Report No. CSS17-04
March 3, 2017

Optimizing the environmental performance of food product-package systems:

A life cycle assessment of the tradeoffs between packaging design and food waste

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Final project report to the Center for Packaging
Innovation and Sustainability

CENTER FOR
SUSTAINABLE SYSTEMS
UNIVERSITY OF MICHIGAN

Executive Summary

Food waste is a critical contemporary issue, both in the U.S. and internationally, in terms of food security and food system sustainability. Addressing this intricate problem will require multi-faceted approaches from corporate, government and personal fronts. Food packaging is ubiquitous in modern food systems, serving the primary function of protecting and distributing the right product to the right end-user in a safe, cost-efficient and user-friendly way. As a highly engineered and designed interface between food and the end user, food packaging offers an acute lever for influencing food wastage, both by inhibiting physical and bio-chemical degradation of food, but also by "scripting" individual behaviors around food handling, preparation, preservation and disposal. Yet, in the sustainable food packaging conversation to date, very little attention has been given to packaging's ability to contribute to net reductions in the environmental impact of food life cycles by reducing food waste.

A primary goal of this research project was to demonstrate the use of life cycle assessment in elucidating the environmental trade-offs between food waste and food packaging. A thorough review of the literature (Section 3) grounds this work in a solid academic foundation among food waste, food packaging, and food life cycle assessment. The major deliverable from the project was development of a life cycle assessment model capable of investigating the influence of both food waste and food packaging on the full life cycle environmental impact (focused on the indicators of greenhouse gas emissions (GHGE) and non-renewable energy demand) for specific food products and packaging configurations. This model was first used to map a wide variety of food types and their typical packaging configurations in order to elucidate general principles dictating the environmental trade off between food waste and food packaging (Section 7). Three specific case studies were also developed based on empirical food waste rates at retail in order to explore how changes in packaging effect food waste and full life cycle environmental performance.

The mapping exercise detailed in Section 7 identifies the "food-to-packaging ratio" – defined as the environmental impact (say, GHGE) associated with producing and processing the food divided by the environmental impact of producing packaging materials – as a useful scan-level indicator of the influence that food waste will have on overall system environmental performance. Often, estimates of this ratio can be generated without conducting a full life cycle assessment on a given product, offering a potential tool to assist in packaging design. At high food-to-packaging ratios, food waste is likely to have a strong influence on system environmental performance, and investments (in terms of increased environmental impact) in packaging that result in reduced food waste are *likely* to lead to net system environmental benefit. On the other hand, very low food-to-packaging ratios (less than unity) indicate that it will be much more difficult for investments in packaging aimed at reducing food waste to lead to net reductions in environmental impact. In these instances, sustainable design efforts are likely better directed at reducing the impact of the packaging itself.

The three case studies documented in this report offer three rather different viewpoints on the food waste/ packaging interaction. The first two cases are parallel in design: both compare bulk distribution and retail of fresh vegetables (with minimal packaging) to vegetables pre-packaged in PET trays/boxes. In both the case of mushrooms (Section 8) and spinach (Section 9), measured retail food waste rates were lower for the pre-packaged product than for the bulk product. With mushrooms, this decrease in food waste led to a net reduction in system GHGE and energy demand, despite the fact that packaging had a larger impact. In the spinach case, however, the food-to-packaging GHGE ratio is much lower (0.27 vs. 6.9 for mushrooms), and reductions in food waste were unable to balance out the increased impact of packaging, resulting in a net increase in GHGE and energy demand when going from bulk to pre-packaged spinach distribution and retailing.

The third case explores the common question of fresh vs. frozen vs. canned fruits and vegetables. Specific packaging is required to allow these preservation techniques to be marketed. The question asked in this case is whether the material and energy investments required for freezing and canning result in a net environmental benefit if retail food waste is taken into account? Pre-packaged, fresh green beans were compared with both frozen and canned green beans; the fresh beans exhibited retail-level waste rates at least a factor of ten higher than frozen or canned. Yet, system GHGE and energy demand were driven largely by processing and retail refrigeration energy requirements, resulting in greater system impacts with frozen and canned beans. Break-even scenarios were considered by assuming the frozen and canned beans also resulted in lower consumer-level food waste. Very low consumer-level waste rates were required for freezing and canning to break-even with the fresh scenario. If the fresh beans were assumed out-of-season and therefore transported a much greater distance, consumer-level waste rates still needed to be decreased in order for the preserved beans to break even, but these reductions were more reasonable. A similar comparison was made between fresh and frozen blueberries. Frozen had lower retail-level waste rates, but GHGE and energy demand were still greater than the fresh scenario. These results are very sensitive to processing energy demand and trends could change with more accurate data.

In conclusion, this project has demonstrated the opportunities, both theoretically and in empirically based case studies, for packaging to contribute to reduced food waste and for such waste reductions to lead to net environmental benefits. The project has also demonstrated, however, that the environmental balance between food waste and food packaging can be delicate, and careful assessment and quality waste rate data are needed in order to demonstrate a net environmental benefit in these tenuous cases. The detailed cases explored in this project lie close to the balancing point, making them interesting case studies. Surely there are other food/packaging combinations where the food-to-packaging ratio is much higher (beef, for instance) and opportunities for food waste reduction to result in system environmental benefit are much more certain. As a fully designed system at the interface between food and the end user, the opportunities for packaging to further influence food waste cannot and should not be overlooked.

Acknowledgements

The authors would like to acknowledge the contributions of the following School of Natural Resources and Environment graduate students that have participated in this project: Kari Paine, Luis Cecco, Wenjuan Liu. We would also like to acknowledge the generous assistance of Cimberly Weir and Susan Selke of CPIS throughout the duration of this project.

1. Summary of project deliverables

Delivered outputs from this project are outlined below. While the research scope was initially proposed for three years and the project was terminated after two years, this list of deliverables closely matches those promised in the initial proposal.

- Quarterly update reports submitted to CPIS.
- Annual presentations of progress and insights to CPIS members at center meetings (9/25/2014 and 11/19/2015).
- Providing CPIS members with a life cycle model for elucidating packaging and food waste trade-offs: the LCA model as developed in SimaPro will be documented and made available to CPIS (Susan Selke).
- At least one conference proceedings paper or peer reviewed journal article published per year of the project.
    1. "Demonstration of the Environmental Interplay between Food Waste and Food Packaging via Life Cycle Assessment", oral presentation at LCA XV, Vancouver, BC October 8, 2015.
    2. "Environmental Trade-offs between Food Packaging and Food Waste: Waste Rate Data Challenges," poster presentation at 10th International Conference on LCA in the Food and Agriculture Sector, Dublin, Ireland, October 19-21, 2016.
    3. "Mapping the Influence of Food Waste in Food Packaging Environmental Performance Assessments," manuscript submitted to *Environmental Science & Technology*, January 26, 2017. (Manuscript included in full in Section 7 of this report)
- Development of three specific case studies, as described in Sections 8-10.

2. Introduction

While the modern food industry has always 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. 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 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?

The remainder of this report is organized as follows. Section 3 provides a thorough literature review including an overview of life cycle assessment (LCA) applied to food, what we know about the extent and impacts of food waste, an overview of LCA applied to packaging and new packaging innovations, insights into opportunities for packaging to affect food waste, and a review of efforts to date to quantify the environmental trade-off between food packaging and food waste. Section 4 orients the remainder of the project by laying out the project objectives. Section 5 documents efforts to gather empirical food waste rates from retailers. Section 6 offers an overview of the LCA model, highlighting important modeling assumptions that were necessary in order to build a generic model that captures complex food system components. Section 7 contains a manuscript already submitted to an academic journal, and serves as a description of the LCA model and offers the mapping exercise that provides insight into the general behaviors of the food packaging/waste/environmental impact space. Section 8 details a case study involving mushrooms, where greater packaging (by weight and environmental impact) reduces retail food waste and net greenhouse gas emissions and energy use. On the other hand, the case study described in Section 9 involving spinach, offers an example where this environmental balance between food waste and packaging falls the other way: increased packaging reduced food waste but resulted in a net increase in greenhouse gas emissions and energy use. In Section 10, cases are presented that demonstrate the influence of other food life cycle stages – specifically processing and refrigeration – on the environmental balance. Section 12 documents some of the other cases that were pursued over the course of this project but were discontinued. The report concludes with overarching conclusions (Section 13) and recommendations for future research direction (Section 14).

3. Literature review

3.1.Life Cycle Assessment of foods

Agricultural and food product systems have offered both an ideal and challenging application of life cycle assessment (LCA) methods due to their complexity and their close interlink between nature and the technical sphere. A host of unique challenges arise when LCA methods are used to analyze food systems: for example, determining adequate boundary conditions, establishing a meaningful functional unit, and choosing allocation methods (Andersson et al., 1994; Roy et al., 2012; Schau and Fet, 2008). As these challenges have been addressed over the past decade and a half, there have been exponential increases in the number of reported food LCA studies ((Heller et al., 2013), Figure 1). An accumulation of food LCA studies now permits estimates of the environmental impact associated with whole meals or diets (Heller et al., 2013), including the average U.S. diet

(Heller and Keoleian, 2014). The International Conference on LCA in the Agri-Food Sector serves as a global forum for the exchange of recent developments in LCA methodology, databases, and tools, as well as applications of LCA to food production systems and food-consumption patterns. In 2014, the 9th LCA Food conference took place in San Francisco, CA (2014), and a 2016 conference is slated to occur in Dublin, Ireland.

A number of important lessons arise from this extensive application of LCA to food and agricultural systems. First, in a broad generalization, it is fair to say that the environmental impact of a food product is dominated by the agricultural production stage (at farm gate). This may run contrary to popular beliefs that focus on the impact of food miles (transportation) or food packaging, and there are, of course, exceptions. Yet, for the majority of foods, agricultural production – including the production and application (and associated emissions) of fertilizers; farm equipment operation; irrigation and, in the case of animal agriculture, the production of feed and emissions from manure management and enteric fermentation – comprises the major impact of most food products.

Second, the environmental impact of animal based foods (meats, milk, cheese, etc) is significantly greater, on a mass basis, than that of plant-based foods (Eshel et al., 2014; Gonzalez et al., 2011; Tilman and Clark, 2014). The livestock sector is responsible for 14.5 percent of all human-induced greenhouse gas emissions (GHGE) (Gerber et al., 2013), nearly a tenth of global human water use (FAO, 2015), and 63 percent of reactive nitrogen mobilization, which influences global warming, reduced air and water quality, and biodiversity loss (Pelletier and Tyedmers, 2010). The main reasons for this impact are the production of animal feed (corn, soybeans, etc.), enteric emissions from ruminant animals, and emissions to air and water from manure management. Feed conversion efficiencies of raising livestock vary greatly by species: by one estimate it takes 36 calories of feed to produce one consumed calorie of beef; this ratio is 11:1 for pork, 9:1 for poultry meat, and ~6:1 for eggs and dairy (Eshel et al., 2014). As a result, the land use, resource needs, and associated emissions for producing feed crops compound for animal products. In regions with high demand for land, this can also lead to deforestation and biodiversity loss. In addition, ruminant animals (beef and milk cows, sheep) emit methane, a powerful greenhouse gas, as part of their normal metabolism, resulting in even larger carbon footprints for these animal products. To put it another way: whereas the differences in environmental impact (say, GHGE) between conventional and organic production can be of a factor <0.1 to 2 (and not always in the same direction), the differences between plant-based and animal-based foods are consistently a factor 4 to >20 (Williams et al., 2006). The notable exceptions to this rule are fruits and vegetables requiring air freight and those produced in heated greenhouses. A sampling of GHGE impact factors from LCA studies of various foods are shown in Figure 3.1.

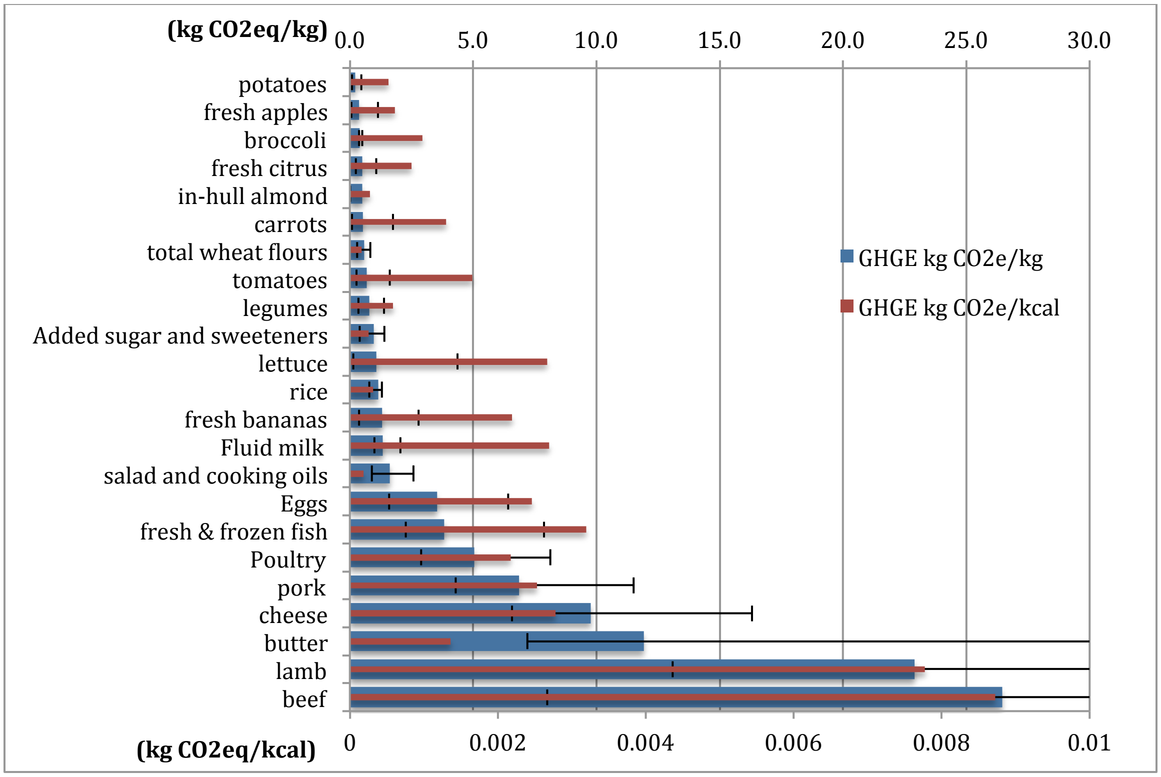


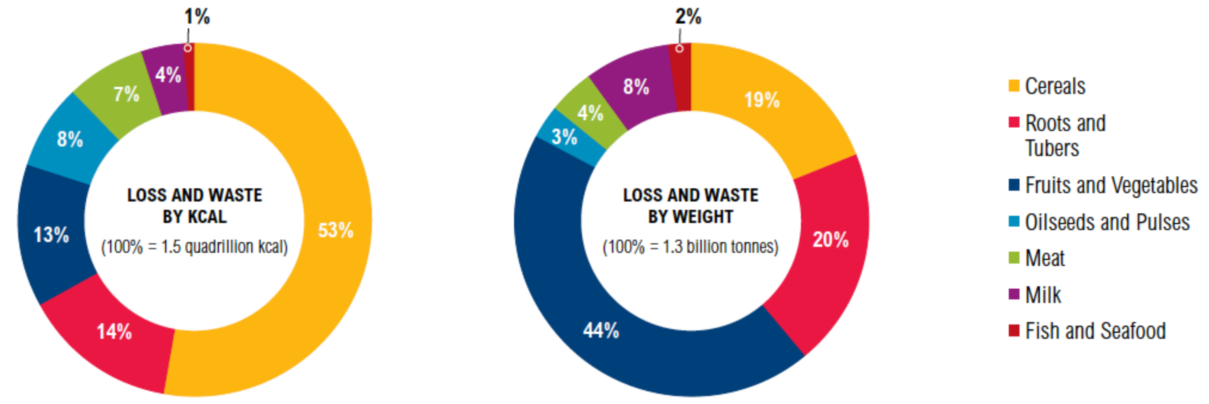
Figure 3.1. Example GHGE impact factors for a number of foods, on both a mass (blue bars) and food energy (red bars) basis. Data reported in (Heller and Keoleian, 2014). Note that the "error bars" represent minimum and maximum values (on per kg basis) from the literature data included in the average shown by the blue bar. Maximum values for butter, lamb and beef are 34, 36 & 50, respectively.

Third, it is important to keep in mind that, unlike many industrial products with limited and fixed production locations, most agricultural commodity production is dispersed over wide geographies, and across diverse climates. Thus, establishing "representative" data from sample farms can be challenging, and establishing true "averages" for commodity production in an agriculture as diverse as the U.S. can be exhausting. Typically, fossil energy use and greenhouse gas emissions, impacts that primarily are felt at the global level, are comparable for the same food production/ cropping style across regions, but other important impact categories, such as water use, land use, and water quality (eutrophication) show strong spatial dependence. Not only do inventories affecting these impacts vary strongly in different agricultural regions (e.g., irrigation water use is much higher in dry area, land use is greater where soils and climates dictate lower yields), but meaningful impact assessment methods also carry a geographical dependence (field edge nutrient emissions have very different impacts depending on nearness to affected water bodies; impacts of water use are greater in regions with high water stress). Perhaps because of this, a large fraction of LCAs of foods focus on energy use and greenhouse gas emissions.

Numerous research challenges remain in the life cycle assessment of food systems. Still, the progress to date provides a significant body of evidence and analytical framework on which to address many more complex and interesting questions. One such inquiry is the causes, impacts, and potential mitigation strategies of food waste.

3.2.Food waste: extent and overall relevance

Food waste is a pressing issue that has garnered recent social and political attention. Not only does the 'wastefulness' of unconsumed food agitate current and future food security concerns, but it also represents a significant unnecessary environmental impact. Studies suggest that roughly one-third of the food produced for human consumption is lost or wasted globally, amounting to about 1.3 billion tons per year (Gustavsson et al., 2011). On a per capita basis, much more food is wasted in industrialized countries than in the developing world; per capita food waste is 95-115 kg/year in Europe and North America, and only 6-11 kg/year in Sub-Saharan Africa and South/Southeast Asia (Gustavsson et al., 2011). Figure 3.2 and 3.3 below, both from (Lipinski et al., 2013), demonstrate the types of foods being wasted globally, as well as the stages in the food value chain where losses occur in various regions around the globe.

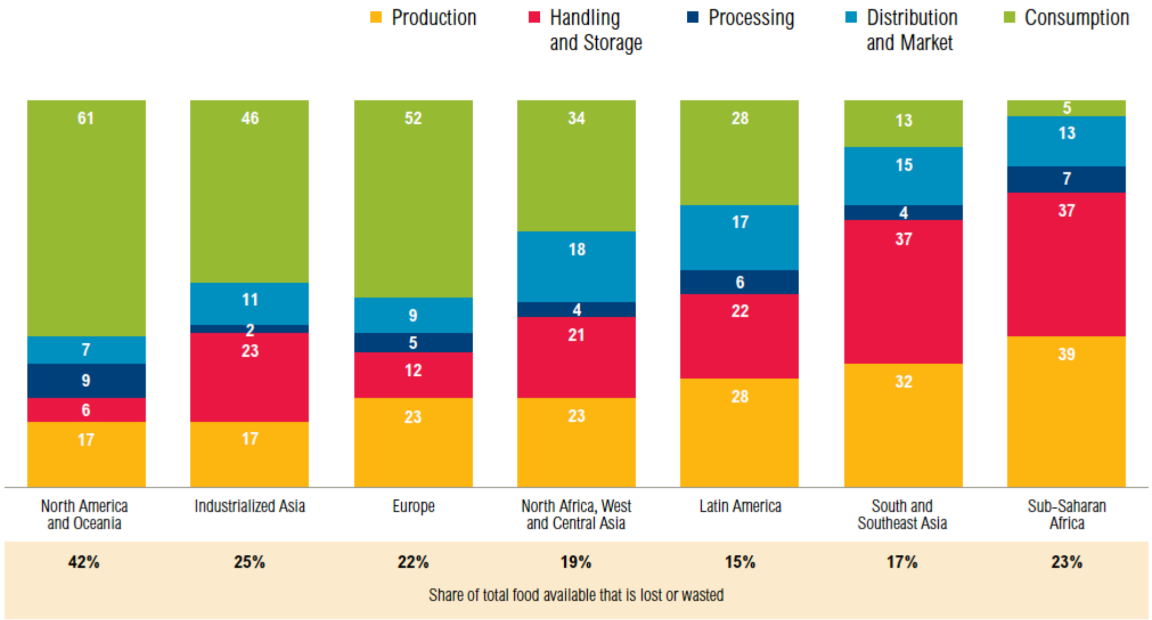


Source: WRI analysis based on FAO. 2011. *Global food losses and food waste—extent, causes and prevention*. Rome: UN FAO.

Figure 3.2. Share of Global Food Loss and Waste by Commodity, 2009. (Lipinski et al., 2013)

3.2.1. Food waste in Europe and the U.S.

The rise of what some term the "new politic" of food waste (Evans et al., 2013) has spawned a growth in studies and scholarship, particularly in Europe, but increasingly also in the U.S., aimed at understanding the extent, causes, and potential reduction strategies of food waste. Recent reports of household food waste in the UK (Quested et al., 2013a) and in Nordic countries (Gjerris and Gaiani, 2013), as well as supply chain-wide waste in Switzerland (Beretta et al., 2013) and Norway (Hanssen and Moller, 2013) all come to roughly the same conclusion: food waste is substantial, and much of it is avoidable. A waste composition analysis among multi-family dwellings in southern Sweden found that, on average, 35% of the generated household food waste can be classed as avoidable (Schott and Andersson, 2015), whereas a more detailed assessment in the UK showed that 60% of household food waste is avoidable (Quested et al., 2013a).



