0264	0.0859	0.355	0.317	0	0.111	0.427
transport to home	0.0122	0.00132	0.00426	0.0177	0.0122	0	0.00384	0.0160
use	0.138	0.0150	0.0483	0.201	0.184	0	0.0582	0.242
food waste disposal	0	0.0764	0.249	0.325	0	0.0764	0.273	0.349
packaging waste recycle/disposal	0.0570	0.00620	0.0201	0.0834	0.00921	0	0.00322	0.0124
Total	1.19	0.205	0.667	2.06	1.48	0.0914	0.787	2.36

Data for Figure 7. Distribution of life cycle energy demand for the romaine lettuce scenarios.

	9 oz. lettuce head	9 oz. bagged, ready-to-eat lettuce
production and processing	16.0	16.3
primary packaging production	0.857	3.29
secondary and tertiary packaging production	1.93	6.39
transport to retail	11.4	10.5
retail	4.85	5.06
transport to home	0.274	0.247
use	3.32	3.92
food waste disposal	-0.0340	-0.0365
packaging waste recycle/disposal	-0.225	-4.51
Total	38.3	41.1

Data for Figure 8. Distribution of blue water use across the life cycle for the romaine lettuce scenarios. Here, blue water use is evaluated based on the ReCiPe impact assessment method's midpoint indicator. Food and packaging disposal stages are not shown because the model does not contain water use estimates for these stages.

	9 oz. lettuce head	9 oz. bagged, ready-to-eat lettuce
production	0.129	0.132
processing	0	0.006
primary packaging production	0.0002	0.0008
secondary and tertiary packaging production	0.0007	0.0022
transport to retail	0.0021	0.0020
retail	4.2E-05	4.2E-05
transport to home	7.6E-05	6.9E-05
use	0.0594	6.9E-07
food waste disposal	0	0
packaging waste recycle/disposal	0	0
total	0.192	0.143

Data for Figure 9. Distribution of greenhouse gas emissions per kg of consumed product, comparing the chub packaging with MAP tray packaging of ground turkey. Note the break in scale in order to show detail of the less contributing life cycle stages.

	3 lb. chub	3 lb. MAP tray
production and processing	8.61	8.42
primary packaging production	0.0329	0.124
MAP gases	0	0.0000576
secondary and tertiary packaging production	0.166	0.162
transport to retail	0.0653	0.0639
retail	0.528	0.548
transport to home	0.00925	0.00925
use	0.0294	0.0626
food waste disposal	0.413	0.390
packaging waste recycle/disposal	0.00739	0.00455
Total	9.86	9.79

Data for Figure 10. System GHGE showing only the contribution due to wasted food and total packaging (does not include contributions from the 1 kg of consumed turkey that is the functional unit).

	3 lb. chub	3 lb. MAP tray
production and processing	0.267	0.0842
primary packaging production	0.0329	0.123
MAP gases	0	0.000057
secondary and tertiary packaging production	0.166	0.160
transport to retail	0.00202	0.00064
retail	0.0164	0.00548
transport to home	0	0
use	0	0
food waste disposal	0.0346	0.0109
packaging waste recycle/disposal	0.00739	0.00455
Total	0.526	0.390

Data for Figure 11. Distribution of cumulative energy demand per kg of consumed product, comparing the two packaging configurations.

	3 lb. chub	3 lb. MAP tray
production and processing	46.6	45.6
primary packaging production	1.15	4.83
MAP gases	0	0.00061
secondary and tertiary packaging production	2.20	2.15
transport to retail	1.04	1.02
retail	7.82	7.82
transport to home	0.136	0.136

use	0.447	0.953
food waste disposal	-0.0432	-0.0407
packaging waste recycle/disposal	-2.39	-2.31
Total	57.0	60.2

Appendix B: Sensitivity to Consumer waste rates

Appendix B presents a series of figures (and accompanied data tables) that demonstrate the effect of a change in consumer waste rate on the results presented in the report. Please note that specific values presented here may differ slightly from values that appear elsewhere: this is due to the fact that the Ecoinvent database has been updated since initial calculations were performed, and some processes have been modified slightly. In all cases, the differences are insignificant.

Case 1a: Beef in PS tray with overwrap vs. high O2 MAP tray.