Note: Number may not sum to 100 due to rounding.

Source: WRI analysis based on FAO. 2011. *Global food losses and food waste—extent, causes and prevention.* Rome: UN FAO.

Figure 3.3. Food Lost or Wasted By Region and Stage in Value Chain, 2009 (Percent of kcal lost and wasted). (Lipinski et al., 2013)

In the U.S., the Economic Research Service of USDA maintains a "Loss Adjusted Food Availability" dataset that provides a means of estimating the post-harvest retail- and consumer-level food losses in the U.S. The most recent report indicates that 31% – 133 billion pounds (59 billion kg) – went uneaten, with retail-level losses representing 10% of the available food supply, and consumer-level losses representing 21% (Buzby et al., 2014). This food loss represents an estimated $161.6 billion in total value and 1249 Calories per capita per day (out of an available 3796 Calories). It is important to note, however, that while many of the European studies mentioned above are based on results of surveys and other sampling methods, these values from USDA are derived from loss assumptions assigned to individual food commodities that are then combined with market availability of those commodities. It is also worth noting that the USDA dataset reports "food loss", which represents the amount of edible food, postharvest, that is available for human consumption but is not consumed for any reason. It includes cooking loss and natural shrinkage (e.g., moisture loss); loss from mold, pests, or inadequate climate control; plate waste; and other causes. The dataset does not differentiate "food waste," which is a component of food loss that occurs when an edible item goes unconsumed, such as food discarded by retailers due to blemishes or plate waste discarded by consumers (Buzby et al., 2014). Since this differentiation is not made, a measure of "avoidable" food loss can not be derived from the USDA data. Figure 3.4 shows the composition of food loss by food group.

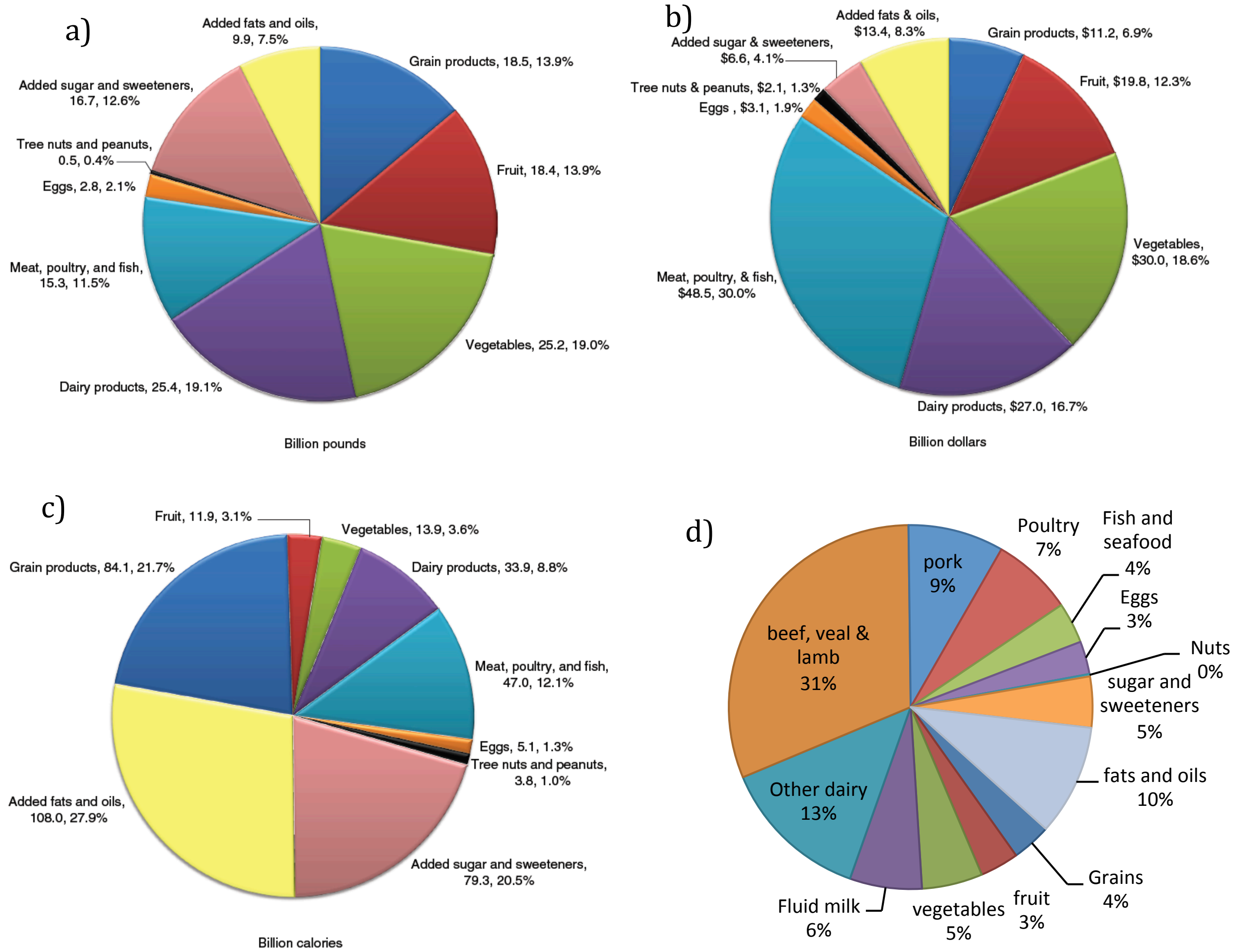


Figure 3.4. Estimated food loss in the U.S. by food group based on a) total amount (billion pounds); b) total value (billion dollars); c) food energy (billion Calories); and d) associated greenhouse gas emissions. Figures a, b & c from (Buzby et al., 2014), figure d from (Heller and Keoleian, 2014).

The Food Waste Reduction Alliance has recently sponsored studies to better understand food waste among food manufacturers, retailers and restaurants in the U.S. Surveys of these industries were conducted for the 2011 and 2013 calendar years, collecting primary data on food waste reuse and recycling, food waste disposal, donations of unsalable food for human consumption, and barriers to higher rates of donation, reuse and recycling (BSR, 2013; BSR, 2014). The 2011 survey showed that while food manufacturers generate a large volume of food waste (extrapolated to 44.3 billion pounds for the entire U.S.), most (95%) was diverted from landfill, primarily through use as animal feed or land application. On the other hand, the retail and wholesale sectors generated only 3.8 billion pounds of food waste, but only 56% was diverted from landfill, and of that diverted, 32% was donated for human consumption, 11% went for animal feed, and 43% was composted (BSR, 2013). According to the 2013 survey, the waste rates per unit of company revenue were 53 pounds per thousand dollars for food manufacturing, 10 pounds per thousand dollars for retail and wholesale, and 33 pounds per thousand dollars for restaurants. Only 16% of restaurant waste was diverted, the vast majority being used cooking oil recycling (BSR, 2014).

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.

3.2.2. Causes of food waste

It is valuable to reflect on causes of food waste across the food product chain in order to consider opportunities for reduction. Here, we focus on post-farm gate food waste, and primarily from a developed world perspective. Table 3.1 offers a generic overview of potential sources or causes of food waste across the value chain.

Table 3.1. Potential Sources/Causes of Food Waste at different stages

Food processing	**transportation**	**Retail**	**Institution or consumer**
Physical damage during handling	Physical damage during handling	Physical damage during handling	Physical damage during handling
Over/underfill	Out of spec temperature fluctuations	Expired sell by date	Expired use by date, or confusion with dating labels
Packaging failure during processing/ fill		Biophysical degradation of product (dehydration, wilting, discoloration, fungal or bacterial growth)	Biophysical degradation of product (dehydration, wilting, discoloration, fungal or bacterial growth)
Production line start up			Over-purchasing or inappropriate purchasing
Batch mistakes			Excessive portioning (uneaten prepared food)
Out-grades in supply chain			Incomplete emptying of container
Destructive QC testing			
Trimmings and other food prep waste			Trimmings and other food prep waste

An interesting interview-based study in the UK and Spain focuses on the causes of food waste at the supplier-retailer interface (Mena et al., 2011). The study details quantity, causes and destinations of waste for different food categories (ambient, chilled, frozen, etc), but also generates causal maps known as "current reality trees" which trace the creation of food waste through intermediate causes and ultimately back to root causes in both the UK and Spanish marketplace.

The UK organization, WRAP, has done a great deal of quality work in the area of food waste quantification, understanding, and prevention. A 2013 WRAP report quantifies the amounts, types and reasons for food waste from UK households (Quested et al., 2013a). Building on this study, a 2014 report further analyzes the underlying dataset from a 'product' perspective, revealing whether wasted items were packaged, the size of waste instances, and meals associated with the most waste (Quested and Murphy, 2014). Figure 3.5 and Table 3.2 below offer many interesting insights into the reasons and compositions of food waste in the UK. While we do not know of comparable studies in the U.S., such work can possibly inform further study based in the U.S.

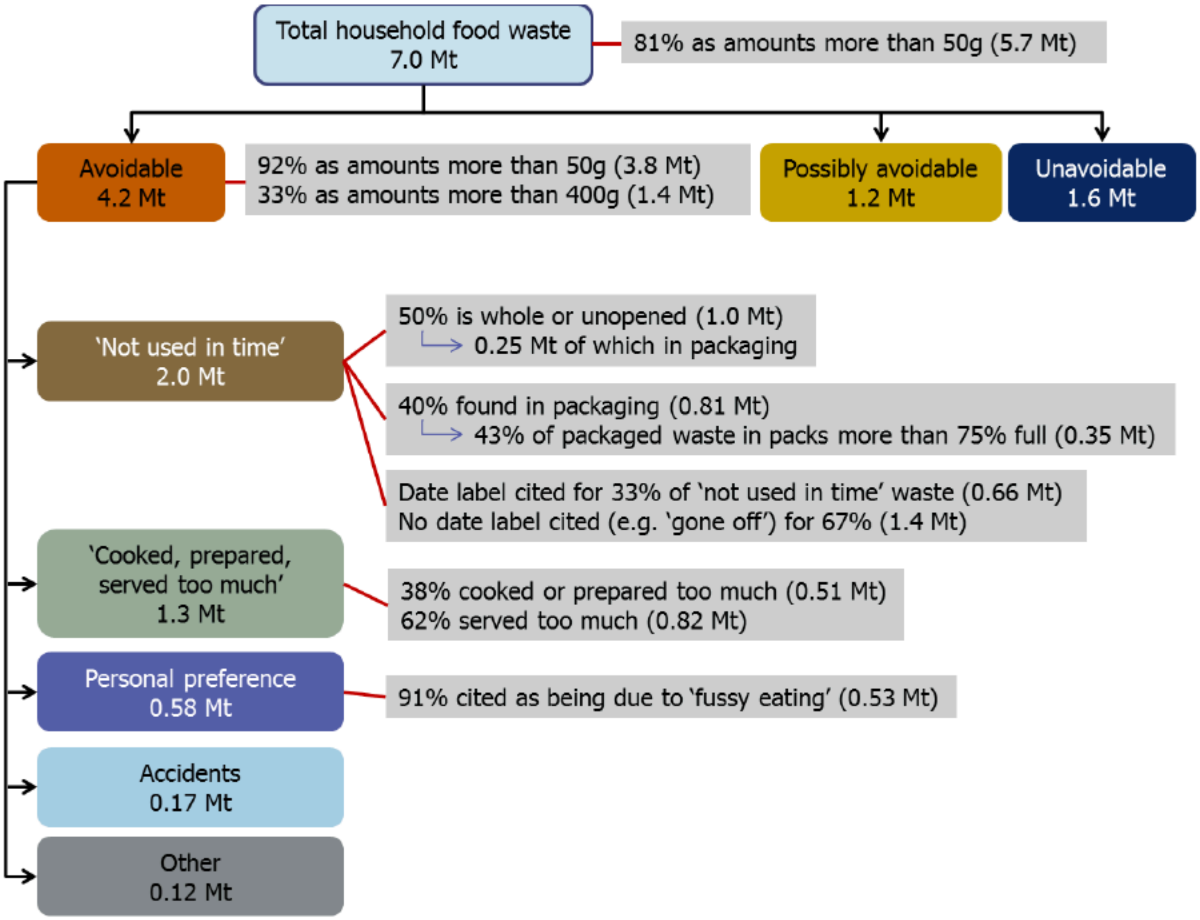
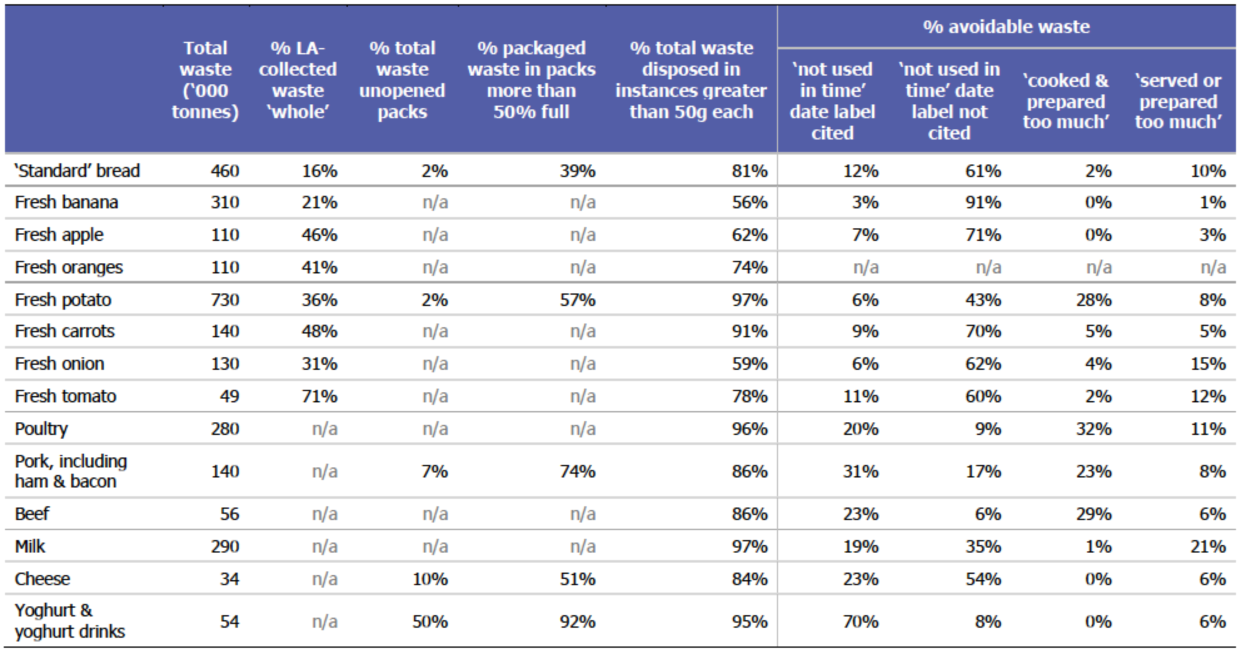


Figure 3.5. Breakdown of UK household food waste on the basis of reason for disposal. From (Quested and Murphy, 2014).

It is also worth mentioning a growing collection of recent work exploring human behavior and social demographics around food waste generation, disposal and minimization (Graham-Rowe et al., 2014; Quested and Luzecka, 2014; Quested et al., 2013b; Tucker and Farrelly, 2015). Perhaps not surprisingly, the behaviors and practices associated with waste prevention (and waste generation) are complex for a number of reasons: food waste is the result of multiple, interacting activities and this leads to separation between the activity and their consequences. These behaviors are usually performed for reasons unrelated to waste prevention and have both a marked habitual element and a pronounced emotional component. In addition, relative to other pro-environmental behaviors, food waste behaviors tend to be less visible to others in the community, thus diminishing potential 'social norm' pressures (Quested et al., 2013b).

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.

Table 3.2. Detailed results of UK household waste findings for specific products from (Quested and Murphy, 2014). Note that "LA" refers to "local authorities."



	Total waste ('000 tonnes)	% LA-collected waste 'whole'	% total waste unopened packs	% packaged waste in packs more than 50% full	% total waste disposed in instances greater than 50g each	% avoidable waste			
						'not used in time' date label cited	'not used in time' date label not cited	'cooked & prepared too much'	'served or prepared too much'
'Standard' bread	460	16%	2%	39%	81%	12%	61%	2%	10%
Fresh banana	310	21%	n/a	n/a	56%	3%	91%	0%	1%
Fresh apple	110	46%	n/a	n/a	62%	7%	71%	0%	3%
Fresh oranges	110	41%	n/a	n/a	74%	n/a	n/a	n/a	n/a
Fresh potato	730	36%	2%	57%	97%	6%	43%	28%	8%
Fresh carrots	140	48%	n/a	n/a	91%	9%	70%	5%	5%
Fresh onion	130	31%	n/a	n/a	59%	6%	62%	4%	15%
Fresh tomato	49	71%	n/a	n/a	78%	11%	60%	2%	12%
Poultry	280	n/a	n/a	n/a	96%	20%	9%	32%	11%
Pork, including ham & bacon	140	n/a	7%	74%	86%	31%	17%	23%	8%
Beef	56	n/a	n/a	n/a	86%	23%	6%	29%	6%
Milk	290	n/a	n/a	n/a	97%	19%	35%	1%	21%
Cheese	34	n/a	10%	51%	84%	23%	54%	0%	6%
Yoghurt & yoghurt drinks	54	n/a	50%	92%	95%	70%	8%	0%	6%

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.

3.2.3. Environmental impacts of food waste

Much of the increased attention to food waste has come from an acknowledgement of the natural resource use and environmental emissions associated with its production. A number of recent efforts have been made to quantify these environmental impacts. The Food and Agriculture Organization of the United Nations (FAO) developed a Food Wastage Footprint model to estimate the global impact of food waste, and concluded that *annual* food produced and not eaten has a carbon footprint of 3.3 Gtonnes CO_2 eq. (making it the 3rd top emitter after US and China). The blue water footprint (consumption of surface and ground water) of food wastage is 250 km^3 (3 times the volume of Lake Geneva), and food produced and not eaten occupies 1.4 billion hectares of land (30% of the world's agricultural land area) (FAO, 2013). Global environmental hotspots identified include: wastage of cereals in Asia; wastage of meat, especially in high income regions and Latin America; fruit wastage as a hotspot of blue water usage in Asia, Latin America and Europe; vegetable wastage constitutes a high carbon footprint in industrialized Asia, Europe, and South and South East Asia (FAO, 2013). FAO also conducted a full-cost accounting of the food wastage footprint, and found that in addition to the $1 trillion of economic costs per year, environmental costs reach around $700 billion, and social costs around $900 billion. The cost of the food wastage carbon footprint in particular, based on the social cost of carbon, is estimated to cause $394 billion of damages per year (FAO, 2014).

Another approach at estimating the wasted resources associated with global food loss suggests that food loss accounts for 24% of total freshwater resources used in food crop production, 23% of total global cropland area, and 23% of total global fertilizer use. Per capita resource use for food losses is largest in North Africa and West-Central Asia (freshwater and cropland) and North America and Oceania (fertilizers) (Kummu et al., 2012).

On a somewhat smaller scale, Scholz, Eriksson and Strid (Scholz et al., 2015) consider the carbon footprint of supermarket food waste (meat, deli, cheese, dairy, and fruit & vegetable departments) in Sweden. They found that while the fruit & vegetable department contributed 85% of the wasted mass, it was only 46% of the total wastage carbon footprint, whereas the meat department was only 3.5% of the wasted mass but contributed 29% to the carbon footprint. They also found that the wastage carbon footprint for each department tended to be highly concentrated in certain products.

Heller and Keoleian estimated the greenhouse gas emissions associated with food loss in the US, based on data from USDA's loss adjusted food availability dataset (Heller and Keoleian, 2014). They found that food losses contribute 1.4 kg CO_2 eq $capita^{-1}$ day^{-1} (28%) to the overall carbon footprint of the average U.S. diet. Across the entire U.S. population, this is equivalent to the emissions of 33 million average passenger vehicles, annually. The distribution of this food loss carbon footprint across food types is included in Figure 3.4d.

3.3. LCA of packaging materials and efforts in sustainable packaging

Food packaging represents the single largest element of consumer packaging, and demand continues to grow (WPO, 2008). The goal of food packaging is to contain food in a cost-effective way that satisfies industry requirements and consumer desires, maintains food safety, and minimizes environmental impact (Marsh and Bugusu, 2007). Materials that have traditionally been used in food packaging include glass, metals (aluminum, foils and laminates, tinplate, and tin-free steel), paper and paperboards, and plastics. Today's food packages often combine several materials to exploit each material's functional or aesthetic properties. As research to improve food packaging continues, advances in the field create opportunity to reduce the environmental impact of packaging.