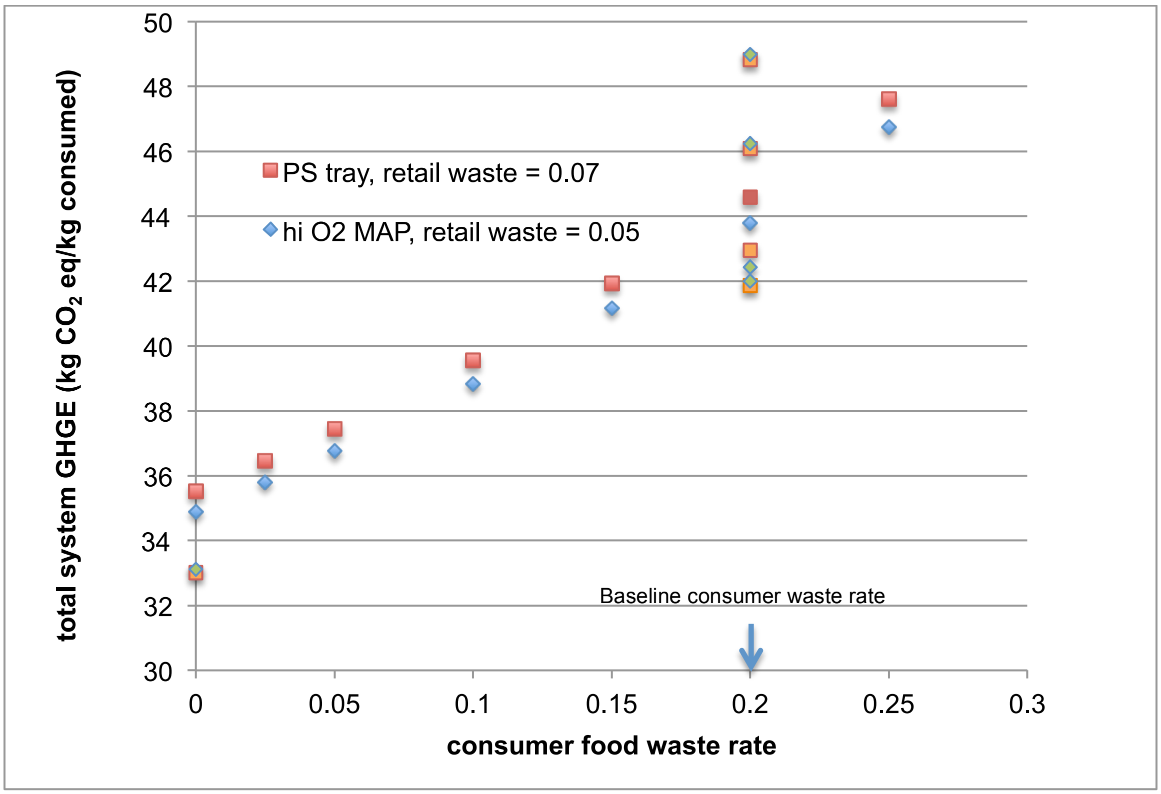

Figure B1. Influence of consumer food waste rate on total system GHGE for beef case 1a. Figure also shows sensitivity to retail waste rate at the baseline consumer waste rate, and values with no edible waste. See Table B1 for these retail waste rate values.

Table B1. Data for Figure B1

waste rates		total system GHGE (kg CO2 eq/kg consumed)	
consumer	retail	PS tray	hi O2 MAP
0.25	0.07	47.6	
0.25	0.05		46.8
0.2	0.15	48.8	49.0
0.2	0.1	46.1	46.2
0.2	0.07	44.6	
0.2	0.05		43.8

0.2	0.035	43.0	
0.2	0.02		42.4
0.2	0.01	41.9	42.0
0.15	0.07	41.9	
0.15	0.05		41.2
0.1	0.07	39.6	
0.1	0.05		38.8
0.05	0.07	37.4	
0.05	0.05		36.8
0.025	0.07	36.5	
0.025	0.05		35.8
0	0.07	35.5	
0	0.05		34.9
0	0	33.0	33.1