3.3.1. Life Cycle Assessment of packaging

LCA of packaging materials traces the history of the LCA method itself. Given the very visible disposal (to the end user) of packaging materials, there has long been a focus on efforts to minimize packaging materials and lessen their environmental impact through material choice (e.g., paper vs. plastic?). Life cycle inventories (LCI) for paper, glass, metal and plastic packaging material production are commonplace in LCI databases (including the Ecoinvent database (Swiss Center for Life Cycle Inventories, 2016)), and studies conducted by Franklin Associates and published by the American Chemistry Council offer North American industry standard data for plastics resins and films (Franklin Assoc., 2006; Franklin Assoc., 2011a; Franklin Assoc., 2011b; Franklin Assoc., 2011c). LCA is often a time consuming (and therefore expensive) endeavor that can be challenging to justify for typical packaging design decisions. As a result, streamlined tools such as PIQET have emerged that are based on LCA principles but catered for packaging design decision-making support (Verghese et al., 2010), and reports of positive experiences are emerging from the packaging development industry (Grönman et al., 2013).

Numerous examples of LCA studies conducted on specific food packaging configurations exist (for example, (Keoleian et al., 2004; Madival et al., 2009; Pasqualino et al., 2011; Siracusa et al., 2014)). The following example studies are just a few that compare packaging configurations without direct assessment of the potential differences in food waste offered by each packaging option. While it is not possible to evaluate with these examples, it is quite possible that explicit inclusion of food waste with each packaging option would change the conclusions in these studies and others like them.

Carrots in various processing/packaging configurations (Ligthart et al., 2005)
A Dutch study performed by the Netherlands Organization for Applied Scientific Research compared environmental, economic and nutritional aspects of carrots in various packaging systems, with a summary of results presented in Figure 3.6.

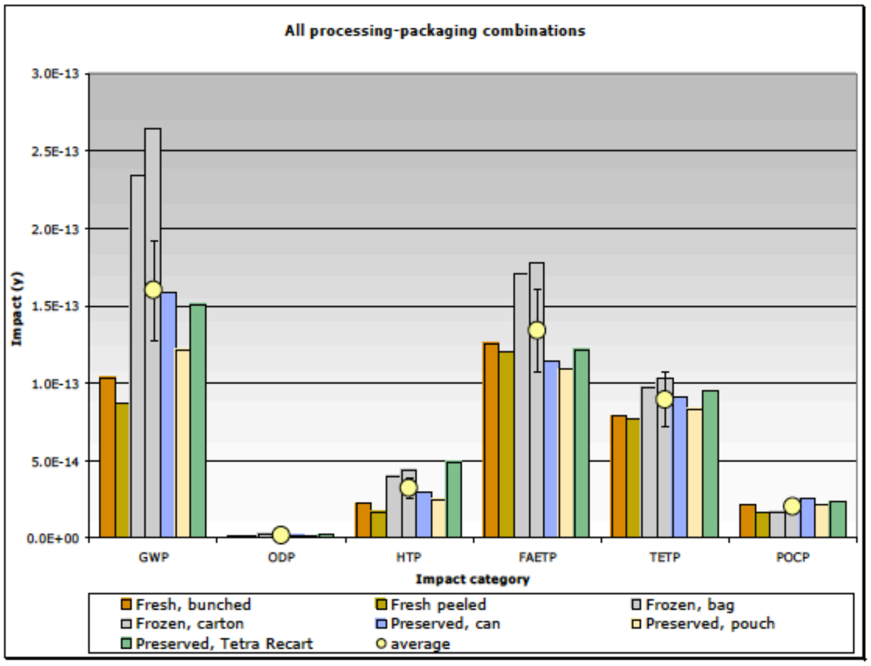


Figure 3.6. The normalized environmental impact of the consumption of 0.6 kg carrots for the current ratio of landfill (22%) and municipal solid waste incineration, MSWI (78%). The average value for an impact category is shown with a plus and minus 20% bar. From (Ligthart et al., 2005). Impact categories are: GWP=global warming potential; ODP=ozone depletion potential; HTP=human toxicity potential; FAETP=freshwater aquatic ecotoxicity potential; TETP=terrestrial ecotoxicity potential; POCP=photochemical ozone creation potential)

"Eco-efficiency" of the various processing-packaging options was determined by evaluating the economic costs of each option and aggregating environmental impacts into a single economic unit using a "shadow price" method (costs needed to abate the impact). The following conclusion on sustainability from the consumer's viewpoint was offered in the report:

> "Due to the insignificance of most of the differences in the nutritional value between the several product-packaging systems, sustainability is almost fully determined by the eco-efficiency. The fresh bunched carrots, together with the canned carrots, the frozen carrots in bag and the fresh peeled carrots, obtain an above average eco-efficiency. When considering the Dutch market offer [that] the consumer is confronted with everyday [i.e., regular imports from other parts of Europe], the canned carrots present the best eco-efficiency profile." (Ligthart et al., 2005)

Dry vs. canned soup: (Conscious Brands, 2009) A study comparing a specific dry soup product with a hypothetical canned comparison considered only the stages of the life cycle which differed between the two products. Thus, the agricultural production of soup components, which often dominate LCA impacts, are not included. Further, the study assumed that consumer-level food waste was the same for both products and was not included. The carbon footprint of the dried soup was found to be 61% lower per 8-ounce ready-to-eat serving than the canned alternative. The product use phase (boiling and simmering soup on kitchen range), followed by transport, were the largest contributors for the dry soup, whereas packaging production (steel can) and transport were most important for the canned soup.

Tuna packaging systems: A comparison of six tuna packaging systems found that a 12-ounce plastic pouch had the lowest energy use, solid waste generation and greenhouse gas emissions per 100,000 ounces of tuna consumed (Franklin Assoc., 2008). Again, food waste was not accounted for. A similar study compared single-serve packaging of tuna in two-piece pull-ring-tab cans, retort pouches and retort cups (Poovarodom et al., 2012). The study reported that packaging constitutes 20-40% of the product's carbon footprint, and found that the retort cups had the lowest overall GHGE, primarily due to packaging production and energy needs during sterilization and processing.

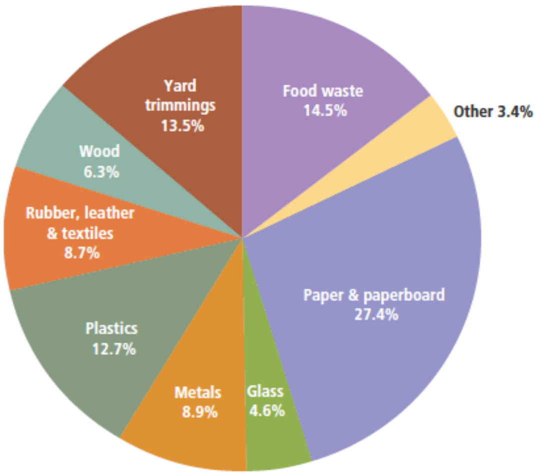
3.3.2. Packaging end-of-life disposal

Disposal options can significantly influence the overall environmental impact of packaging, as demonstrated repeatedly in example LCAs (Rigamonti et al., 2014; Siracusa et al., 2014). Municipal solid waste (MSW) generation, compositions and recycling rates have changed significantly in the U.S. in the past few decades. In 2012, containers & packaging comprised 30% of the 251 million tons of MSW generation (before recycling), and food waste was 14.5% (US EPA, 2014). The material composition of the MSW stream before and after recycling is shown in Figure 3.7. Reported current recycling rates of selected food packaging products are: steel cans, 71%; aluminum beer & soda cans, 55%; glass containers, 34%; PET bottles & jars, 31%; HDPE (white translucent) bottles, 28% (US EPA, 2014). Recycling rates of polymer films used in food packaging applications are very low because of contamination levels, mixed polymer composition from multilayer films, and difficulty in identifying polymer type (Barlow and Morgan, 2013). Of the MSW that is discarded, 82% ends up in landfill, with the remaining 18% combusted with energy recovery (US EPA, 2014).

A recent LCA study of plastic waste management scenarios in Western Europe found no clear optimal strategy (Rigamonti et al., 2014). The study modeled five scenarios: 1) a baseline with no source separation, 90% waste-to-energy, and 10% to mechanical-biological treatment producing "refuse derived fuel"; 2) source separation of bottles which are then recycled; 3) source separation of all plastic (80% efficiency for bottles, 50% for other plastic) resulting in PET, HDPE & polyolefin recycling and a remaining residue used as fuel in cement kilns; 4) plastic collection by the "dry bin" scheme, leading to overall plastic collection efficiency of 43.5%; 5) no source separation, but mechanical separation of PET and HDPE for recycling before incineration. Not surprisingly, since the scenarios are built around energy recovery from the disposed plastic, results are dependent on the chosen displaced marginal energy source (coal & typical fuel mix vs. natural gas).

Interestingly, packaging and packaging waste is one of only a few types of waste that are specifically regulated by authorities in Europe, under the Packaging Waste Directive 94/62 (European Council, 1994). The objective of this directive has been to promote packaging waste reduction through packaging minimization, and thereby reducing the total environmental burdens of packaging systems. As will be demonstrated in Section 3.5, however, minimizing packaging waste does not always lead to a reduction in environmental burdens for the product/packaging system, especially in the case of perishable foods.

a) . Total MSW Generation (by material), 2012
251 Million Tons (before recycling)



b) . Total MSW Discards (by material), 2012
164 Million Tons (after recycling and composting)

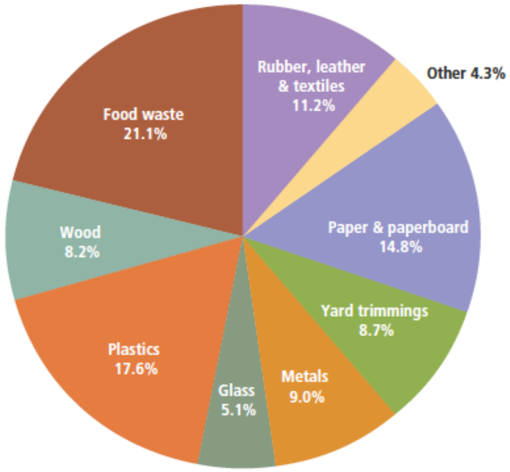


Figure 3.7. Composition of U.S. MSW in 2012 before (a) and after (b) recycling and composting. (US EPA, 2014)

3.3.3. Sustainability developments in food packaging

Early sustainability efforts in packaging tended to be reactionary in nature, largely responding to the popular perception of packaging as simply an environmental burden and an annoying waste. As a result, efforts have focused on opportunities to reduce packaging in the municipal solid waste stream, such as material light-weighting and recyclability (Grönman et al., 2013). Some limited LCA studies suggest that moving toward packaging that is more recyclable should not be the highest priority (Barlow and Morgan, 2013). There has also been significant recent interest in food packaging made with bio-based and/or biodegradable polymers (Barlow and Morgan, 2013; Mahalik and Nambiar, 2010; Siracusa et al., 2008; Yates and Barlow, 2013). In general, there remain structural and performance problems with many of these bio-based polymers, and while specific applications have been successful, widespread commercial adoption is slow (Mensitieri et al., 2011; Siracusa et al., 2008). In addition, while reduced energy consumption and GHGE has been demonstrated for production of bio-based polymers (relative to petroleum based equivalents), higher impacts in other categories and geographical differences in agricultural production of feedstock make it difficult to draw definitive conclusions about the environmental benefits of bio-based polymers (Barlow and Morgan, 2013; Yates and Barlow, 2013). Light-weighting, recyclability, and bio-polymers are all undoubtedly important pursuits in their own right, but they tend to overlook the key role packaging plays in protecting products and thus reducing waste. Below are some recent or emerging food packaging trends that hold promise in reducing food waste.

Modified Atmosphere packaging

Modified atmosphere packaging (MAP) has been an option for increasing shelf life and maintaining food quality since the widespread availability of polymeric packages in the 1970s. It involves modifying or altering the gases inside a food enclosure in order to optimize safety and stability, and can be active (displacing air with desirable gas mixture) or passive (as a result of food respiration and the controlled permeation of gases through a film) (Robertson, 2013). With the exception of baked goods, MAP is almost always used in combination with chill temperatures, and typically involves reducing aerobic respiration of foods by reducing O_2 concentration, and slowing or inhibiting microbial growth by increasing CO_2 concentrations. MAP is most commonly applied to flesh foods (meats, seafood), some fruits and vegetables, bakery products, pastas, and ready meals. Beyond these generalities, MAP is an elaborate art and science with specific optimization strategies aimed at different food types and applications (Mangaraj et al., 2009; McMillin, 2008; Sandhya, 2010; Sivertsvik et al., 2002; Smith et al., 2004).

Active packaging

Active packaging is defined by Robertson as *packaging in which subsidiary constituents have been deliberately included in or on either the packaging material or the package headspace to enhance the performance of the package system* (Robertson, 2013). Active packaging is thus a system in which the product, the package, and the environment interact in a positive way to extend shelf life, improve the condition of packaged food, or to achieve some characteristics that cannot be obtained otherwise. Again, according to Robertson, despite intensive research and development over the past 30 years, only a few commercially significant systems are on the market, including O_2 absorbers in small sachets, moisture absorbers, ethanol emitters/generators, ethylene absorbers and CO_2 emitters and absorbers. Recent literature reviews also identify antimicrobial (De Azeredo, 2013; Realini and Marcos, 2014) and antioxidant (Gómez-Estaca et al., 2014; Realini and Marcos, 2014; Sanches-Silva et al., 2014) active packaging as new and emerging technologies.

"Intelligent" packaging

Intelligent packaging contains an indicator that enables the monitoring of the condition of packaged food or the environment surrounding the food during transport and storage. Intelligent packaging is thus a system that provides the user with reliable and correct information on the conditions of the food, the environment and/or the packaging integrity. Intelligent packaging is an extension of the communication function of traditional food packaging, and communicates information to the consumer (or retailer/distributor) based on its ability to sense, detect, or record changes in the product or its environment. Recent reviews (Realini and Marcos, 2014; Vanderroost et al., 2014) indicate that the field of intelligent packaging is rapidly expanding and maturing, and intelligent packaging technologies to date can be divided into three major categories: sensors, indicators, and radio frequency identification (RFID) systems. The review by Vanderroost provides an extensive overview of R&D projects in the past decade, framing an optimistic view of a "next generation" of intelligent food packaging systems (Vanderroost et al., 2014). Heising et al (Heising et al., 2014) demonstrate how different applications are needed to monitor quality depending on the nature of perishable foods. Foods with relatively well known initial quality, such as pasteurized milk, can be monitored via time-temperature indicators, whereas foods with highly variable initial quality, such as fresh fish, may require sensors directly monitoring compounds correlated with quality.

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.

Most studies and analyses of food/packaging systems provided to date have been case-by-case "eco-assessments" on already existing options. Typically, these environmental impact studies do not incorporate the important fact that packaging technologies strongly affect food quality and safety and therefore food loss reduction potential (Angellier-Coussy et al., 2013), despite recognition from various places that it is a necessary condition for properly assessing sustainability of food packaging (Barlow and Morgan, 2013; Grönman et al., 2013; Williams et al., 2008a; Williams et al., 2012). In the following section, we briefly review opportunities for packaging to reduce food waste, and then in Section 3.5 we address the environmental trade-off that arises when both the impact of food waste as well as the impact of packaging production and disposal are included in an LCA.

3.4. Opportunities for packaging to reduce food waste

The primary function of packaging is to protect and distribute the right product to the right end-user in a safe, cost-efficient and user-friendly way (Grönman et al., 2013). It should be of no surprise then, that food packaging plays a major role in the control of food waste. A statistical examination of municipal solid waste (MSW) composition found that, in the U.S. from 1960 to 2000, as the use of packaging materials increased, the fraction of food waste in MSW decreased, and this correlation held over many countries (Alter, 1989). Yet, there is a commonly held impression that food packaging merely constitutes unnecessary solid waste and that packaging should be reduced whenever possible. In the UK, between 75% and 90% of consumers agreed that discarded packaging is a greater environmental issue than food that is wasted (Cox and Downing, 2007). Among organized efforts to reduce food waste in the supply chain, there has been limited attention to the potential contribution of packaging.

Of course, within the food manufacturing and distribution industry, there is keen awareness of the role of packaging in providing product protection and extending shelf life, and a robust food packaging industry has emerged, as is well documented in numerous texts and articles (e.g., (Marsh and Bugusu, 2007; Robertson, 2012)). Yet, businesses usually only market environmental packaging improvements when it concerns packaging material reductions or increased use of renewable materials. Opportunities abound for packaging and its functions to significantly influence the amount of food waste in households. In one Swedish survey sampling, it was observed that 20-25% of food waste was related to the packaging design attributes (Williams et al., 2012).

A report from the Centre for Design at RMIT University (Australia) details opportunities to reduce food waste through packaging improvements (Verghese et al., 2013). The following were highlighted:

1) Distribution packaging that provides **better protection and shelf life for fresh produce** as it moves from the farm to the processor, wholesaler or retailer. This may require the development of tailored solutions for individual products.

> *"We need suppliers to work with us to develop solutions for particular product lines. This means working smarter; looking at shelf life requirements and how long it lasts at home. There should be a lot more innovation. We have a good working relationship with our packaging supplier but they don't put enough resources into product trials and R&D. They need to be more flexible and adaptive."*
>
> Interviewee (grower/wholesaler).

2) Distribution packaging that supports **recovery of surplus and unsalable fresh produce** from farms and redirects it to food rescue organizations.

3) Improved design of secondary packaging to ensure that it is **fit-for-purpose**, i.e. that it adequately protects food products as they move through the supply chain. Packaging developers need to understand the distribution process and where and why waste occurs.

4) A continuing shift to **pre-packed and processed foods** to extend the shelf life of food products and reduce waste in distribution and at the point of consumption (the home or food services provider). The packaging itself also needs to be recoverable to minimize overall environmental impacts.

5) Adoption of **new packaging materials and technologies**, including multi-layer barrier packaging, modified atmosphere packaging, edible coatings, ethylene scavengers, moisture absorbers, oxygen scavengers, and aseptic packaging to extend the shelf life of foods.

6) Education of manufacturers, retailers and consumers about the meaning of **use-by and best-before date labels** on primary packaging to ensure that these are used appropriately. Confusion about date labeling results in food being thrown away when it is still safe to eat.

7) Product and packaging development to cater for **changing consumption patterns and smaller households**. Single and smaller serve products will reduce waste by meeting the needs of single and two person households.

> *"Because of their focus on value, retailers are pushing for larger format products ... This might be driving product into the pantry, but some product will degrade before it's consumed. 'Two for one' and large formats are going against demographic trends, which are towards smaller households and people eating alone."*
>
> Interviewee (food brand owner)

8) Collaboration between manufacturers and retailers to **improve the industry's understanding of food waste** in the supply chain. Greater attention to be given to where and why this occurs, tracking over time, will reduce the costs and environmental impacts of waste.

9) More synchronized supply chains that use **intelligent packaging and data sharing** to reduce excess or out-of-date stock.

> 10) Increased use of **retail ready packaging** to reduce double handling and damage and improve stock turnover, while ensuring that it is designed for effective product protection and recoverability (reuse or recycling) at end of life.
>
> > Retailers claim that single use shelf-ready packaging (SRP) (generally cartons and boxes) reduces product waste because it promotes more efficient stock rotation by increasing sales (through better visibility and availability) and increasing the speed of replenishment. SRP could also facilitate better product recall processes, promoting more efficient stock accountability and potentially less waste in the process. However, some brand owners argue that single use SRP increases product waste in transport and storage.

As is highlighted by Angellier-Coussy et al., "food preservation can be defined in terms of reduction of degradation reactions: physico-chemical and microbial reactions for non-living products but also physiological reactions for living products." (Angellier-Coussy et al., 2013) Food degradation rates are functions of temperature, light transmission, and atmospheric composition around the food. Modified atmosphere packaging and "intelligent" packaging, described in the previous section, are relatively recent developments aimed at minimizing food degradation (and therefore food waste) by controlling the headspace atmosphere around a food or monitoring product conditions and recording specific storage conditions throughout the supply chain.

Wikstrom et al. (Wikström et al., 2013) offer a list of packaging attributes that can "script" individual behavior and experiences by enabling or restricting consumers to act in a particular way, thereby creating the potential to reduce (primarily consumer-level) food waste. These attributes include: *mechanical protection; physical-chemical protection; resealability; easy to: open, grip, dose and empty; Contains the correct quantity; supplies food safety/freshness information; and facilitates sorting of household waste*. They offer LCA case studies, detailed in the following section, to demonstrate how some of these attributes can lead to system environmental benefits through reduced food waste.

Included among the RMIT report recommendations for future research were life cycle assessment of primary packaging formats that extend shelf life in order to better understand the trade-offs between packaging use and food waste generation (Verghese et al., 2013). Such is the purpose of the present study. The following section reviews the understanding of these trade-offs in the current literature.

3.5. Trade-off in environmental impact between food waste and food packaging

As we saw in Section 3.2, food waste can be significant in both industrialized and pre-industrial societies, and food waste carries a notable environmental burden. Food packaging holds great potential for reducing waste in the food supply chain, but packaging optimization approaches don't always take the environmental impact of food waste into account. While packaging materials have environmental impacts just as any other consumer product, they often are relatively small compared to the impacts of the food within the package (see Table 3.3 for examples). In some cases, food losses can be reduced while also reducing the environmental impact of the package, but often it will be necessary to increase the impact of packaging in order to reduce food losses (Wikström and Williams, 2010). This presents a potential balancing act between the impacts of the food that is wasted (and thus the environmental benefits in reducing food waste) and the environmental costs of producing and disposing of the package itself. A systems-based approach can assist in identifying situations where this trade-off results in a net environmental benefit for the food production/distribution system.

A handful of researchers have laid the foundation for consideration of food waste in packaging design and optimization. Helén Williams and Fredrik Wikström of Sweden have made significant contributions to this area, as have Erik Svanes and colleagues in Norway. Here, we summarize their works, along with others, that have brought attention to what Wikstrom and Williams call a "neglected topic."

Table 3.3. Comparison of the GHGE associated with the product and packaging for common food types. Reformatted from (Hanssen, 2012).

Type of Product	**Kg CO_2 eq per 1 kg of Product**	**Kg CO_2 eq per Packaging of 1 kg or Product**	**Product /Packaging Ratio for GHG-Emissions**
Chicken fillet	3.37	0.23	14.7
Milk	0.97	0.026	37.0
Cheese	8.75	0.049	178.6
Rocket salad	0.75	2.1	0.36
Little Gem Salad	0.15	0.11	1.36
Carrots	0.062	0.11	0.56
Cod	1.39	0.16	8.7

Williams, et al. (Williams et al., 2008b) studied consumer sentiment of several main food packaging quality indicators to uncover how environmental impact could be reduced while also increasing consumer satisfaction with the packaging. These quality indicators included protection and preservation of the product enclosed, declaration of contents, recyclable material, and appropriate quantity. Consumers identified prevention of leakage and protection of the product as most important packaging qualities, which can also have environmental benefits by preventing food losses at the consumption stage. The study emphasized the need for further LCA approaches to show how packaging can be improved to meet consumer demands while also yielding net environmental gains. Additionally, the study showed that consumers are in favor of reducing food losses through packaging measures, even if it means increased environmental impact of the package itself.

Svanes, et al. present a holistic methodology for evaluating sustainable packaging design where several indicators are grouped into five main categories: environmental sustainability, distribution costs, product protection, market acceptance and user friendliness (Svanes et al., 2010). The method emphasizes the inclusion of indirect impacts of packaging, such as product losses and transport efficiency, but does not offer a means of evaluating indicators relative to one another or resolving trade-off situations, beyond visualizing them through spider diagrams.

Case studies by Silvenius, et al. (Silvenius et al., 2011) looked at the life cycle greenhouse gas emissions of food packaging options for three different items while also taking into account the food wasted in each packaging size scenario. The products studied were two different soy based yogurt packages, four rye bread package options, and four ham package options. While the researchers conducted and reported an internet-based consumer survey of the amount of food waste generated in households, they determined that the responses were small compared to other studies, and instead used assumed values for consumer-level food waste rates in the different scenarios. The study found that packaging production and waste management usually comprised a negligible portion of the carbon footprint. For all results except one soy yogurt package, food waste caused greater environmental impacts than the entire packaging production chain. This study concluded that packaging solutions that can minimize food waste will lead to the lowest life cycle environmental impacts, highlighting the importance of the food packaging and food waste trade-off.

Case studies presented in a chapter of 2012's *LCA Handbook* demonstrate how LCA can be provide a holistic perspective for packaging optimization along with food waste prevention, while also documenting the efficiency of packaging improvement options (Hanssen, 2012). Coffee, cheese, and rocket salad (arugula) cases are explored through LCA, both by analyzing the effects on GHGE of specific real-world packaging and distribution system improvements, but also by analyzing the potential effect on system GHGE of a hypothetical 20% improvement in each of five packaging optimization strategies. The optimization strategies considered include using packaging innovation to:

1. Reduce food waste in the total value chain
2. Reduce transport work by improving degree of filling of product in packaging (both primary, secondary and tertiary packaging)
3. Increase use of recycled materials in the packaging (within restrictions defined by food safety regulations) and increase recycling of materials after use
4. Reduce material intensity of packaging, both in primary, secondary and tertiary packaging
5. Select low-impact materials and suppliers with low-impact production

Although details of the LCA studies are not reported, a number of the presented results offer insight into the packaging/food waste trade-off. A comparison of whole cheese pieces with packaged cheese slices showed that while sliced cheese has increased GHGE from packaging, distribution, and processing, it also demonstrates (in the author's study) reduced food waste at the consumer level, which sufficiently compensates for the increases in other stages (Figure 3.8).

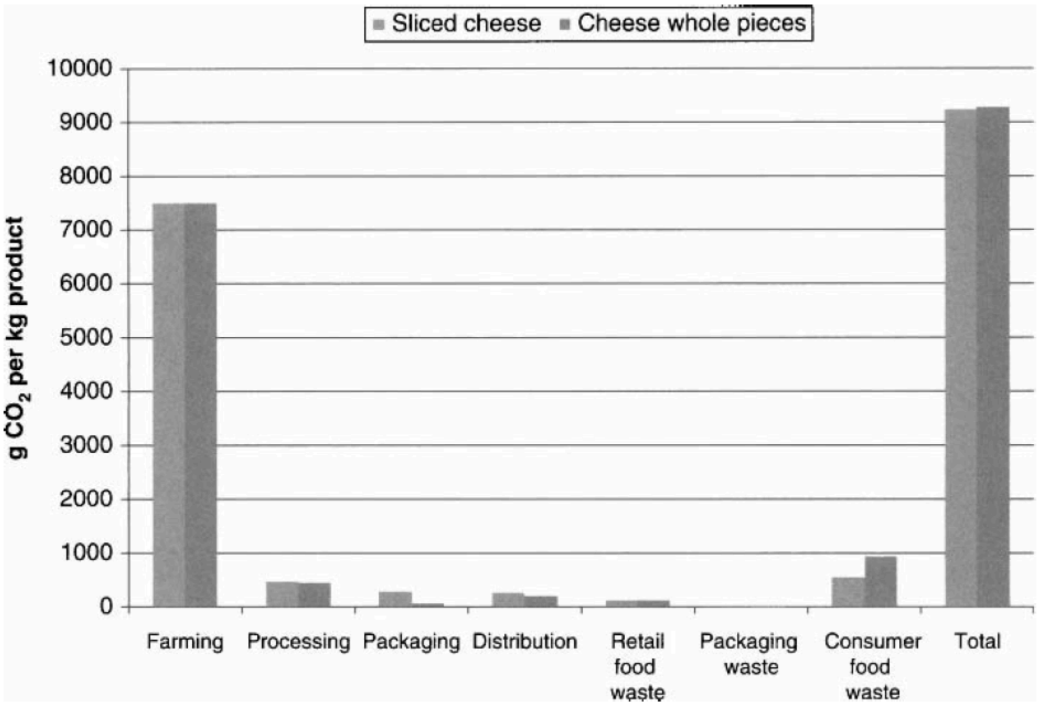


Figure 3.8. Greenhouse gas emissions from production, packaging and distribution of whole and sliced cheese. From (Hanssen, 2012).

When hypothetical improvements in the optimization strategies listed above were considered, in most cases, food waste reduction had the largest impact on overall product/packaging system GHGE, with a 20% reduction in food waste leading to GHGE reductions of 18.6% for coffee, 17.3% for whole cheese, 10.8% for cheese slices. However, with rocket salad in a PET tray with a PP flowpack film, a hypothetical 20% reduction in food waste led to only 5% reduction in system GHGE, whereas 20% improvements in using recycled materials, reduced materials consumption, and more environmentally preferable materials led to 12%, 17%, and 17% reductions, respectively. These results can be broadly explained by the ratio in impact between producing the food and its packaging, as shown in Table 3.3 (note that the ratio for coffee appears to be even higher than for cheese). In other words, when the impacts of food production outweigh those of packaging production, the influences of food waste become more relevant. When the ratio is small (as with the rocket salad example), efforts to reduce system environmental impact may be better directed at reducing the impacts of packaging.

In the consumer-waste oriented case studies presented by Wikstrom, et al. (Wikström et al., 2013), the packaging attributes "*contains the correct quantity*" and "*easy to dose*" are investigated via LCA to determine the overall impact on GHGE. Yogurt and rice packaging options of different size, material composition, and convenience features (e.g., par-boiled rice or rice container with measuring cup to assist with portion control) were first compared on the basis of the environmental impact of the packaging system itself. This showed that the packages with the lowest material weight per unit of food had the lowest environmental impact. When food waste was added into the analysis (based on assumed rates of 5, 12 and 20% food waste at the consumer level), differences in packaging material production became negligible. The results of this study provide a compelling case for why food waste reductions are important to incorporate into LCA analyses because it can drastically change what system improvements are recommended from the study. Here, incorporation of food losses showed that an increase in packaging that reduces food waste could help achieve a net positive environmental outcome for the system (Wikström et al., 2013).

Wickstrom and Williams (Wikstrom and Williams, 2010) mathematically describe the links between the environmental impact of food waste and food packaging. Typical food LCA studies are conducted with a functional unit of food at farm-gate or distributed to retailer. Wikstrom and Williams demonstrate the need to utilize a functional unit based on the food *eaten* in order to account for consumer-level food losses. The relationship between food purchased at retail and food consumed can we written as:

$$B = \frac{e}{1-L}$$

Equation 3.1

where:

e = Amount of eaten food
B = Amount of purchased food
L =fraction of food lost

This relationship reminds us that the amount of food purchased, and therefore produced on farm, is non-linear with food waste. Thus, system environmental impacts – which are most often dominated by on-farm production – can be high for foods with large losses even if the per kilogram environmental impact of the food is low.

Total system environmental impact can be expressed as in Equation 3.2:

$$E^i = B\left(F^i + P^i + W_P^i\right) + W^i BL = \frac{\left(F^i + P^i + W_P^i + W^i L\right)e}{1-L}$$

Equation 3.2

where:

E^i = Energy use or environmental impact of interest
F^i = Environmental impact to produce and distribute one unit of purchased food to the consumer
P^i = Environmental impact of the packaging used for one unit of purchased food
W^i_p = environmental impact of the disposal of the packaging
W^i = Environmental impact of wasted food disposal

In the second part of Equation 3.2, Equation 3.1 is substituted for B, leaving an expression for the environmental impact in terms of food consumed.

To determine whether a change in packaging scenarios results in an environmental net gain or loss, an initial state with food losses of L_1 and impact from packaging P_1, is defined, along with a proposed packaging solution P_2 and corresponding food losses L_2.
The new packaging solution will decrease total environmental impact, E, if the following condition is met (Wikstrom and Williams, 2010):

$$E_2 < E_1$$

Equation 3.3

Substituting Equation 3.2 and rearranging gives:

$$\frac{P_2^i}{P_1^i} < \frac{1-L_2}{1-L_1} + \frac{W_{P_1}^i(1-L_2) - W_{P_2}^i(1-L_1) + W^i(L_1-L_2) + F^i(L_1-L_2)}{P_1^i(1-L_1)}$$

Equation 3.4

In a later paper, Williams and Wikstrom (Williams and Wikström, 2011) explore this relationship by looking at a number of common foods. If one further simplifies Equation 3.4 by assuming that the impact of both food and packaging waste disposal is negligible (equal to zero) as is done by Williams and Wikstrom, a straightforward linear expression emerges:

$$\frac{P_2^i}{P_1^i} < \frac{1-L_2}{1-L_1} + \frac{F^i}{P_1^i(1-L_1)}(L_1-L_2)$$

Equation 3.5

In the plots shown in Figure 3.9, the energy use, global warming, eutrophication and acidification impacts for cheese, beef, milk, bread, and ketchup in “typical” packaging configurations are shown, with an assumed initial loss rate, L_1 of 20%. In these figures, the *maximum* allowable increase in the impact of the packaging that results in a system decrease in environmental impact (i.e., where the left and right side of equation 3.5 are equal) is plotted against the difference in food loss rates ($L_1 - L_2$). The ratio F/P then becomes the slope of the lines in Figure 3.9. This ratio, shown in Table 3.3 for some foods, is an important defining parameter in considering the trade-off between food packaging and food waste. For example, if beef waste could be reduced by 10%, beef packaging could be made with 1.5 times as much energy and three times the GHGE and still yield a net environmental benefit. On the other hand, increased energy use for ketchup packaging may not justified because F/P for ketchup is relatively low.

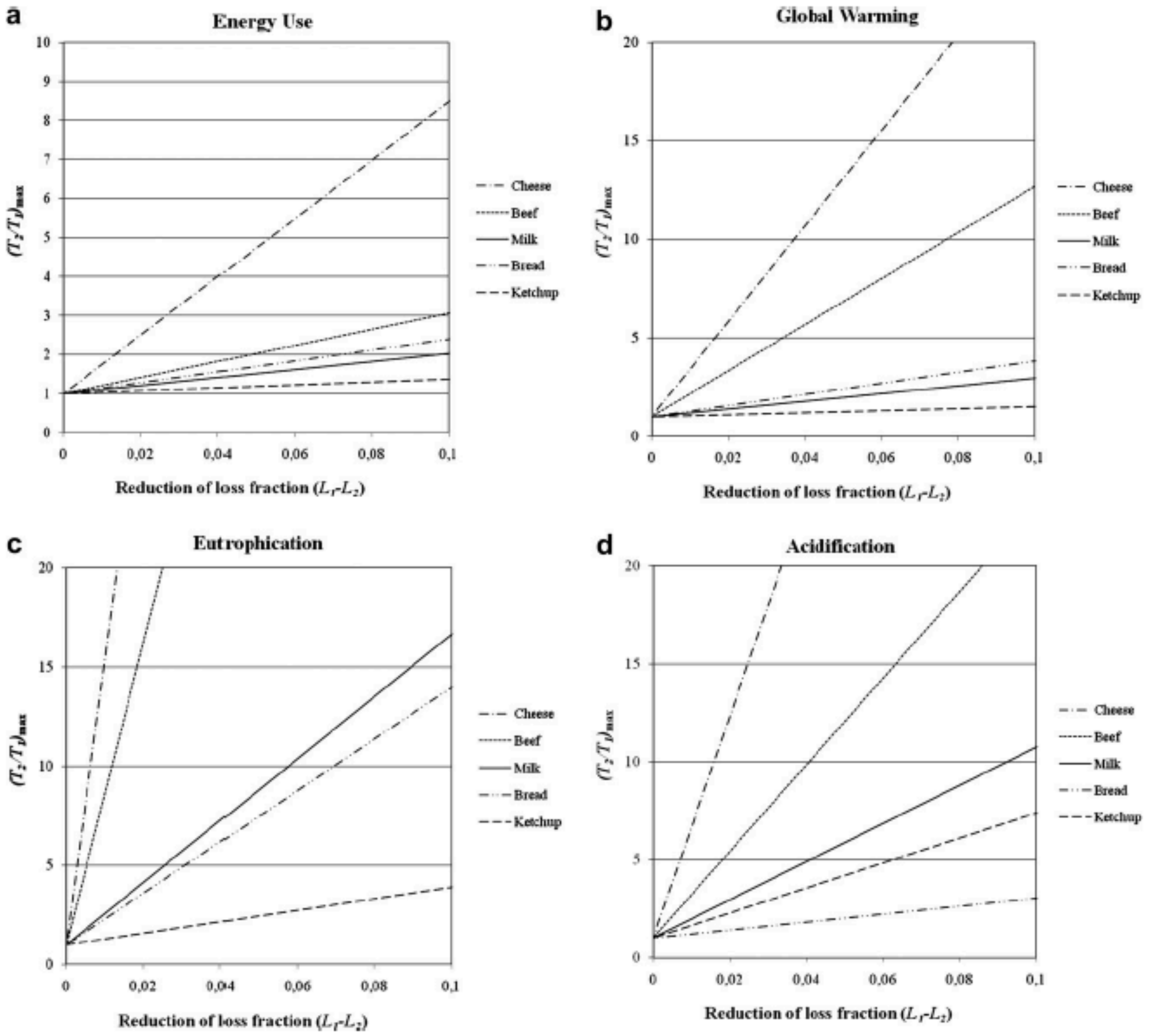


Figure 3.9. Plots of the maximum increase in environmental impact (P_2/P_1 in Equation 3.5) that still results in a net system environmental benefit, for various environmental impact indicators and a variety of food types. From (Williams and Wikström, 2011). Note that the authors change variable names from previous publications (and from the above equations and descriptions) in these figures; $T_2=P_2$ and $T_1=P_1$.

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.

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4. Research Project Description

Based on available literature, we hypothesize that there are opportunities to improve the environmental benefits of food packaging systems by optimizing design parameters based on the full life cycle impact of the combined food product-package system. The purpose of this project was to elucidate these opportunities through LCA modeling based on empirical food waste rates, when available.

The specific objectives of this project as outlined in the initial proposal are to:

- Develop a life cycle assessment model capable of evaluating the full-system environmental trade-offs between packaging design and food waste.
  This model is described in Sections 6&7.
- Demonstrate opportunities for packaging innovation to reduce system environmental impacts by decreasing food waste across food processing, retail and consumer stages.
  Given restraints in data availability for food waste at the processing level, these efforts were limited to considering retail and consumer stages. Such opportunities come to light in the mapping described in Section 7 as well as the specific cases detailed in Sections 8-10.
- Provide a scan-level mapping of food packaging options, delineating situations where food waste effects (across entire product chains) are likely to be significant as well as those likely to be only marginal.
  This mapping is also described in Section 7.
- Identify in partnership with CPIS members specific case studies (combinations of packaging technologies and food types) of current relevance to the industry, and evaluate up to three such case studies to further reveal the packaging/food waste trade-offs.
  While identifying specific cases where empirical food waste rate data were available proved far more difficult than initially envisioned, we nonetheless developed three case studies, as detailed in Sections 8-10.
- Identify data gaps and perform uncertainty analyses to evaluate the significance to packaging sustainability outcomes of missing or uncertain data.
  Outcomes from this objective are limited due to early termination of the project.

In addition, a further objective was proposed in the year-two renewal proposal:

- Develop methodological protocol for capturing food waste rates from retail grocery data systems.

  Lessons learned in this process are described in Section 5.

5. Capturing food waste rates from retail grocery data systems: Lessons learned

Empirical data on food waste rates, especially for very specific products with specific packaging configurations is extremely difficult to obtain. Virtually no data is publically available. A principle aim of this project was to gather empirical data on food waste rates at the product level in order to make comparisons between packaging configurations. We focused efforts on retail-level food waste, and contacted several food retailer chains including Busch's, Kroger, Meijer, Wegman's, Whole Foods Market, and Plum Market to estimate these waste rates for research purposes. Based on interviews with individuals at the corporate as well as individual store levels, we learned that food waste data *is* typically collected at the product level as "disposed" products are usually scanned, but that this data is not readily available as it is often not directly presented on manager reports (i.e., by individual product).

Over the course of this project, we were able to develop a relationship with the Director of Environmental Compliance and Sustainability of a mid-sized regional food retailer (to remain anonymous). This eventually led to identification of the Director of Shrink Reduction as someone who had easy access to waste data for individual products (specific UPC IDs). Concern with shrink and efforts to reduce it were part of this individual's daily work. We were able to access company wide (circa 200 storefronts) "throwaway" data, aggregated over 2 years of sales, in both quantity and dollar value, along with total sales, for any identified product with an UPC ID. Note that this meant that foods sold in bulk (produce) or sold across a sales counter (meat department, bakery) were not as easily traceable, limiting comparisons with these products (e.g., meats custom wrapped) with pre-packaged equivalents. Note also that it appeared that it was common practice to calculate a "percent shrink" as "throwaway quantity"/"sales quantity" whereas for our purposes, a waste rate would be better defined as "throwaway"/"total throughput", where total throughput = throwaway + sales. This was easily corrected in the gathered data, but offered here as a note of caution for future studies.

As data on throwaways and sales were easily and readily available through this contact, no additional method protocol development was necessary. In future efforts to access retail level food waste rates, it is recommended that similar "shrink reduction" managers/directors be approached as directly as possible. Again, it took considerable effort in conversation with various levels of management at this retail company to finally identify someone who could readily access the data of interest. Knowledge of a "shrink reduction" or equivalent entity could greatly expedite this process.

Effort to involve additional retail partners in these waste rate data captures came up short. Additional food retailer participation would allow improved statistical representation, allow development of additional specific cases, as well as make it easier to mask data from individual retailers (by averaging over multiple companies). Invitations for participation to Publix, Wegman's Costco, and Kroger were either ignored (no reply) or rejected. This does not seem to be as much about an unwillingness to share data (although that may play a role) as it is limited staff time to dedicate to such side projects and a lack of priority to participate.

6. LCA model overview

At the heart of this project is an LCA model developed with the specific capability of elucidating the influence of food waste and food packaging on overall food product system environmental impact. The general model structure is shown in Figure 6.1. While details of the model, including the underlying data sources, are presented in Section 7, this section provides an overview of the model and discusses important aspects of each model component.

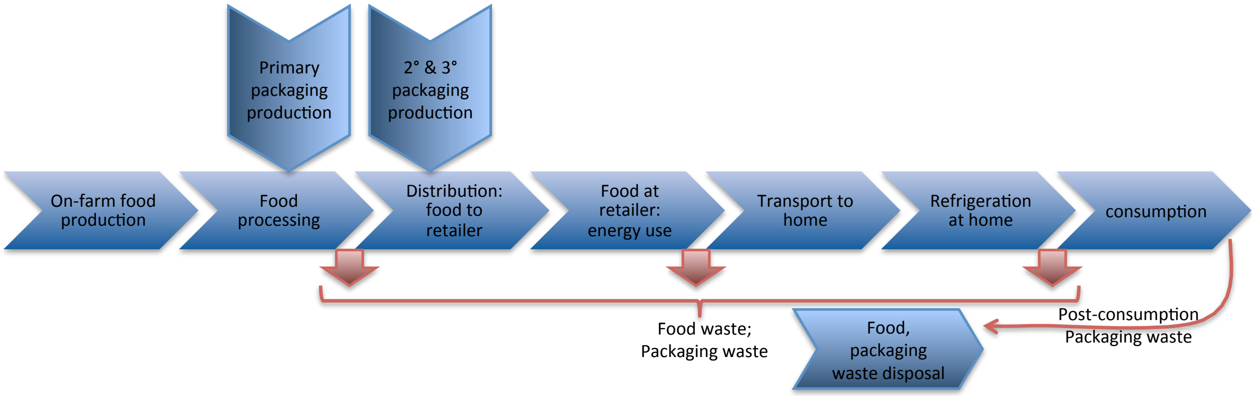

Figure 6.1. Graphical representation of LCA model.