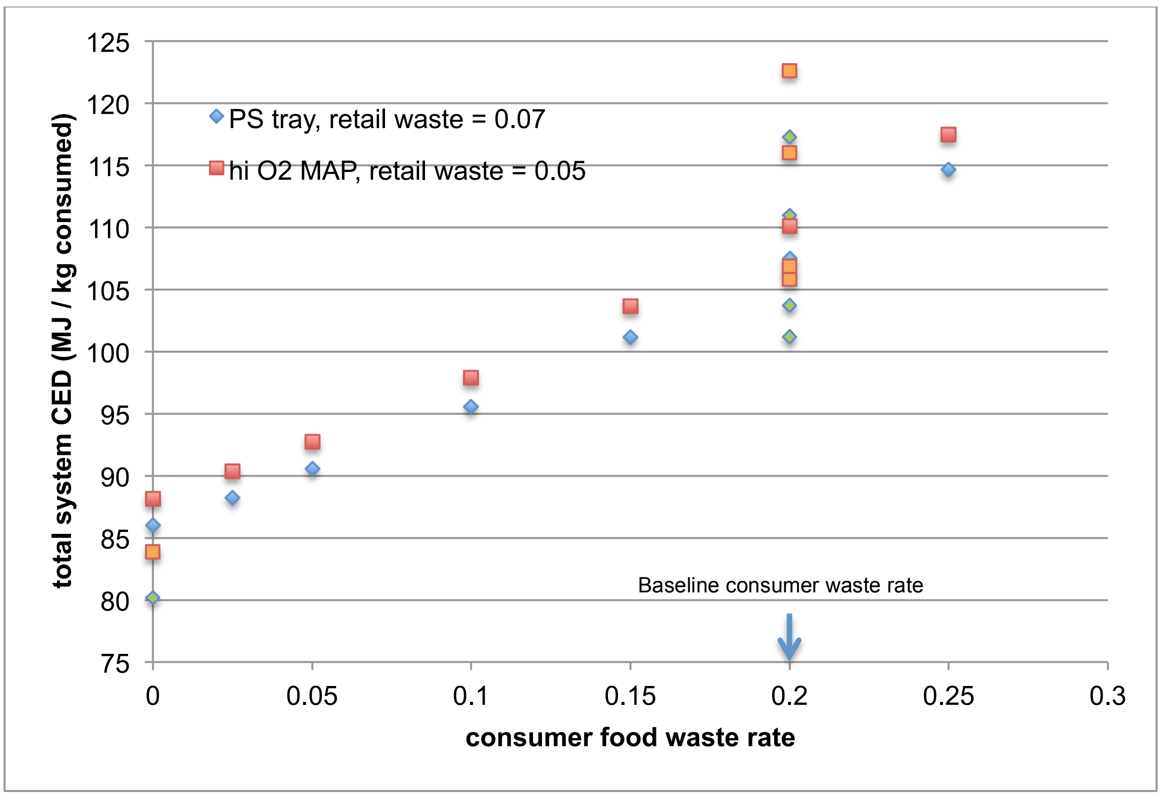

Figure B2. Influence of consumer food waste rate on total system cumulative energy demand for beef case 1a. Figure also shows sensitivity to retail waste rate at the baseline consumer waste rate, and values with no edible waste. See Table B2 for these retail waste rate values.

Table B2: Data for Figure B2.

waste rates		total system CED (MJ/kg consumed)	
consumer	retail	PS tray	hi O2 MAP
0.25	0.07	114.7	

0.25	0.05		117.5
0.2	0.15	117.3	122.6
0.2	0.1	111.0	116.0
0.2	0.07	107.5	
0.2	0.05		110.1
0.2	0.035	103.7	
0.2	0.02		106.9
0.2	0.01	101.2	105.8
0.15	0.07	101.2	
0.15	0.05		103.6
0.1	0.07	95.6	
0.1	0.05		97.9
0.05	0.07	90.5	
0.05	0.05		92.7
0.025	0.07	88.2	
0.025	0.05		90.4
0	0.07	86.0	
0	0.05		88.1
0	0	80.2	83.9

Case 1c: Denkstatt example. Beef in EPS tray vs. skin packaging.

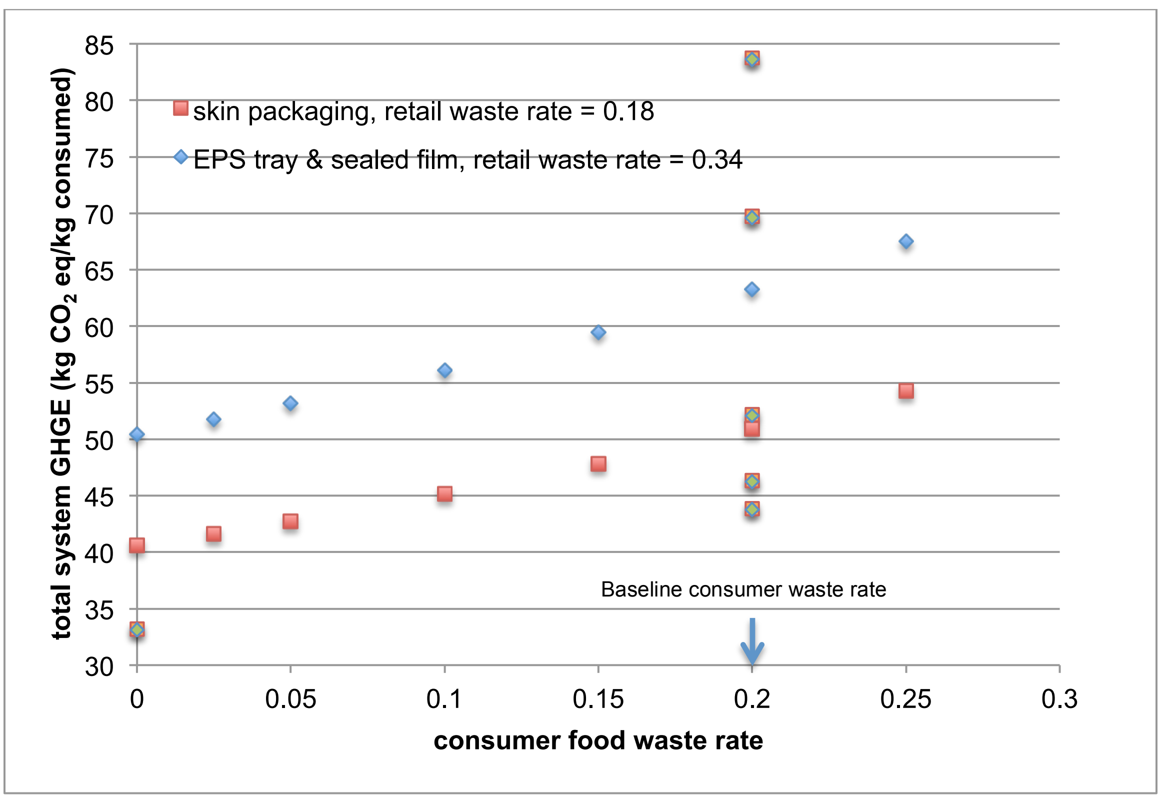

Figure B3. Influence of consumer food waste rate on total system GHGE for beef case 1c. Figure also shows sensitivity to retail waste rate at the baseline consumer waste rate, and values with no edible waste. See Table B3 for these retail waste rate values.

Table B3: Data for Figure B3.

waste rates		total system GHGE (kg CO2 eq/kg consumed)	
consumer	retail	EPS tray	skin pack
0.25	0.34	67.5	
0.25	0.18		54.3
0.2	0.5	83.6	83.8
0.2	0.4	69.6	69.7
0.2	0.34	63.2	
0.2	0.2	52.1	52.2
0.2	0.18		50.9
0.2	0.1	46.2	46.3
0.2	0.05	43.8	43.9
0.15	0.34	59.5	
0.15	0.18		47.9
0.1	0.34	56.1	
0.1	0.18		45.2
0.05	0.34	53.1	
0.05	0.18		42.7
0.025	0.34	51.8	
0.025	0.18		41.6
0	0.34	50.5	
0	0.18		40.6
0	0	33.1	33.2