On-farm food production and food processing: In our model, these critical stages are dependent on existing LCA studies. Thus, in most cases, impacts of these stages are represented in the model as straightforward emission factors or energy demand derived from literature or other sources (kg CO_2eq/kg food produced, MJ/kg food produced)

Packaging production (primary, secondary, tertiary): Impacts of packaging production are derived from existing material production processes available in the SimaPro software (see Section 7 for details). Elemental material formations (extrusion, blow molding, injection molding, foaming, thermoforming, etc.) are also included. All packaging material quantities are input into the model relative to a kg of food, and therefore scale with the food flows throughout the model. Recycling content in packaging materials is accounted for in the *material production* stage by utilizing processes based on recycled material (key materials are parameterized to allow adjustment of virgin/recycled fraction). Thus, the model does *not* offer a credit of displaced virgin material at the disposal stage (however, recycling rate at disposal displaces material from other disposal mechanisms).

Distribution to retailer: Simple distribution via trucks is modeled with a process expressed on a *ton-km* basis. Therefore, while details such as packing densities, fraction of load capacities, and backhaul characteristics certainly affect actual distribution impacts, given the generic nature of the information available for distribution of individual products, these were kept constant at the assumptions built into the transportation process (see Section 7 for details). In addition, a refrigeration modification is built into the distribution process, as described in Section 7.

Energy use at retailer: Energy use at retail is divided into two components: refrigeration, and other energy demands (space heating, water heating, cooling, ventilation, lighting, office equipment, etc). The "other" energy demands are treated as "overhead" costs in the retail business, and impacts of energy use are allocated to a given unit of food on an economic basis:

(average retail price per kg of food in question * total annual kg sold at US retail of food in question)/ (total annual US grocery sales) / (total annual kg sold at US retail of food in question).

Refrigeration energy is allocated on the basis of display area occupied by a given food product. As this is extremely challenging to determine for a representative national retail market, some simplifying assumptions are made. A consumer-facing area per kg of product, based on the specific packaging configuration, is calculated. This is divided by an assumed total refrigeration unit display area of 60 ft^2 to provide an estimate of the fraction of the refrigeration unit occupied by the product of question. This fraction is multiplied by the energy demands for the modeled refrigeration unit and the total number of US grocery retail outlets, and then divided by the annual kg sold at retail for the product in question (an approximation of product "throughput"). Typical refrigerant leakage emissions (also potent GHGs) are allocated by the same method. This approach essentially assumes that one kg of product is on display in the refrigeration unit at all times. While certainly a coarse assumption, refining this allocation method required detailed information on product display "real estate," which is not readily available. Thus retail refrigeration impacts, which dominate retail energy use, are driven by: the approximated area per kg of product and the assumed total kg sold at retail (in addition to the energy demands of a given refrigeration unit configuration). While these drivers are of little consequence in many food life cycles, they can play an important role in some comparisons, such as the ones described in Section 10.

Transport to home: The grocery shopping trip is modeled based on an assumed shopping trip distance in an average passenger vehicle. This trip is allocated to the food product in question on an economic basis by assuming that the average shopper purchases a given product at the same ratio as the total annual US retail sales of that product divided by total annual US grocery sales (i.e., fraction of total sales represented by product in question). This also assumes that every shopping trip involves the same "average" shopping basket of food. Thus, this transport to home stage is driven by the average retail price per kg of a given product and the assumed kg sold at retail of the product.

Refrigeration at home: Refrigeration at home is based on an assumed average annual refrigeration energy, an assumed number of days in the home refrigerator (assumed to be 4 days for refrigerated products and 45 days for frozen products in the cases presented, although this is a parameterized variable in the model), and an assumed average refrigerator size. Energy use is allocated to a given product based on it's volume fraction in the refrigerator: product volume per kg / total refrigerator volume. Thus, home refrigeration is primarily driven by the parameter, "product volume per kg".

Food waste, packaging waste: The model is built to consider food waste at three points in the life cycle: at "manufacturing", i.e., the general processing/handling stage, at the retail level, and at the consumer level. Manufacturing food waste exits the system before packaging and distribution and carries all of the burdens upstream from that point. While it is intended to capture losses during processing, filling, etc., no data on these losses were available, so this food waste level was not considered in subsequent analyses. Retail-level food waste exist the system at the point of retail sale, and therefore carries the same retail-level impacts and upstream burdens as food that is sold. Associated packaging waste is also considered with this level. Consumer level food waste exists the system at consumption and therefore carries the same life cycle burdens as food that is consumed. Associated packaging is also included. In addition, the packaging associated with consumed food is also disposed of at the consumer stage.

Food and packaging waste disposal is allocated to composting, recycling, incineration, and landfill based on US national averages, although these fractions are parameterized in the model and can be adjusted to suit other conditions. Impacts of disposal are based on the US EPA WARM model, as described in Section 7.

A thorough documentation of model parameters and function will be provided with the SimaPro model. Additional description of the model as well as data sources used throughout the project are offered in the following section.

7. Model description and Food/Packaging Mapping

The following manuscript has been submitted for publication in the journal, *Environmental Science & Technology*. Documentation of methods herein describe the LCA model used both in this mapping effort as well as subsequent case studies (later sections). Supplemental materials have been included along with this report.

Mapping the Influence of Food Waste in Food Packaging Environmental Performance Assessments

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ABSTRACT

Scrutiny of food packaging environmental impacts has led to a variety of "sustainability" directives but has largely focused on the direct impacts of packaging materials. A growing awareness of the impacts of food waste warrants a recalibration of packaging environmental assessment to include the *indirect* effects due to reduced food waste and the associated burdens of producing wasted food. In this study, we model thirteen food products and their typical packaging formats through a consistent life cycle assessment framework in order to demonstrate the effect of food waste on overall system greenhouse gas emissions (GHGE) and cumulative energy demand. Starting with food waste rates from the only known consistent U.S. data set, we calculate the effect of a 10% decrease in food waste rate on GHGE and energy demand. This provides a bound for increases in packaging impacts from innovative packaging solutions that will still lead to net system environmental benefits. The ratio of food production to packaging production environmental impact provides a guide to predicting food waste effects on system performance, and we present the variability and trends across food types for this ratio as demonstrated by a meta-analysis of the LCA literature.

7.1. 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. The FAO estimates that one-third of food produced for human consumption is lost or wasted globally.[1] Food produced and not eaten has an annual carbon footprint of 3.3 Gtonnes CO_2 eq. (if it were a country it would be the 3rd top emitter after U.S. and China) and occupies 30% of the world's agricultural land area.[2]

In response, USDA and US EPA announced in 2015 the first U.S. food waste reduction goal, calling for a 50% reduction by 2030.[3] An estimated 70 MMT of edible food is lost annually in the U.S., with nearly 60% of this occurring at the consumer level.[4] Greenhouse gas emissions (GHGE) associated with production of this food loss are estimated at 1.4 kg CO_2 eq. $capita^{-1}$ day^{-1} (160 MMT CO_2 eq. in annual total), increasing the carbon footprint of the average U.S. diet by 39%.[5] Meeting the ambitious waste reduction goal will require concerted effort from stakeholders throughout the food value chain.

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. Environmental concerns about packaging tend to focus on the direct environmental impacts of packaging material production and packaging end-of-life, despite indication that efforts to reduce indirect impacts of food waste often far outweigh options to reduce direct impacts.[6-10] A recent collaborative effort in the U.S. between business, non-profit, foundation and government leaders reports that packaging adjustments alone have the potential to divert 189000 metric tonnes of food waste annually in the U.S., with an economic value of $715 million; active intelligent packaging aimed at slowing spoilage offers an additional potential 65000 metric tonnes of food waste diverted.[11]

Life cycle assessment (LCA) is a tool to assess the potential environmental impacts of product systems and services, accounting for the emissions and resource use throughout a product's life cycle, from raw material acquisition through production, distribution, use, and disposal.[12] Agricultural and food product systems have offered both an ideal and challenging application of LCA methods due to their complexity and their close interlink between nature and the technical sphere. As the unique challenges that arise in applying LCA to food systems[13-15] have been addressed over the past decade and a half, there have been exponential increases in the number of reported food LCA studies.[16]

LCA of food packaging dates back to the earliest applications of the LCA method. Yet, limited attention has been given to the balancing act that arises between the environmental impact of producing and disposing of the packaging itself and its ability to moderate food waste (and the associated environmental impact) along the food value chain. Wikström and Williams have made significant contributions in the literature aimed at raising awareness of the importance of considering food waste in food packaging design and sustainability.[7,9,10,17-19] They have mathematically described the relationships between environmental impact of food waste and food packaging within a life cycle perspective[18], and established the need to utilize a functional unit based on the food *eaten* in order to account for consumer-level food losses. These authors and others have demonstrated through specific case studies the importance of including food waste when estimating the environmental impact of packaging systems. As an example, the climate impact of bread packaging could be doubled without increasing overall climate impact if it led to a reduction in bread waste of 5%.[9] A packaging LCA that has not included bread waste may lead to contradictory results, favoring larger packaging for geometrical reasons, or a lower ratio of packaging material per kg of food product. In addition, such studies have established the importance of the ratio between the environmental impact of the specific food item and its packaging as a predictive parameter of food waste effects.

The goal of this paper is to consider a large number of food items and their typical packaging configurations using a consistent LCA model in order to map the potential influence of food waste effects on environmental performance. We expect that this mapping exercise will offer packaging design engineers preliminary guidance on the significance of food waste in optimizing the environmental performance of packaging. We also aim to raise awareness in general to the potential role that packaging can play, when properly designed, in reducing food waste and, in turn, the environmental impacts of our food system.

7.2.Methods

The foods and packaging configurations under consideration in this mapping exercise are shown in Table 7.1, along with the assumed baseline retail and consumer-level waste rates, taken from the USDA Loss Adjusted Food Availability (LAFA) dataset.[20] It is important to note that the USDA LAFA database reports food *loss* rates, often based on the differences between per capita availability and survey-based consumption of specific foods. These losses include losses due to cooking that are not differentiated from consumer-level spoilage or plate waste. To account for this in meats, which are expected to be most affected by cooking losses, we considered typical cooking losses as reported by USDA.[21] The reported cooking losses (100 - cooking yield %) vary greatly by meat cut and cooking method, but averaging over entries results in 23% for turkey, 24% for pork, and 26% for beef. These cooking losses are then subtracted from consumer loss rates from LAFA to provide an estimate of spoilage and plate waste for the meats. However, LAFA reports a consumer loss rate for beef of 20%, lower than many reported cooking loss rates; we therefore assume a waste rate of 4% for beef.

7.2.1. 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.

Table 7.1. Foods, primary packaging, and baseline food waste rates considered in this study. "NFC OJ" = not-from-concentrate orange juice; "PCR" = post-consumer recycled.

food	**Primary package**	**USDA LAFA food waste rates**[a] **retail**	 **consumer**
spinach	PET clam, 100% virgin PET	14%	9%
spinach	PET clam, 100% PCR PET	14%	9%
ready-to-eat lettuce	LDPE/PP bag	13.9%	24%
NFC OJ	1 L PET, 100% virgin PET	6%	10%
NFC OJ	1 L PET, 100% PCR PET	6%	10%
NFC OJ	1 gal HDPE, 100% virgin HDPE	6%	10%
NFC OJ	1 gal HDPE, 100% PCR HDPE	6%	10%
chopped tomatoes	steel can	6%	28%
mushrooms	8 oz PET tray 100% virgin PET	12.7%	21%
mushrooms	8 oz PET tray 100% PCR PET	12.7%	21%
potatoes	5 lb LDPE bag	6.5%	16%
eggs	PET carton, 100% virgin PET	9%	23%
eggs	PET carton, 100% PCR PET	9%	23%
eggs	paperboard carton	9%	23%
potato chips	PP bag	6%	4%
milk	1 gal HDPE, 100% virgin HDPE	12%	20%
milk	1 gal HDPE, 100% PCR HDPE	12%	20%
milk	1/2 gal paperboard	12%	20%
ground turkey	3 lb. MAP	3.5%	(35-23)=12%[b]
ground turkey	3 lb. chub	3.5%	(35-23)=12%[b]
pork	PS tray w overwrap	4.4%	(29-24)=5%[b]
cheese	PET bag, 100% virgin PET	11%	6%
cheese	PET bag, 100% PCR PET	11%	6%
beef	PS tray w LDPE overwrap	4.3%	4%[b]

[a] USDA reports these as food loss rates, but after correcting for cooking losses, we consider them equivalent to food waste rates. In numerous cases (e.g., ready-to-eat lettuce, ground turkey), the waste rates are from the more generic food (lettuce, turkey)

[b] Consumer loss rates modified to account for cooking losses. See Section 7.2 for description.

7.2.2. System boundaries

A generic system diagram in Figure 7.1 outlines the stages and processes to be considered in this study. Given the intended focus on packaging trade-offs, food losses/waste at the agricultural production and primary food processing stages are not explicitly considered. The study instead focuses on food loss/waste during retail and consumption stages. As shown in Figure 7.1, the environmental impacts from final disposal of food waste are included, as are the impacts of recycling and/or disposing of packaging waste. Transportation is accounted for between major stages, although generalized assumptions have been made to reasonably represent U.S. national average transportation distances.

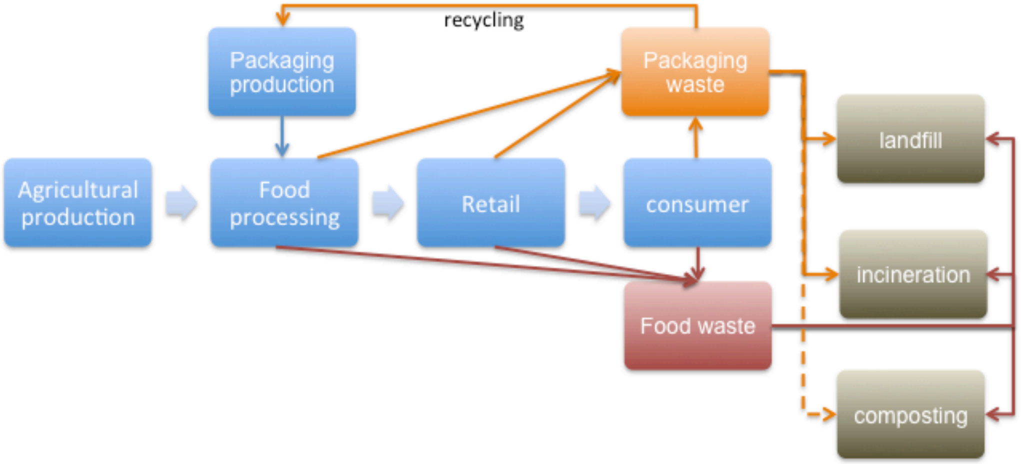

Figure 7.1. System diagram indicating the life cycle stages to be included in this study. Thick blue arrows represent stages where transport is included

7.2.3. 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, including emission factors for agricultural production and food processing, and their citations, are detailed in Supporting Information.

7.2.3.1. 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 7.2. Note that transport of packaging materials is not included in our assessment.

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.

7.2.3.2. 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 3.1 does not offer a process for refrigerated shipping), the trucking process was modified to account for refrigeration 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[22, 23]; we chose a value of 2 L per hour diesel consumption. Assuming an average operating truck speed of 56.3 miles per hour[24] and 6 hours of idling per day[25], 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[23] was also assumed.

Table 7.2. Data sources for packaging material production and transformation

process	Dataset origin
General purpose polystyrene	USLCI
High density polyethylene resin (virgin)	USLCI
Recycled postconsumer HDPE pellet	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
Polyethylene terephthalate resin (virgin)	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

*the "dummy" ethylene glycol manufacturing process included in the Ecoinvent 3 version of this process was replaced with "ethylene glycol, at plant" from the USLCI dataset.

Transport distance from unspecified processors to retail outlets across the country is extremely difficult to determine accurately. Where no additional information was available to estimate otherwise, 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.[26] Specific transport distances for each food are reported in Supporting Information.

7.2.3.3. 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. "Food sales" sector data from the 2003 U.S. EIA Commercial Buildings Energy Consumption Survey[27] is used to represent non-refrigeration energy use. This energy use is then allocated to product categories on an economic basis. While a physical basis for allocation (likely area in this case) is preferred where possible according to ISO 14044 standards, the complexity and variability of the national food retail sector prohibits such methods here. To perform the economic allocation, 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.[28]) 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, because packaging configuration can influence impacts, it is desirable to 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.[29] 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, and 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[30]) and divided by the kg of food commodity sold annually at retail (i.e., annual throughput).

Refrigerant leakages also contribute to global warming. EPA estimates annual U.S. supermarket refrigeration leakage to be 397 kg/year, and assumes R-404A to be the typical commercial refrigerant used.[31] To estimate the refrigerant leakage per kWh refrigeration energy used, this value is divided by the total annual refrigeration energy for food sales.[27] 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.

7.2.3.4. Transport: retail to home:

The 2009 National Household Transportation Survey[32] 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 3.1, we 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).

7.2.3.5. Home refrigeration:

The 2009 Residential Energy Consumption Survey[33] reports that the annual energy consumption per household by refrigerators is 1259.9 kWh, and the average refrigerator volume is 22 ft^3 (0.62 m^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 divided by 22 ft^3). A default of 4 days in home refrigeration is assumed.

7.2.3.6. Food waste rates:

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[20] as an estimate 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 (see Table 7.1).

7.2.3.7. 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).[34] The WARM model uses a life cycle approach to estimate energy use (or credit) and GHGE associated with recycling, combustion, composting and landfilling of different materials. While the WARM model credits the displacement of virgin material to recycling, in our model we account for the influence of recycling content in material production. Thus, end-of-life recycling benefits the system by avoiding landfill or incineration, but does not result in a material displacement credit.

US EPA Municipal Solid Waste data[35] 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 7.3.

Table 7.3. 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	0b	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[35]

[b] represents percentage composted

[c] derived by subtracting recycling fraction and distributing remaining by national average MSW disposal ratio: 82% landfill, 18% incineration.

7.2.4. Impact assessment methods

Global warming impact was characterized using the IPCC 2013 GWP 100a method.[36] Non-renewable cumulative energy demand was calculated using the method published by Ecoinvent version 2.0:[37] Non-renewable fossil, nuclear and biomass energy demands were summed in the results presented, although sums throughout are dominated by fossil non-renewable energy demand.

7.3.Results

While impacts associated with agricultural production dominate many food life cycles, this can vary significantly depending on food type and scenario specifics, as revealed in a review of existing literature applying LCA to various food product chains. Figure 7.2 presents the Food To Packaging (FTP) GHGE ratio for a large number of food products, aggregated by food type. While large variation clearly exists, general trends are informative: cereals, dairy, fish and seafood, and meats have large FTP ratios relative to other food types. When FTP ratios are high, it is more likely for changes in packaging configuration that lead to food waste reduction to result in net system decreases in environmental impact even when packaging impacts increase.