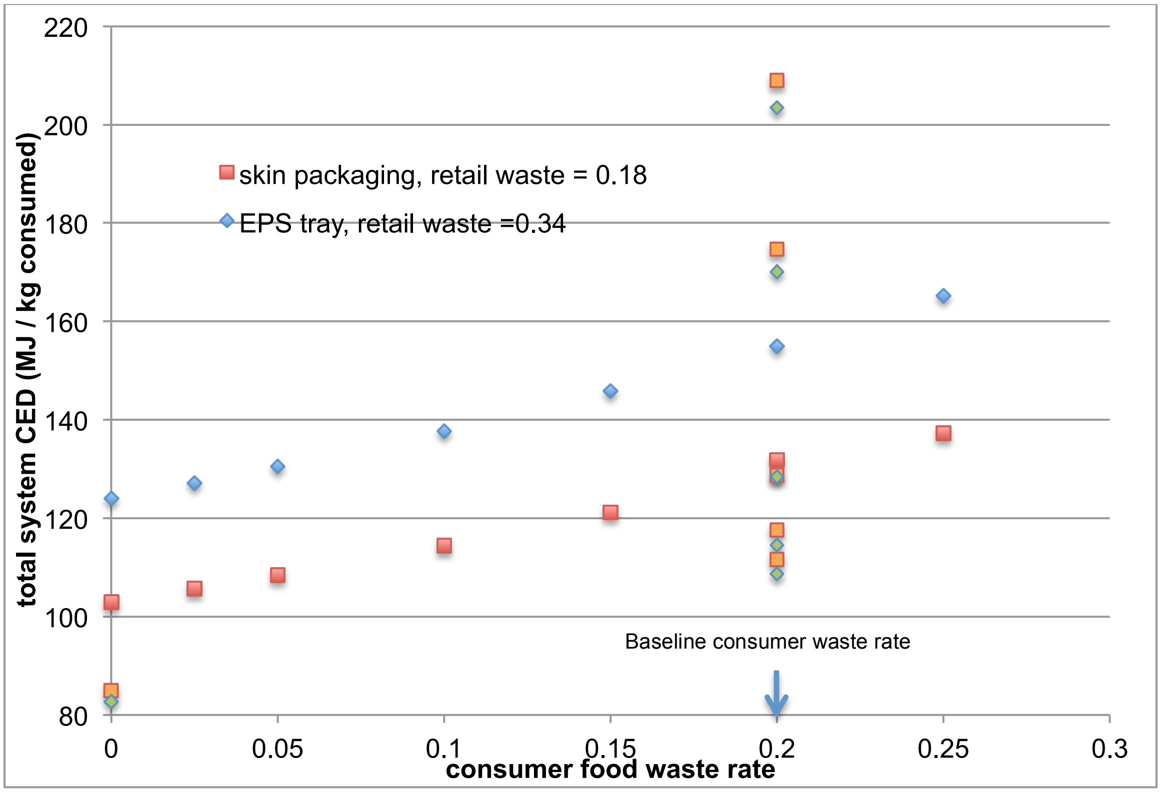

Figure B4. Influence of consumer food waste rate on total system cumulative energy demand for beef case 1c. Figure also shows sensitivity to retail waste rate at the baseline consumer waste rate, and values with no edible waste. See Table B4 for these retail waste rate values.

Table B4: Data for Figure B4

waste rates		total system CED (MJ/kg consumed)	
consumer	retail	EPS tray	skin pack
0.25	0.34	165.3	
0.25	0.18		137.3
0.2	0.5	203.4	209.0
0.2	0.4	170.1	174.7
0.2	0.34	154.9	
0.2	0.2	128.4	131.9
0.2	0.18		128.7
0.2	0.1	114.5	117.6
0.2	0.05	108.7	111.6
0.15	0.34	145.8	
0.15	0.18		121.2
0.1	0.34	137.7	
0.1	0.18		114.4
0.05	0.34	130.5	
0.05	0.18		108.4
0.025	0.34	127.1	

0.025	0.18		105.6
0	0.34	124.0	
0	0.18		103.0
0	0	82.7	84.9

Case 2: Romaine head lettuce vs. ready-to-eat, bagged.

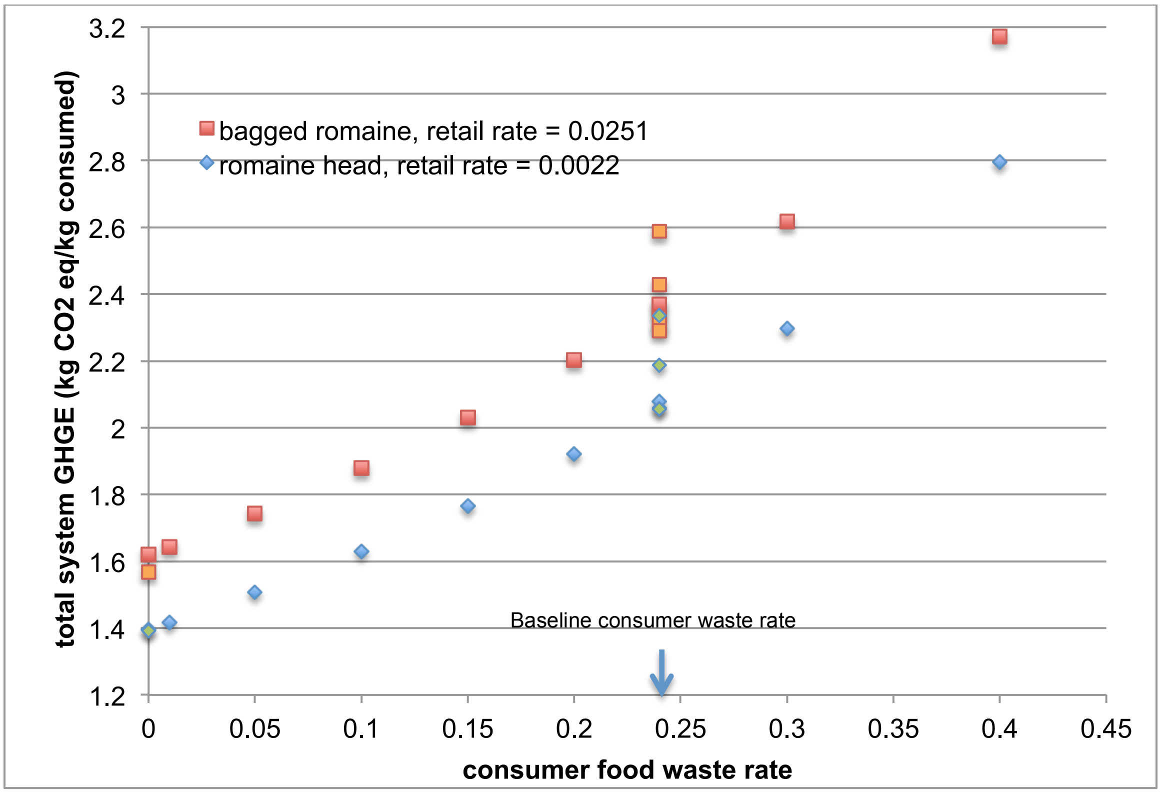

Figure B5. Influence of consumer food waste rate on total system GHGE for lettuce case 2. Figure also shows sensitivity to retail waste rate at the baseline consumer waste rate, and values with no edible waste. See Table B5 for these retail waste rate values.

Table B5: Data for Figure B5

waste rates		total system GHGE (kg CO2 eq/kg consumed)	
consumer	retail	Head lettuce	Bagged lettuce
0.4	0.0251		3.17
0.4	0.0022	2.80	
0.3	0.0251		2.62
0.3	0.0022	2.30	
0.24	0.1	2.34	2.59
0.24	0.05	2.19	2.43
0.24	0.03		2.37
0.24	0.0251		2.36

0.24	0.01	2.08	2.31
0.24	0.0022	2.06	
0.24	0.002		2.29
0.24	0.001	2.06	
0.2	0.0251		2.20
0.2	0.0022	1.92	
0.15	0.0251		2.03
0.15	0.0022	1.77	
0.1	0.0251		1.88
0.1	0.0022	1.63	
0.05	0.0251		1.74
0.05	0.0022	1.51	
0.01	0.0251		1.64
0.01	0.0022	1.42	
0	0.0251		1.62
0	0.0022	1.40	
0	0	1.39	1.57

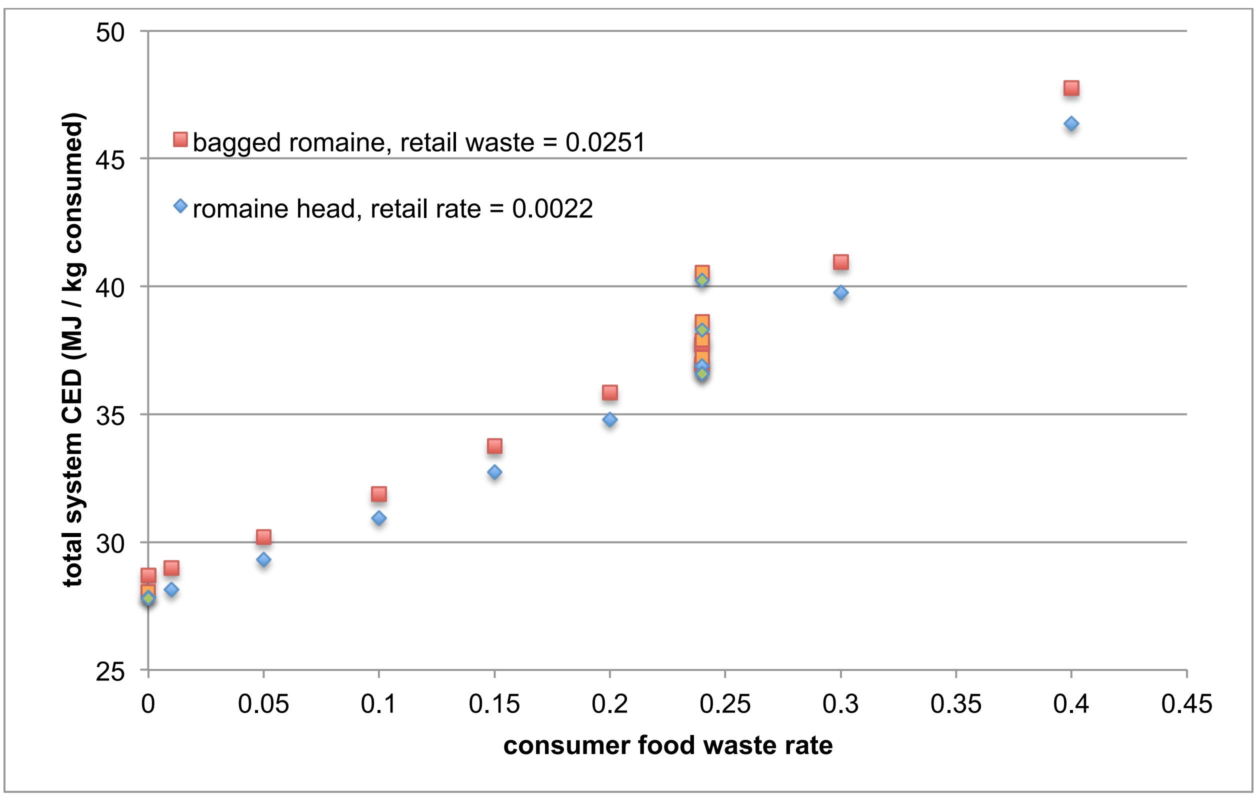

Figure B6. Influence of consumer food waste rate on total system cumulative energy demand for lettuce case 2. Figure also shows sensitivity to retail waste rate at the baseline consumer waste rate, and values with no edible waste. See Table B6 for these retail waste rate values.