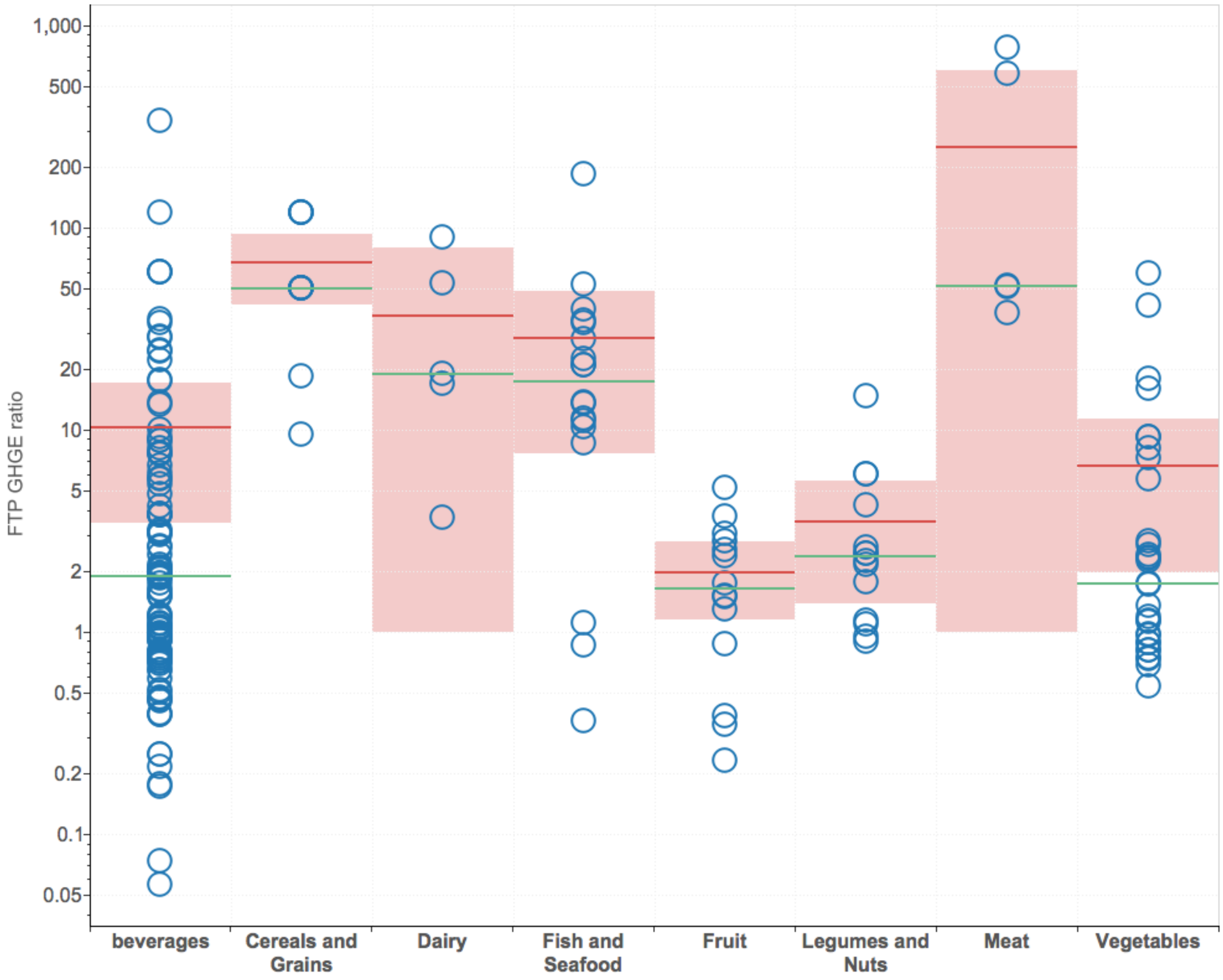

Figure 7.2. Demonstration of the "food to packaging" (FTP) GHGE ratio for a large number and variety of foods, based on LCA data collected from the literature. Here, the FTP ratio is calculated as [("agricultural (farm-gate) production/kg food" + "food processing/kg food")/"packaging materials/kg food"]. Details of the literature review and calculations are provided in Supporting Information. The vertical scale is presented as logarithmic in order to compactly show a wide range of values. Horizontal red lines represent average values for each food grouping, and pink bars are 95% confidence intervals around the average. Horizontal green lines represent median values for each food grouping. Note that the cases modeled in the current study are not contained in this figure.

Figure 7.3 provides the distribution of GHGE across life cycle stages for the food/packaging combinations modeled in this study. Note that contributions due to food waste accumulate across the life cycle, but are represented as a separate “stage” in Figure 7.3 in order to demonstrate their relative contribution. Foods in Figure 7.3 are ordered left to right by the percent contribution from food production and processing. Thus, on the left are foods where GHGE from producing the consumed portion is small relative to the contribution from other stages (packaging, transport, accumulated food waste impacts). Foods on the right are dominated by food production impacts. Lettuce and orange juice show disproportionately high distribution burdens because it was assumed that they were produced in a single U.S. location and distributed to the continental U.S. population; upwards of 75% of U.S. lettuce is produced in California whereas 90% of U.S. orange juice is made from Florida-grown oranges. The distribution of non-renewable energy demand across life cycle stages is provided in Supporting Information. The trend is similar to Figure 7.3, although packaging production represents a larger percentage of energy demand due to the embodied energy of the packaging materials.

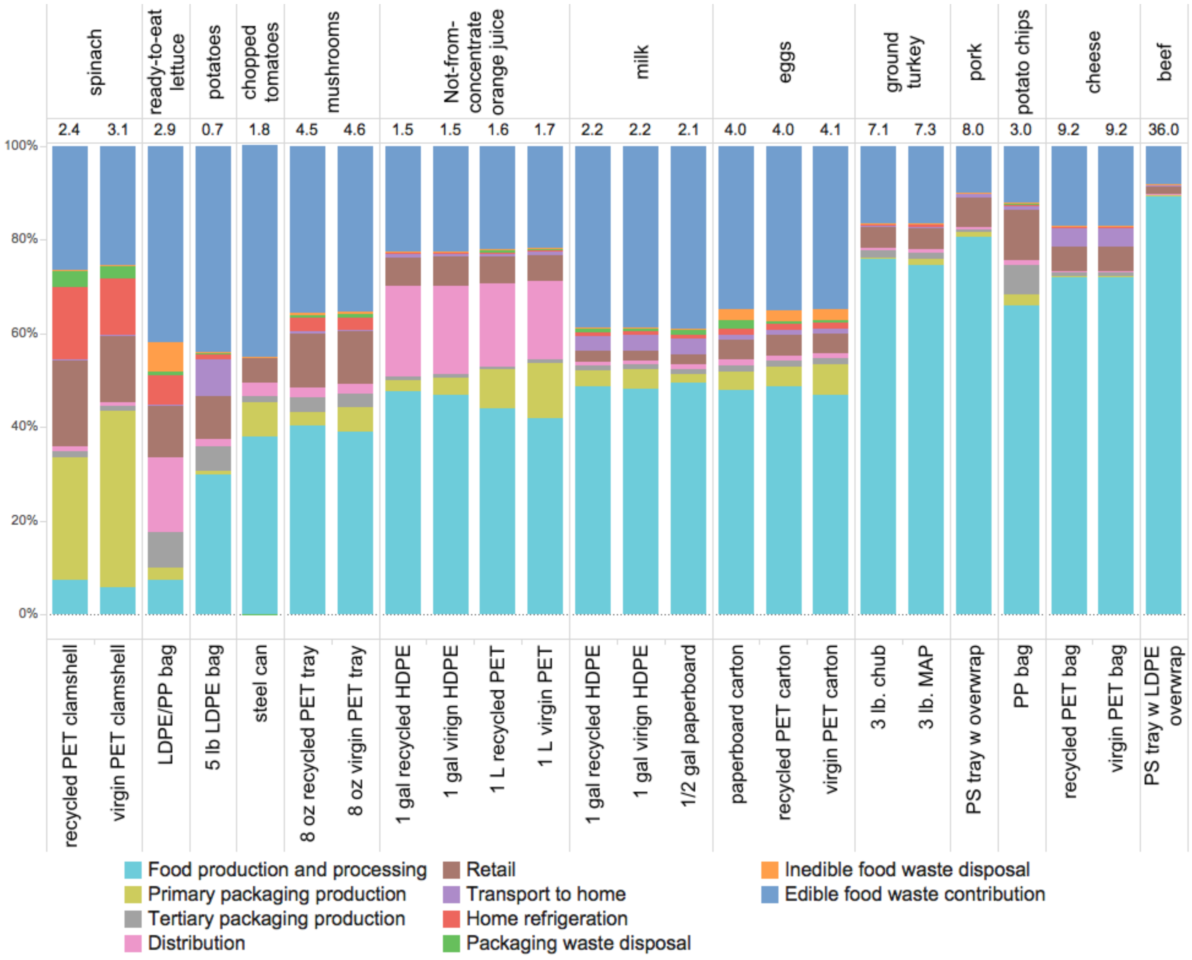

Figure 7.3. Distribution of GHGE across life cycle stages for the food/package combinations in Table 7.1. Values above bars represent total GHGE in kg CO_2 eq. (kg consumed)$^{-1}$. Note that “edible food waste contribution” includes emissions associated with edible retail- and consumer-level food waste accumulated throughout the life cycle: production, packaging, distribution, retail, refrigeration, and disposal.

The underlying premise in including the impact of food waste in evaluating packaging environmental performance is that improvements in packaging that can reduce food waste may result in net system environmental benefits even if the impacts of the packaging itself increases. To demonstrate the relationships between environmental impacts of food production, packaging and food waste, we assume a 10% hypothetical reduction in the baseline waste rates and use the LCA model to calculate the relative increase in primary packaging impacts that could be afforded by such waste reductions. Figure 7.4 shows this increase in GHGE associated with primary packaging that would break even with 10% reductions in retail waste rate, consumer waste rate, or both.

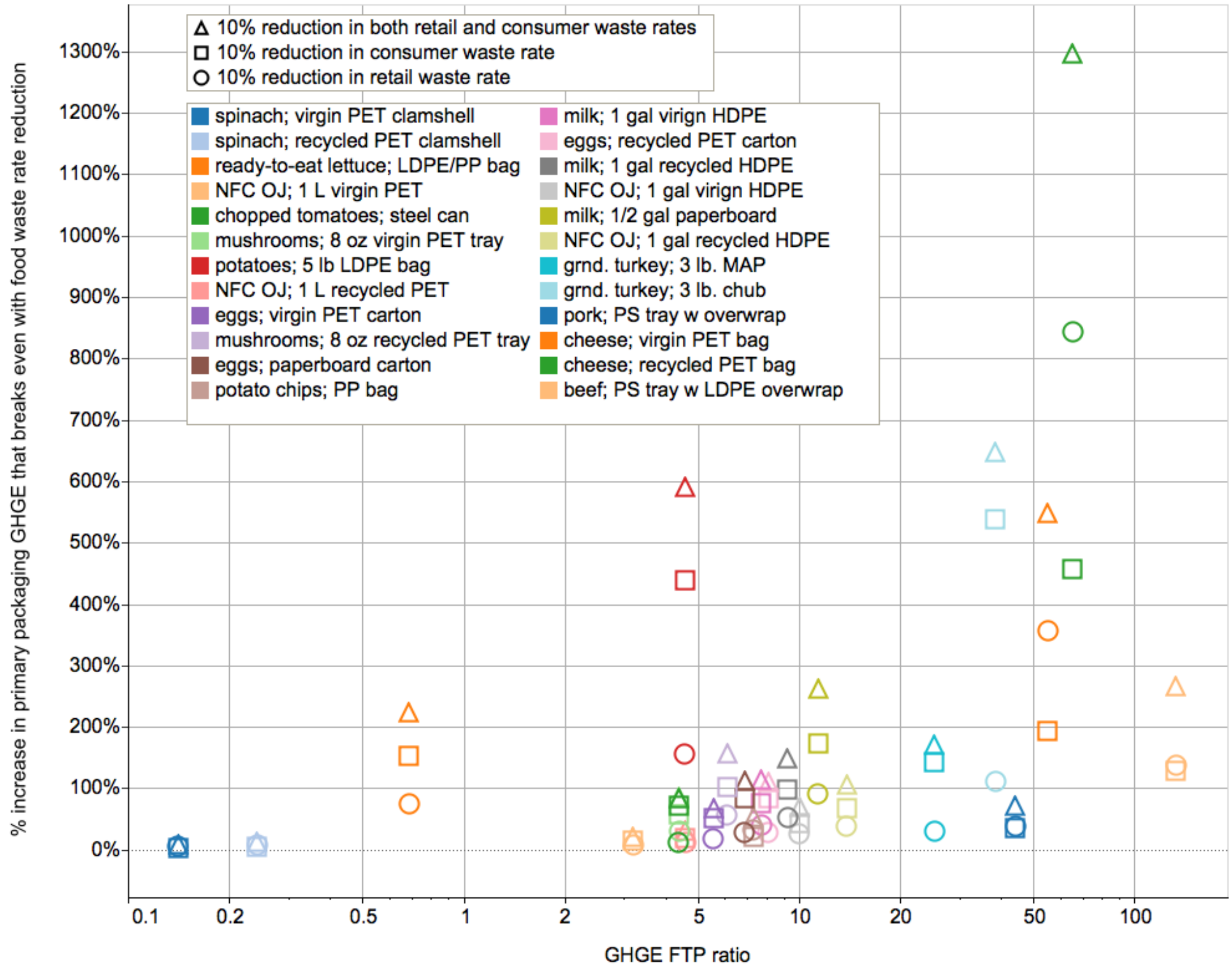

Figure 7.4. Demonstration of the increase in GHGE associated with primary packaging that would balance a 10% reduction in food waste rate (at the retail ○, consumer □, and retail & consumer △ level) for the food: packaging combinations in Table 7.1. The allowable percent increase in primary packaging GHGE is plotted against the FTP ratio (food production GHGE to packaging production GHGE, calculated without food waste contributions). Note that the x-axis is logarithmic merely to display a wide range of values efficiently.

In Figure 7.4, this allowable increase in primary packaging GHGE is plotted against FTP GHGE ratio for the food/packaging combinations. A trend begins to emerge in Figure 7.4: at very low FTP ratios, limited increases in packaging impacts are permitted with food waste reduction. At high FTP ratios, large increases in packaging impacts can be tolerated if they lead to such food waste reductions. While there is a notable trend with FTP ratio, this ratio alone is not predictive of system response to a reduction in food waste rate; the magnitude of the baseline waste rate is also important.

Figure 7.5 gives the same relationships but with non-renewable energy demand. A similar trend exists, but the influence of food waste is not as strong for non-renewable energy demand, largely because of the embodied energy in packaging materials (which does not present itself in GHGE) and the agricultural emissions not related to fossil fuel use (enteric methane and field-level N_2O emissions). Because of these factors, the difference between the energy demand for food production and energy demand for packaging production is smaller, resulting in lower values of FTP ratio.

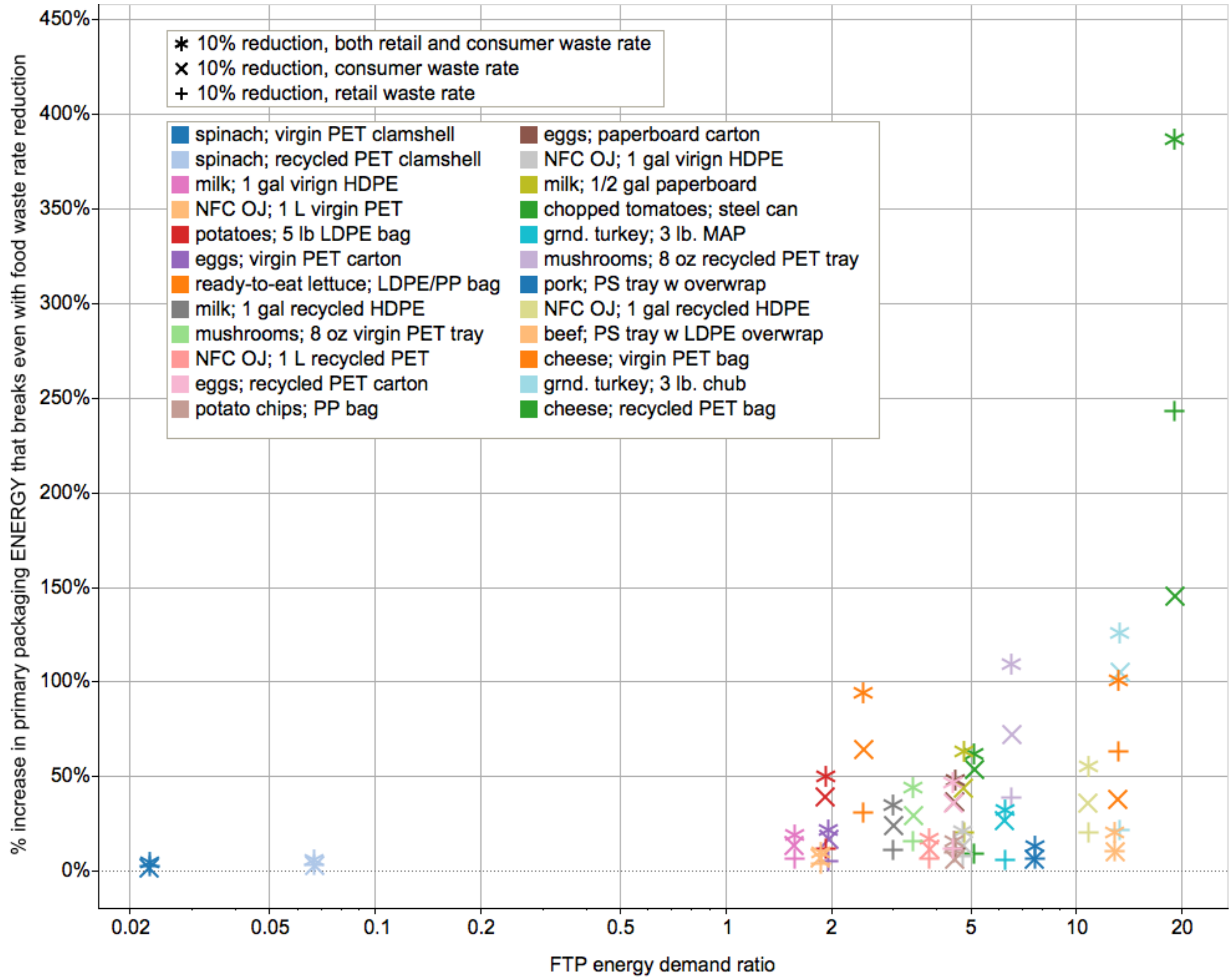

Figure 7.5. Demonstration of the increase in non-renewable energy demand associated with primary packaging that would balance a 10% reduction in food waste rate (at the retail ×, consumer +, and retail & consumer ∗ level) for the food : packaging combinations in Table 7.1. The allowable percent increase in primary packaging energy demand is plotted against the ratio of food production energy demand to packaging production energy demand (calculated without food waste contributions). Note that the x-axis is logarithmic merely to display a wide range of values efficiently.

7.4. Discussion

This study analyzes a group of generic foods in typical packaging configurations in order to demonstrate the influence of food waste on product system (food plus packaging) environmental performance. The underlying implication is that changes in food packaging configurations aimed at reducing food waste at the retail and consumer level can reduce environmental impacts of the product system even with considerable increases in the impact of the packaging itself. Food packaging design can influence food waste in a variety of ways. The most obvious, of course, is through protecting food from mechanical damage (e.g., bruising, crushing) and physical-chemical degradation (e.g., oxidation, microbial spoilage). Countless examples of packaging that extend product shelf-life exist, but consumer preference often interferes with optimization of shelf-life extension (consider, e.g., vacuum packaging of beef). Packaging can also influence food waste at the consumer-level *beyond* its ability to postpone spoilage. A survey of Swedish households determined that 20-25% of household food waste was related to packaging design attributes, including the attributes *easy to empty* and *contains the correct quantity*.[19] Additional packaging attributes that can influence food waste include *resealability*, *easy to: open, grip and dose,* and communication of *food safety/freshness information*.[10, 38] When such attributes are considered from the standpoint of reducing food waste, the potential of packaging to improve system environmental performance may be realized.

In Figures 7.4 and 7.5, the FTP ratio offers a general orienting trend to the role of food waste reduction in total system environmental impact. Figure 7.2 provides a broader perspective on the variability of FTP ratios across food types, based on literature reported food LCAs. Consideration of this ratio, even at a scan-level approximation using best available data, may help packaging engineers direct attention to appropriate impact reduction strategies. At very low FTP ratios, it is likely preferable to focus attention on reducing the impact of the packaging – through lightweighting, alternative material selection, etc. – as food waste reduction will not have significant influence on the total system environmental performance. At very high FTP ratios, where emissions or resource use of food production are much larger than that of the packaging, emphasis on food waste reduction will likely yield larger system benefits. At intermediate FTP ratios, trade-offs require evaluation on a case-by-case basis. Key product chain characteristics, most notably heated greenhouse production and air freighting, are important to consider in such a scan-level approximation, however, as they could greatly influence food production impacts. Tomatoes grown in heated greenhouses can have carbon footprints 2-3 times those grown in open field or under unheated, protective structures.[39-41] One example of air freighted green beans places the carbon footprint at 20-26 times that of regional production without air freight.[42]

The differences between results based on renewable energy demand and GHGE also emphasize the danger of relying on single environmental category assessments, especially when involving agricultural products. While it may be common with industrial products for other impact categories to trend with fossil fuel use, biological and field-level emissions in agriculture can disrupt this trend. Speaking very generally, we can expect food product system eutrophication and water use impacts to be dominated by agricultural production; other categories such as acidification potential, ozone depletion potential, photochemical smog potential, and human health impacts such as respiratory effects will require case-by-case evaluation.

We use food loss data from the USDA LAFA dastaset as our baseline estimates of retail- and consumer-level food waste rates. This dataset is the only known collection that provides a consistent estimate of food losses across all food commodities in the U.S. diet, but it certainly presents challenges. First is the generic nature of food commodity categories. For example, the relatively high consumer loss rate for turkey likely reflects whole turkeys prepared for holidays and special occasions and may not be as reflective of the ground turkey products considered here. Second, LAFA reports food *losses,* which include avoidable food waste (spoilage, plate waste) as well as unavoidable losses of moisture and fat from cooking. We have attempted to account for these cooking losses with meats, but available estimates are strongly dependent on specific cuts of meat and cooking methods and, in the case of beef at least, do not appear to be compatible with LAFA reported losses. We have gathered actual retail-level waste rates from a U.S. regional food retailer for the foods considered here to compare against LAFA data. These waste rates, averaged over two years of sales at circa 200 storefronts, are notably smaller (factor of 10 or more) than the LAFA loss rates in most cases (see Supporting Information for values). Meats (turkey, pork, beef) are the exception, where LAFA retail loss rates are close to the empirical values collected from our retail partner. At this stage, it is impossible to determine whether our gathered data reflect a more efficient retail business and the LAFA data is a more appropriate national average for retail losses.