Table B6: Data for Figure B6

waste rates		total system CED (MJ/kg consumed)	
consumer	retail	head lettuce	bagged lettuce
0.4	0.0251		47.78
0.4	0.0022	46.37	
0.3	0.0251		40.96
0.3	0.0022	39.75	
0.24	0.1	40.24	40.54
0.24	0.05	38.29	38.62
0.24	0.03		37.90
0.24	0.0251		37.73
0.24	0.01	36.88	37.22
0.24	0.0022	36.62	
0.24	0.002		36.95
0.24	0.001	36.58	
0.2	0.0251		35.85
0.2	0.0022	34.79	
0.15	0.0251		33.75
0.15	0.0022	32.75	
0.1	0.0251		31.88
0.1	0.0022	30.94	
0.05	0.0251		30.20
0.05	0.0022	29.31	
0.01	0.0251		28.98
0.01	0.0022	28.13	
0	0.0251		28.70
0	0.0022	27.85	
0	0	27.79	28.05

Case 3: Ground turkey chub vs. MAP tray

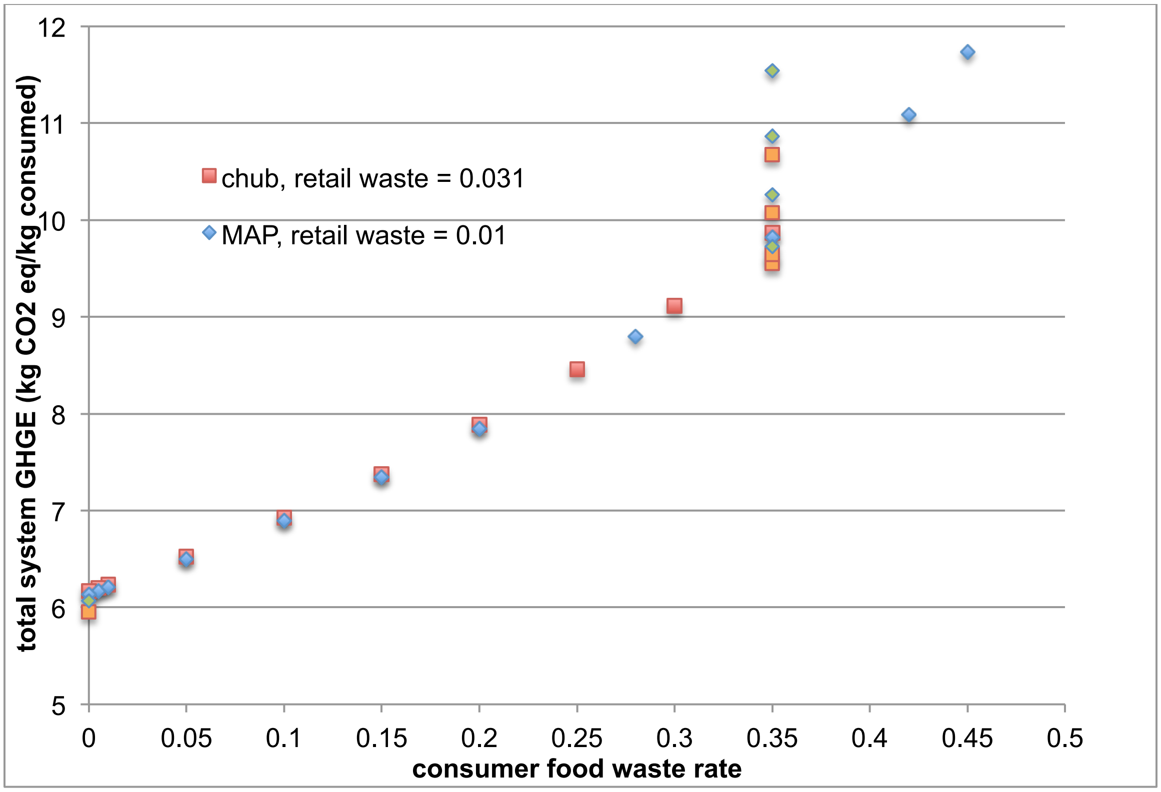

Figure B7. Influence of consumer food waste rate on total system GHGE for turkey, case 3. Figure also shows sensitivity to retail waste rate at the baseline consumer waste rate, and values with no edible waste. See Table B7 for these retail waste rate values.

Table B7: Data for Figure B7

waste rates		total system GHGE (kg CO_2 eq/kg consumed)	
consumer	retail	chub	MAP tray
0.45	0.01		11.73
0.42	0.01		11.09
0.35	0.15		11.54
0.35	0.1	10.67	10.86
0.35	0.05	10.08	10.26
0.35	0.031	9.87	
0.35	0.01	9.64	9.82
0.35	0.001	9.55	9.73
0.3	0.031	9.11	
0.28	0.01		8.80
0.25	0.031	8.46	
0.2	0.031	7.88	
0.2	0.01		7.85
0.15	0.031	7.38	
0.15	0.01		7.34
0.1	0.031	6.93	

0.1	0.01		6.90
0.05	0.031	6.53	
0.05	0.01		6.50
0.01	0.031	6.24	
0.01	0.01		6.21
0.005	0.031	6.20	
0.005	0.01		6.17
0	0.031	6.17	
0	0.01		6.14
0	0	5.95	6.07

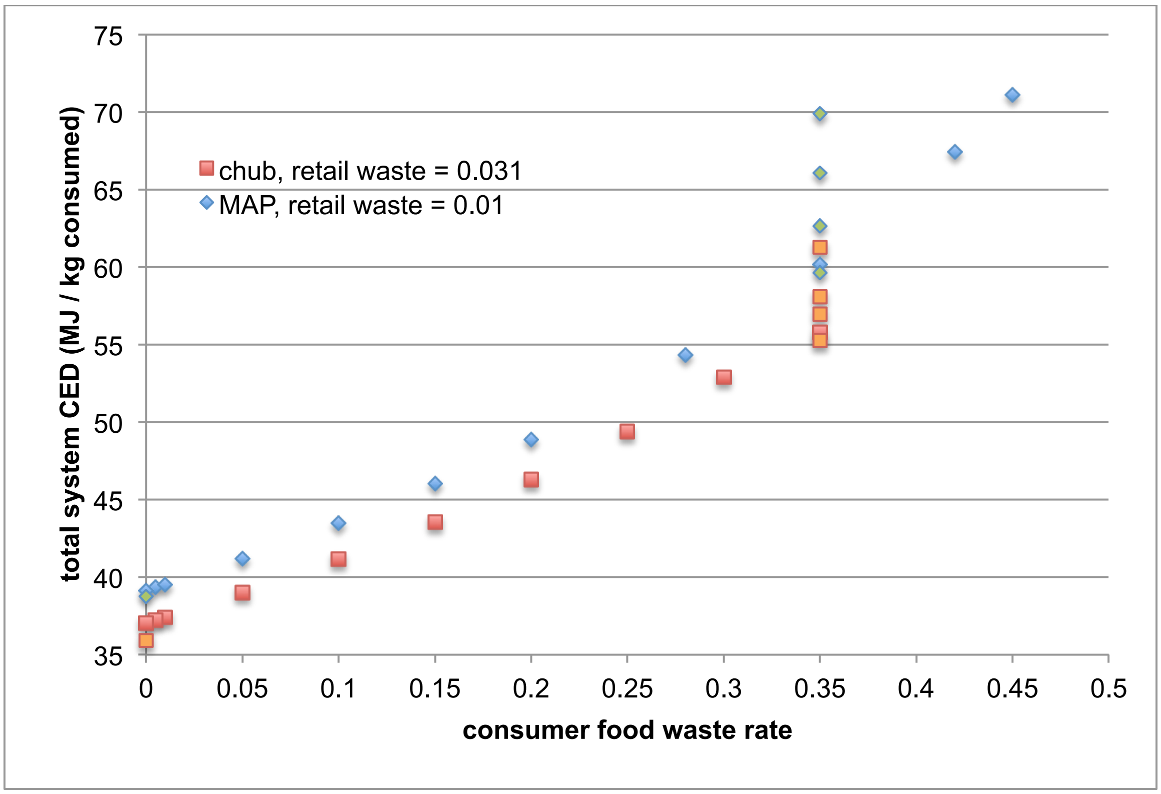

Figure B8. Influence of consumer food waste rate on total system cumulative energy demand for turkey, case 3. Figure also shows sensitivity to retail waste rate at the baseline consumer waste rate, and values with no edible waste. See Table B8 for these retail waste rate values.

Table B8: Data for Figure B8

waste rates		total system CED (MJ/kg consumed)	
consumer	retail	chub	MAP tray
0.45	0.01		71.1
0.42	0.01		67.4
0.35	0.15		69.9
0.35	0.1	61.3	66.1
0.35	0.05	58.1	62.7

0.35	0.031	57.0	
0.35	0.01	55.8	60.2
0.35	0.001	55.3	59.6
0.3	0.031	52.9	
0.28	0.01		54.3
0.25	0.031	49.4	
0.2	0.031	46.3	
0.2	0.01		48.9
0.15	0.031	43.6	
0.15	0.01		46.0
0.1	0.031	41.2	
0.1	0.01		43.5
0.05	0.031	39.0	
0.05	0.01		41.2
0.01	0.031	37.4	
0.01	0.01		39.5
0.005	0.031	37.2	
0.005	0.01		39.3
0	0.031	37.1	
0	0.01		39.1
0	0	35.9	38.8

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