The above concerns signal the need for high quality food waste rate data. Numerous efforts to improve our understanding of food waste are underway, including an international standard for food loss and waste accounting and reporting,[43] improved measurements by the Food Waste Reduction Alliance,[44] efforts to make decision-makers and consumers aware of food waste through the Save Food Initiative,[45] and others. Repeated analyses highlight the challenges presented by food date labeling schemes that vary in terminology and uses from region to region, and are largely misunderstood by industry and consumers, leading to significant unnecessary food waste. A recent review of the history and current practices of date labeling concludes with a call to action to move toward uniformity in date labeling.[46] Innovations in "intelligent" packaging strive to augment or replace date labeling through various indicator technologies that sense, detect, or record changes in the product, the package or its environment,[47, 48] whereas the emerging field of "responsive" food packaging is designing stimuli response systems enabling real time food quality and food safety monitoring or remediation.[49] These technologies may likely offer additional means for packaging to reduce food waste, but also further emphasize the need for LCA of the product/package system to assure net environmental benefits.

Establishing accurate consumer-level food waste rates is extremely difficult, especially for specific products. Conducting household surveys can be costly and laden with methodological challenges. A growing body of information on consumer behavior and psychology with regard to both packaging and food waste provides a starting point for initiatives and packaging design aimed at reducing consumer-level food waste.[7,50-54] Trade-offs between consumers' desire for convenience, consumer perceptions of packaging, food waste generation and whole product chain environmental impact have also been explored by comparing ready-to-eat meals with meals prepared at home.[55]

Investments in packaging have the potential to reduce overall environmental impacts associated with food production, distribution, and consumption, through reducing food loss and waste. A systems approach using life cycle assessment may help to determine the potential benefits. However, much more information about the relationship between package configuration and food waste is needed to fully inform decision-making.

Associated Content

Supporting Information:

Heller Supporting Information.docx

Heller Supporting Information Modeling parameters.xlsx

Author Information

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Acknowledgements

This research was sponsored by the Center for Packaging Innovation and Sustainability at Michigan State University.

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8. Case study 1: Mushrooms

Mushrooms represent a relatively high value, delicate fresh produce item that requires special handling through distribution and retail. Because of their high moisture content, mushrooms respire readily and efforts to extend shelf life focus on maintaining a moisture barrier to minimize this water loss. While much of the fresh mushroom market has shifted to pre-packaged units (for example, pint-sized trays with film overwrap), some retailers still offer fresh mushrooms in bulk, allowing shoppers to purchase the quantity desired. This creates an interesting comparison for the purposes of this research: is there a distinguishable difference in retail-level waste rate between pre-packaged and bulk mushrooms, and does this difference in food waste justify the additional primary packaging from an environmental impact standpoint?

8.1.System Description

The photos below show representative examples of the scenarios considered in this case. The top two photos show pre-packaged mushrooms in 8 ounce PET trays with PVC overwrap. There are then distributed as 12 units in a corrugated cardboard box. The second two photos show bulk mushrooms distributed in 5 pound corrugated cardboard boxes. As shoppers are likely to take bulk mushrooms home in a produce bag, a HDPE produce bag was included with every 8 ounces of mushrooms in this case. Primary plus tertiary packaging weight was 31% greater in the pre-packaged mushroom case than in bulk.

Discussion with produce purchasers led to a contact at Highline Mushrooms in Leamington, Ontario. Highline is the largest mushroom grower in Canada and a dominant supplier to

Meijer grocery chain. While Meijer does not offer mushrooms in bulk at their stores, production and distribution was modeled based on Meijer orders.

8.2.Data Sources

8.2.1. Mushroom production

Highline Mushrooms was willing to share information on their production process, allowing us, in this case, to model mushroom production based on primary data. Table 8.1 shows the inventory data surrounding the mushroom production process. While Highline produces a number of different types of mushrooms, the inventory data reflects production in general, and production by type is therefore not differentiated.

Table 8.1. Inventory data for production of mushrooms at Highling Mushroom.

INPUTS			**Modeled process (origin database)**
chicken manure compost	3409290	lbs	Poultry manure (Ecoinvent 3)
straw	10819825	lbs	Straw (Ecoinvent 3)
gypsum	810080	lbs	Mineral gypsum (Ecoinvent 3)
Wharf supplements	82213	lbs	Limestone (USLCI)
feather meal (supplements)	270467	lbs	Chicken co-product, other, at slaughterhouse (Agrifootprint)
lime	1385700	lbs	Lime (Ecoinvent 3)
peat moss	1607716	lbs	Peat moss (Ecoinvent 3)
mushroom spawn	110377	lbs	Based on (Leiva et al., 2015b)
water use	5.00E+06	liters	[flow] = water, well, ground, US
electricity	4123538.72	kWh	Electricity, at grid, NPCC, 2008 (USLCI)
natural gas	673901.8	m^3	Natural gas, combusted in industrial boiler/US (USLCI)
diesel for generators	380.4077	gallons	Diesel, burned in diesel-electric generating (Ecoinvent3)
OUTPUTS			
annual production	6500500	lbs	mushrooms

Based on this inventory, mushroom production at farm gate had GHGE of 1.72 kg CO_2eq / kg produced, with 68% from electricity and natural gas use. Non-renewable energy use totaled 24.8 MJ/kg, with 78% due to electricity and natural gas use. Peat moss was also a notable contributor to both GHGE and energy use. These values are notably lower than others reported in the literature. A study of mushroom production in Spain reported GHGE of 4.42 kg CO2eq/kg (Leiva et al., 2015a), whereas another of production in Thailand reported a range of 3-5 kg CO2eq/kg (Ueawiwatsakul et al., 2014). It is unclear whether these differences represent real differences in efficiency with Highline's production methods.

8.2.2. Mushroom food waste rates

As our primary retail partner in this project does not market mushrooms in bulk, we sought retail waste rate data elsewhere. Oryana Natural Foods Market in Traverse City, MI is a single-storefront cooperative business with $16 million in annual sales. Alongside pre-packaged mushrooms (often from Highline), they offer the same white button mushrooms in bulk to their customers. Table 8.2 shows the throughput and shrink rate for a month of mushroom sales at Oryana. While we acknowledge the limits in the representativeness of this sample, it will serve as the baseline waste rate data for our mushroom comparison.

Table 8.2. Mushroom retail waste rate data as measured at Oryana Natural Foods Market

configuration	Store throughput, Aug. 2015 (pounds)	waste %
Bulk	240	15.4%
8 oz. PET tray	255	1%

While the primary retail partner does not sell mushrooms in bulk, they do sell an identical trayed mushroom product. As a check the waste rates in Table 8.2, we also gathered data on 8 oz. tray packaged white button and mini portabella mushrooms averaged over circa 200 storefronts and 2 years of sales. With a total throughput quantity of 15,049,888 units, the waste rate was 1.26%. This makes the waste rates from Oryana somewhat more believable, and perhaps representative.

USDA’s Loss Adjusted Food Availability (LAFA) dataset reports food waste rates of 12.7% at retail and 21% at the consumer level. We use the consumer-level waste rate from LAFA in this case study as no other data are available.

8.2.3. Additional modeling parameters

Table 8.3 summarizes the modeling parameters needed for the LCA model.

Table 8.3 Modeling Parameters for Mushroom case

	8 oz. pre-packaged mushrooms		Bulk mushrooms, 5 pound box	
	value	source	value	source
Weight of primary packaging (kg / kg food)	0.071	Highline	0.011	
Primary packaging composition	83.1% PET, 6.8% PVC, 10.2% paper	Highline	100% HDPE	Produce bag only
Distribution packaging (3°) (kg/ kg food)	0.116	Highline	0.08283	Highline
Distribution packaging composition	99.7% corrugated cardboard, 0.1% PVC, 0.2% LLDPE (pallet cover)	Highline	98.9% corrugated cardboard, 0.2% PVC	Highline
Pallets (#/kg)	0.00352		0.00441	
Retail-level food waste	1%	Shrink data from Oryana Natural Foods Market, Traverse City, MI, August 2015 purchases (255 lbs. purchased)	15.4%	Shrink data from Oryana Natural Foods Market, Traverse City, MI, August 2015 purchases (240 lbs. purchased)
Consumer-level food waste	21%	USDA LAFA	21%	USDA LAFA
Inedible waste	3%	USDA LAFA	3%	USDA LAFA
Product volume (ft^3/kg)	0.167	Based on dimensions for 8 oz. of 5.7 inches x 5 inches x 3 inches	0.167	Based on box dimensions of 16.375 inches x 8 inches x 5 inches
Consumer-facing area (ft^2/kg)	0.87	5.7 inches x 5 inches	0.4	16.375 inches x 8 inches
Average retail price per kg	8.77	Mushroom Council Tracker, Total US, year ending 06/14/2015	8.77	Mushroom Council Tracker, Total US, year ending 06/14/2015
Annual kg sold at retail	3.234e8	Mushroom Council Tracker, Total US, year ending 06/14/2015	3.234e8	Mushroom Council Tracker, Total US, year ending 06/14/2015
Transport distance to retail (km)	647.5	Average transport distance from production facility to 4 Meijer distribution hubs	647.5	Average transport distance from production facility to 4 Meijer distribution hubs
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	

In addition to the recycled PET case, we have considered mushroom trays made of 100% virgin PET, poly-lactic acid (PLA) and HDPE with $CaCO_3$. The assumed primary packaging weights for PLA and HDPE are given in Table 8.4. All other modeling parameters remain the same as the PET tray case in Table 8.3.

Table 8.4 Primary packaging weights and compositions for PLA and HDPE scenarios.

	PLA	HDPE w/ $CaCO_3$
Weight of primary packaging (kg / kg food)	0.096	0.077
Primary packaging composition	87.6% PLA, 4.96% PVC, 7.44% paper	63.33% HDPE, 21.11% $CaCO_3$, 6.22% PVC, 9.34% paper

8.3.Results

The baseline comparison of GHGE across the life cycle between mushrooms packaged in bulk and those pre-packaged in PET trays (assumed here to be from 100% post-consumer recycled PET) is shown in Figure 8.1. Impacts from primary packaging increase notably due to the PET tray, however emissions from tertiary packaging – where the actual cardboard box that the bulk mushrooms are distributed in is included – are slightly larger in the bulk case. Figure 8.1 demonstrates quite clearly that in the absence of food waste effects, the pre-packaged case has greater emissions (unshaded portion in Figure 8.1). However, because retail-level food waste is reduced with the pre-packaged mushrooms, the savings in GHGE due to less food waste offsets the increased GHGE from packaging, resulting in a net benefit. Across the full life cycle, food waste in the pre-packaged and bulk scenarios represent 26% and 38%, respectively, of the total GHGE.

Figure 8.2 shows the same comparison between pre-packaged and bulk for non-renewable cumulative energy demand.

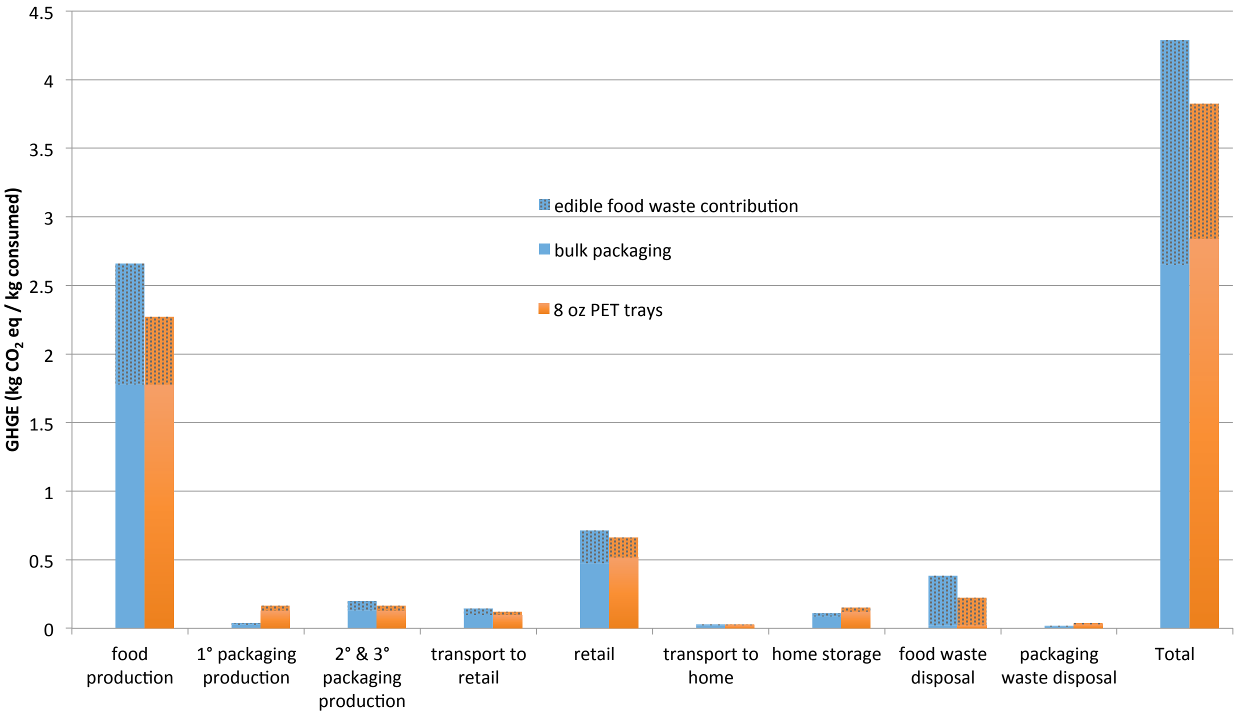

Figure 8.1 Life cycle GHGE comparing mushrooms sold in bulk and those pre-packaged in 8 oz. recycled PET trays. While GHGE from packaging (primary and tertiary) are 38% greater with the trays, food waste reduction compensates for this increase, resulting in a net system reduction in GHGE of 11%.

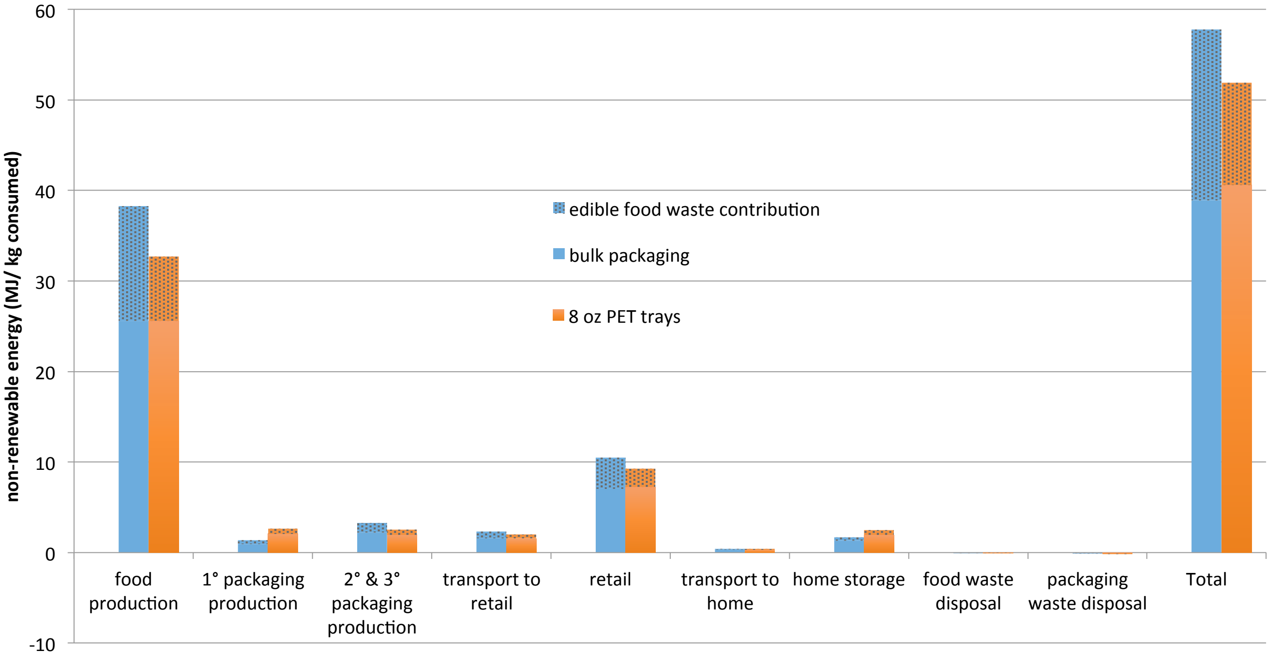

Figure 8.2 Life cycle cumulative energy demand comparing mushrooms sold in bulk and those pre-packaged in 8 oz. recycled PET trays. While energy demand from packaging (primary and tertiary) is 11% greater with the trays, food waste reduction compensates for this increase, resulting in a net system reduction in energy demand of 10%.

Changes in tray material for the pre-packaged mushrooms has minor effect on the overall food/packaging life cycle impacts (Table 8.5), and the trend with respect to bulk packaging remains largely the same, although differences in energy use diminish with alternative materials.

Table 8.5. Life cycle stage-wise results of GHGE and energy use, comparing tray packaging materials.

	food production	1° packaging	2° & 3° packaging	trans. to retail	retail	trans. to home	home storage	food waste dispose	pack. waste dispose	Total	total as % of bulk
	GHGE (kg CO_2 eq/kg consumed)										
recycled PET	2.27	0.16	0.16	0.12	0.66	0.03	0.15	0.22	0.04	3.83	89%
virgin PET	2.27	0.31	0.16	0.12	0.66	0.03	0.15	0.22	0.04	3.97	93%
PLA	2.27	0.49	0.16	0.12	0.66	0.03	0.15	0.22	-0.15	3.96	92%
HDPE w/ CaCO3	2.27	0.23	0.16	0.12	0.66	0.03	0.15	0.22	0.04	3.89	91%
BULK	2.66	0.04	0.20	0.14	0.71	0.03	0.11	0.38	0.02	4.29	100%
	non-renewable energy demand (MJ/ kg consumed)										
recycled PET	32.7	2.7	2.5	2.0	9.3	0.4	2.5	0.0	-0.1	51.9	90%
virgin PET	32.7	7.3	2.5	2.0	9.3	0.4	2.5	0.0	-0.1	56.5	98%
PLA	32.7	6.9	2.5	2.0	9.3	0.4	2.5	0.0	-0.2	56.1	97%
HDPE w/ $CaCO_3$	32.7	6.6	2.5	2.0	9.3	0.4	2.5	0.0	-0.2	55.7	96%
BULK	38.3	1.4	3.3	2.3	10.5	0.4	1.7	0.0	-0.1	57.8	100%

8.4.Discussion and conclusions

The mushroom case described here offers a simple, straightforward example of the environmental balance between food packaging and food waste. In this case, distributing mushrooms in pre-packaged PET trays increases the total weight of packaging as well as the GHGE and energy use associated with packaging materials. In the retailing sample from which we drew food waste data, however, the additional packaging also reduced retail-level food waste rates. The savings in GHGE and energy use represented by this reduced food waste more than offset the additional packaging impacts, resulting in a net environmental benefit.

In the comparison presented here, waste rates at the consumer level were held at a constant 21%, the estimate provided for mushrooms by the LAFA dataset. One might imagine that a benefit of bulk produce purchases is that the customer can purchase only what they need, thus potentially leading to reduced consumer-level food waste. We currently have no data to support this assertion, and it is feasible that the effect (buy only what you need) could just as easily lead in the opposite direction (over-purchase), resulting in greater food waste. However, if one assumes the bulk scenario can lead to reduced consumer food waste, in order to break even with the pre-packaging scenario GHGE, consumer-level waste would need to reduce from 21% to 13%. The break-even point for energy use is also right around this level of consumer waste. Note that this break-even exercise does not adjust for the number of produce bags required (base case assumes one bag for every 8 oz. of mushrooms, an equivalent "serving" as the pre-packaged scenario), but it is not anticipated that this will have a strong effect.

As structured in our LCA model, the benefits of recycled packaging materials come in the form of reduced impacts in the packaging production itself: this recycling benefit is *not* double-counted as a material displacement credit at the disposal stage (although there is the benefit of reduced material going to landfill). These factors can be seen in comparing 100% recycled PET trays with 100% virgin PET trays, where production of the latter contributes nearly twice the GHGE of the former. While these changes certainly carry through to the system total GHGE, they are minor relative to the influence of food waste rates.

In conclusion, the mushroom case demonstrates how primary packaging configurations can influence food waste at the retail level and lead to net environmental savings in spite of increased impacts from the packaging itself. It is also clear from this example, however, the high sensitivity that such comparisons have to food waste rates, and thus the need for improved data on food waste rates. Aggregated "shrink" data from the food retailing industry could aid in designing "sustainable" food packaging that takes food waste effects into account. Understanding consumer-level food waste at the individual product level, however, is a far more onerous task. Investment in sound social science aimed at understanding the behaviors and habits that lead to food waste may be the most beneficial approach to this challenging topic.

9. Case study 2: Spinach

Fresh spinach, and especially the small leaf "baby spinach", has become a ubiquitous salad green in the US marketplace. Per capita use of fresh-market spinach averaged 1.7 pounds per person in 2014, down from a record 2.8 pounds per person in 2007, which was the highest level since the mid-1940s.[1] The fresh market now accounts for about three-fourths of all U.S. spinach consumed. Much of the growth over the past decade has been due to sales of triple-washed cello-packed spinach and, more recently, baby spinach. These packaged products have been one of the fastest-growing segments of the packaged salad industry.

While pre-packaged spinach in "clamshell" trays/boxes or sealed bags have become standard in many markets, some customers prefer to purchase their fresh greens in bulk. As with mushrooms, this permits purchase of the quantity desired (rather than pre-sized packages) and may offer the perception of higher quality, if for no other reason than all of the product can be inspected. As with mushrooms, this sets up a potential balance between food packaging and food waste: is there a notable difference in food waste between bulk and pre-packaged spinach, and can the consumer preference for added packaging be justified from an environmental perspective due to reduced food waste?

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[1] http://www.agmrc.org/commodities-products/vegetables/spinach/

9.1.System Description

Oryana Natural Foods Market (see section 8.2.2) sells fresh baby spinach pre-packaged in 5 oz. PET clamshell boxes as well as in bulk. These formats serve as the comparison in this case.

9.2.Data Sources

9.2.1. Spinach production

LCA data for spinach production in the US is unavailable. This study relies on spinach production data from the Agri-footprint database (Blonk Consultants, 2015) as a proxy. Spinach production data is available for the Netherlands and Belgium in the Agri-footprint database: an average of the two was assumed in this study. Impacts per kg of spinach produced are shown in Table 9.1.

Table 9.1. Emission factors for spinach production, based on Agri-footprint data, used in this study.

	AVERAGE of NL & BE	Netherlands (NL)	Belgium (BE)
GHGE (kg CO2 eq/kg)	0.180	0.224	0.135
Non-renewable energy demand (MJ/kg)	0.659	0.779	0.539

An additional report of spinach production from the LCA literature places GHGE at 0.13 (SD=0.11-0.27) kg CO_2eq/kg (Stoessel et al., 2012).

It is important to note that these emission/energy use factors are for production to the farm-gate and do not necessarily include additional washing, sorting and other cooling and handling that may occur before packaging. While these stages *may* have a notable contribution to the overall life cycle impacts of spinach, there is no reason to expect them to be different between the scenarios under comparison here. Therefore, we do not anticipate this omission to affect the conclusions drawn for this case study.

9.2.2. Spinach food waste rates

Waste rates collected from Oryana Natural Foods Market are shown in Table 9.2. As expected, bulk distribution of spinach shows a higher waste rate. Values reported in the USDA LAFA dataset are 14% at retail and 9% at the consumer level (consumer level value assumed in this case study). Again, our retail partner does not market bulk spinach, but realized a waste rate of 0.77% for 5 oz. PET clamshell packaged spinach, with a throughput of 3,404,927 units across circa 200 storefronts and two years of sales.

Table 9.2. Spinach retail waste rate data as measured at Oryana Natural Foods Market

configuration	Store throughput, Aug. 2015 (pounds)	waste %
Bulk	190	5.3%
5 oz. PET clamshell	261	1.1%

9.2.3. Additional modeling parameters

Table 9.3 Modeling Parameters for Spinach case

	5 oz. pre-packaged spinach		Bulk spinach	
	value	source	value	source
Weight of primary packaging (kg / kg food)	0.366	Weighed container	0.0176	HDPE produce bag per every 5 oz. spinach
Primary packaging composition	94.2% PET, 5.8% paper		100% HDPE	
Distribution packaging (3°) (kg/ kg food)	0.02	Based on box retrieved from grocery	0.07	Assumed 20lb. delivered in large LDPE bag.
Distribution packaging composition	100% corrugated cardboard		100% LDPE	
Pallets (#/kg)	N/A		N/A	
Retail-level food waste	1.1%	Oryana shrink rates	5.3%	Oryana shrink rates
Consumer-level food waste	9%	USDA LAFA	9%	USDA LAFA
Inedible waste	0		0	
Product volume (ft^3/kg)	0.725	Measured container	0.725	Assumed same pack density as clamshell
Consumer-facing area (ft^2/kg)	0.49	Measured front of container	0.49	Assuming same display area as clamshell
Average retail price ($) per kg	4.30		4.30	
Annual kg sold at retail	5.65E7	http://produceuniverse.com/blogs/11241/83/spinach	5.65E7	http://produceuniverse.com/blogs/11241/83/spinach
Transport distance to retail (km)	188	(U.S. Department of Transportation, 2015), Table 24, SCTG code 032	188	(U.S. Department of Transportation, 2015), Table 24, SCTG code 032
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	

9.3. Results

Results show the comparison of the life cycle GHGE (Figure 9.1) and non-renewable energy (Figure 9.2) between bulk spinach and pre-packaged spinach in PET clamshells, with PET assumed at the extremes of 100% post-consumer recycled material and 100% virgin material. While the pre-packaged spinach shows reduced waste at the retail level – 1.1% vs. 5.3% with bulk – this is insufficient to balance the increased impact from primary packaging material. This result appears to be driven primarily by two things (in comparison to the mushroom case): the relatively low impact per kg of producing spinach and the high ratio of packaging weight to food weight. Given that spinach is a relatively low density food, more packaging per unit weight is required to contain it: a PET clamshell containing 5 oz. of spinach weighs 49g (including hard PET lid) whereas an 8 oz. tray for mushrooms weighs only 14g (plus 1g overwrap film).

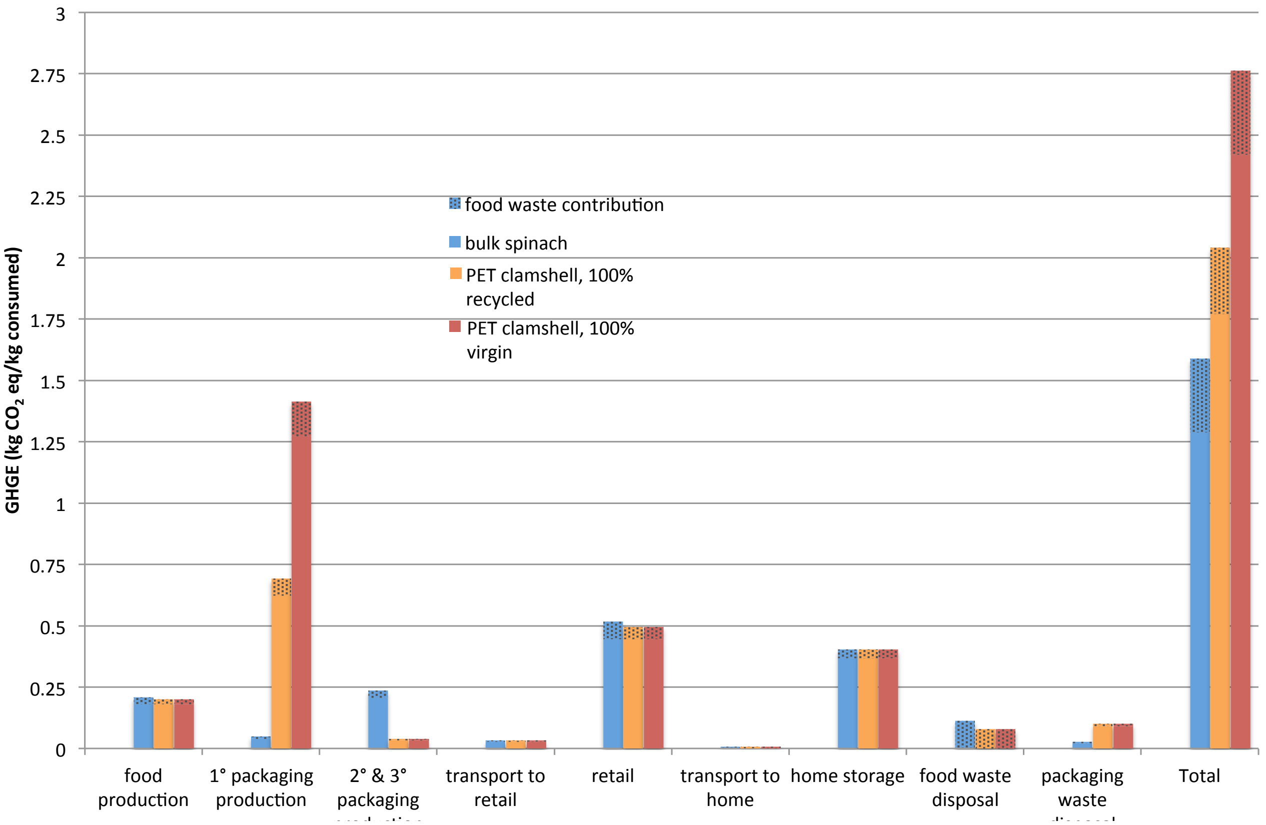

Figure 9.1. Life cycle GHGE comparing spinach sold in bulk and pre-packaged in 5 oz. recycled or virgin PET clamshells. GHGE from recycled PET packaging (primary and tertiary) are 155% greater than bulk, and food waste reduction does not compensate for this increase, resulting the pre-packaged (recycled) spinach having net system GHGE 28% greater than bulk. PET containers derived from virgin material only exacerbate these effects.

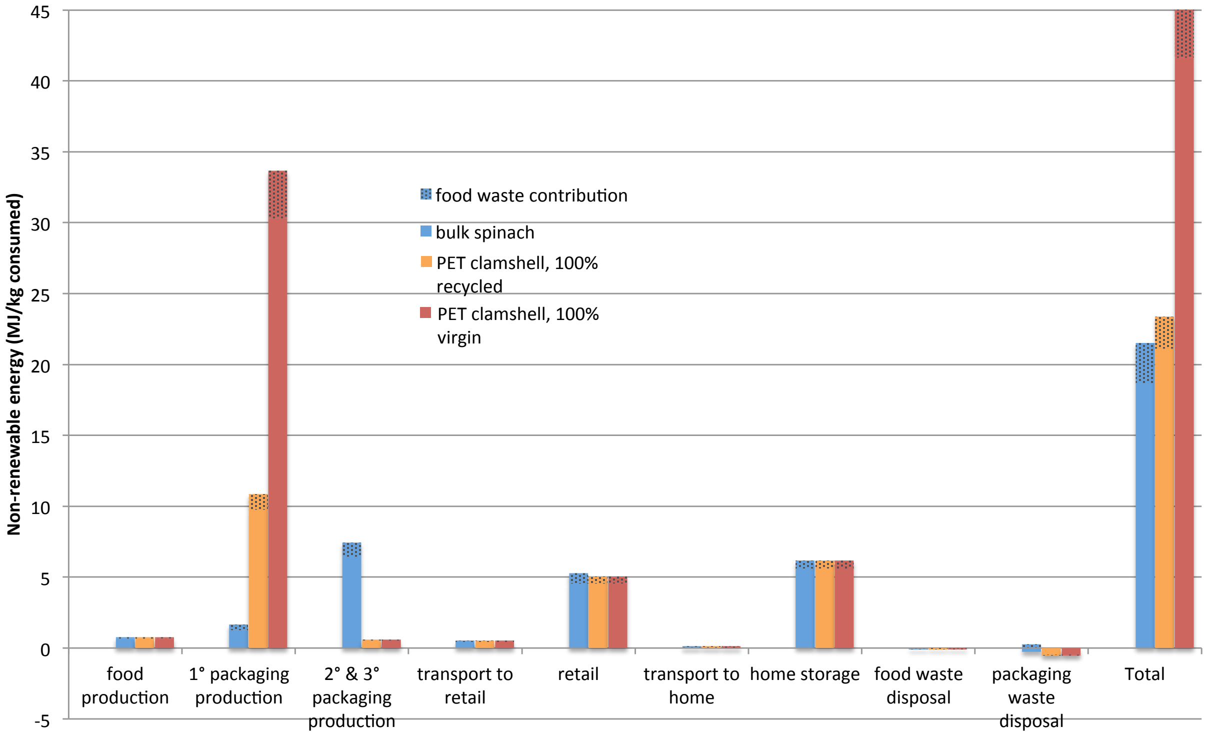

Figure 9.2. Life cycle cumulative energy demand comparing spinach sold in bulk with pre-packaged 5 oz. PET clamshells (recycled or virgin PET). The energy demand from packaging (primary and tertiary) is 26% greater with recycled PET clamshells. Food waste reduction almost compensates for this increase, but the resulting net system energy for pre-packaged spinach is 22% greater than bulk.

9.4. Discussion and conclusions

The spinach bulk vs. pre-packaged case offers a good example where reduced food waste is *not* able to compensate for the increased impacts (GHGE and energy demand) of additional packaging. Referring back to the discussion in the mapping exercise (Section 7), the pre-packaged spinach scenario has a much lower food-to-packaging ratio than pre-packaged mushrooms: 0.27 vs. 6.9, when calculated without the influence of food waste. Thus, food waste effects – the influence of food waste on overall system performance – are diminished in the spinach case.

Again, consumer-level food waste was not varied in the comparison between bulk and pre-packaged. It is challenging to speculate which case may have greater consumer level waste: if pre-packaged leads to greater waste because consumers are forced to purchase a set quantity that is perhaps more than can be eaten before it spoils, then this will further exacerbate the trend seen here. If, however, bulk spinach leads to greater waste at the consumer level, perhaps because the bulk packaging offers less physical protection, then a trade-off could be realized. Our estimates suggest that consumer-level waste rates would need to increase from the assumed 9% to over 24% in order for the pre-packaged (with recycled PET) case to have net lower GHGE.

10. Case study 3: Canned vs. refrigerated vs. frozen vegetables and fruits (green beans and blueberries)

10.1. System Description

Canning and freezing fruits and vegetables is a common way of preserving them. Canned fruits and vegetables are shelf-stable for long periods of time (years), but are sometimes criticized for reduced nutrient content resulting from processing steps, or for added sodium or sugars necessary for preservation. Freezing fruits and vegetables can preserve them form months, and is often thought to better preserve nutrients, but requires energy to maintain a consistently frozen product.

Neither canning nor freezing preservation would be successful without proper packaging. Thus, while there are other processes involved that contribute to extending the shelf life (i.e., blanching, pasteurization, salt or sugar additions, freezing), these processes would not be possible without the addition of packaging. Comparing such products using the LCA model offers an opportunity to investigate the potential role that other life cycle stages beyond agricultural production – i.e., processing, distribution, retail – have in influencing net system environmental performance.

Here we explore example cases of green beans sold fresh and pre-packaged in a microwavable, modified atmosphere bag, frozen green beans, and canned green beans. All three of these products are "ready to eat" in that they don't require additional trimming (the fresh beans have been "snipped"). We explore the influence of out-of-season production and long distance shipping of the fresh beans.


[redacted] [redacted] [redacted]

We also consider a case of fresh blueberries in a 4.4 oz. PET clamshell with frozen blueberries. Canned blueberries are not represented explicitly in the USDA LAFA dataset and are therefore not consider here.


[redacted]

10.2. Data Sources

10.2.1. Green bean production

No known LCA data exist for green bean production in the US. A process for green bean production from the Agri-Footprint database, based on production in the Netherlands, is used as a proxy (see Table 10.1). Table 10.1 also shows the resulting GHGE and energy profiles for the processing stages used in this comparison.

It is important to note that we have observed discrepancies in the impacts (energy use, GHGE) associated with freezing and canning vegetables, and these discrepancies can have a notable influence on the results presented here. The effect of these uncertainties are presented in the discussion section.

Table 10.1. Resulting GHGE and energy demand for green bean production (farm gate), frozen processing, and canned processing.

	GHGE (kg CO2eq/kg)	Non-renewable energy demand (MJ/kg)
Green bean production (at farm gate)	0.36	0.955
Frozen green bean processing (farm gate to processor gate, excluding packaging)[a]	0.402	5.90
Canned green bean processing (farm gate to processor gate, excluding packaging)[b]	0.896	14.2

[a] Frozen green bean processing from (Masanet et al., 2008), Table 4.4 and 4.5

[b] Canned bean processing from (Schenck, 2007); values here are on kg canned bean basis, based on a canning yield of 1.33 kg fresh beans per kg canned beans.

10.2.2. Green bean food waste rates

The table below shows the waste rates for green beans from both the USDA LAFA dataset as well as retail level waste rates measured by our retail partner. Once again, the LAFA retail waste rates are overestimates relative to those realized by our retail example.

Table 10.2. Waste rates utilized in this study for green beans marketed fresh, frozen and canned.

	USDA LAFA dataset		Retail partner	
	Retail waste rate	Consumer waste rate	Total throughput[a]	Retail waste rate
Fresh	18.6%	24%	1,418,998	4.92%
Frozen	6%	24%	1,301,458	0.27%
canned	6%	24%	582,934	0.43%

[a] units purchased by retailer (sales plus waste) summed over circa 200 storefronts and 2 years of sales. This forms the basis for the waste rate value.

10.2.3. Additional modeling parameters: green beans

The following table summarizes modeling parameters used in the green bean case.

Table 10.3. Modeling parameters for green bean scenarios

	Fresh, pre-bagged	frozen	Canned 15 oz. #300 cans	
Weight of primary packaging (kg / kg food)	0.01714	0.0066	0.1521	
Primary packaging composition	100% polypropylene	100% LDPE	99.69% steel, 0.07% LDPE, 0.24% paper	
Distribution packaging (3°) (kg/ kg food)	0.0357	0.04687	0.0321	Fresh: 24 packs/case Frozen: 8 units per carton Canned: 24 cans per case
Distribution packaging composition	100% corrugated cardboard	100% corrugated cardboard	100% corrugated cardboard	
Retail-level food waste	4.92%	0.27%	0.43%	
Consumer-level food waste	24%	24%	24%	
Product volume (ft^3/kg)	0.1224	0.073	0 (not refrigerated at home)	
Consumer-facing area (ft^2/kg)	0.7345	0.465	0 (not refrigerated at retail)	
Average retail price ($) per kg	4.72	3.68	1.83	http://www.ers.usda.gov/data-products/fruit-and-vegetable-prices.aspx
Annual kg sold at retail	2.61e7	3.05e7	2.95e7	http://produceuniverse.com/blogs/11241/20/beans
Transport distance to retail (km)	188	188	188	(U.S. Department of Transportation, 2015), Table 24, SCTG code 032
Assumed retail refrigerator unit	horizontal open, remote condenser, medium temp (38F), 60 ft^2 total display area	vertical closed with transparent doors, remote condenser, low temp (0F), 60 ft^2 total display area	N/A	

Frozen products are assumed to be stored for 45 days in refrigeration at home, whereas fresh products are assumed 4 days.

10.2.4. blueberry production

GHGE from farm gate blueberry production was taken from a study comparing conventional and organic production of a number of different crops in California (Venkat, 2012); conventional production was assumed. Because this California study did not report energy use (or report GHGE in enough detail that energy use could be inferred), a value for energy use from blueberry production was used from a different source (Peano et al., 2015).

Table 10.4. Resulting GHGE and energy demand for blueberry production (farm gate) and frozen processing.

	GHGE (kg CO2eq/kg)	Non-renewable energy demand (MJ/kg)
blueberry production (at farm gate)	0.829[a]	3.232[b]
Frozen blueberry processing (farm gate to processor gate, excluding packaging)[c]	0.395	5.80

[a] from (Venkat, 2012); conventional blueberry production in California
[b] from (Peano et al., 2015)
[c]Frozen fruit processing from (Masanet et al., 2008), Table 4.4 and 4.5

10.2.5. blueberry food waste rates

The table below shows the waste rates for green beans from both the USDA LAFA dataset as well as retail level waste rates measured by our retail partner. Retail waste rates from the retail partner are used in calculations, whereas consumer waste rates rely on LAFA data. It is unclear why the consumer-level waste rate for frozen blueberries is significantly greater than fresh.

Table 10.5

	USDA LAFA dataset		Retail partner	
	Retail waste rate	Consumer waste rate	Total throughput[a]	Retail waste rate
Fresh	5.2%	8%	1,273,483	0.717%
Frozen	6%	29%	819,104	0.325%

[a]units purchased by retailer (sales plus waste) summed over circa 200 storefronts and 2 years of sales. This forms the basis for the waste rate value.

10.2.6. Additional modeling parameters: blueberries

The following parameter are used in the scenario modeling

Table 10.6. Modeling parameters for blueberry scenarios

	Fresh, 4.4 oz. PET clamshell	frozen	source
Weight of primary packaging (kg / kg food)	0.1042	0.02	
Primary packaging composition	100% recycled PET	100% LDPE	
Distribution packaging (3°) (kg/ kg food)	0.1685	0.0667	
Distribution packaging composition	100% corrugated cardboard	100% corrugated cardboard	Fresh: 12 packs per tray Frozen: 30 packs/case
Retail-level food waste	0.717%	0.325%	Retail partner
Consumer-level food waste	8%	29%	LAFA
Product volume (ft^3/kg)	0.0688	0.0918	
Consumer-facing area (ft^2/kg)	0.699	1.1023	
Average retail price ($) per kg	10.43	8.02	http://www.ers.usda.gov/data-products/fruit-and-vegetable-prices.aspx
Annual kg sold at retail	1.44e8	2.36e7	based on total retail dollars at $1.5 billion for fresh and $189.6 million for frozen, in 2015 from [http://www.thepacker.com/shipping-profiles/summer-berries/council-says-blueberry-demand%E2%80%99s-never-been-higher] and ave. retail price
Transport distance to retail (km)	922	922	(U.S. Department of Transportation, 2015), Table 24, SCTG code 033
Assumed retail refrigerator unit	horizontal open, remote condenser, medium temp (38F), 60 ft^2 total display area	vertical closed with transparent doors, remote condenser, low temp (0F), 60 ft^2 total display area	

Frozen products are assumed to be stored for 45 days in refrigeration at home, whereas fresh products are assumed 4 days.

10.3. Results

10.3.1. Green beans

Results comparing the life cycle GHGE and energy demand are shown in Figure 10.1 and 10.2, respectively. While retail level food waste for frozen and canned beans are notably lower than fresh, this is not sufficient to balance the increased impacts due to processing, packaging (particularly the steel can) and refrigeration.

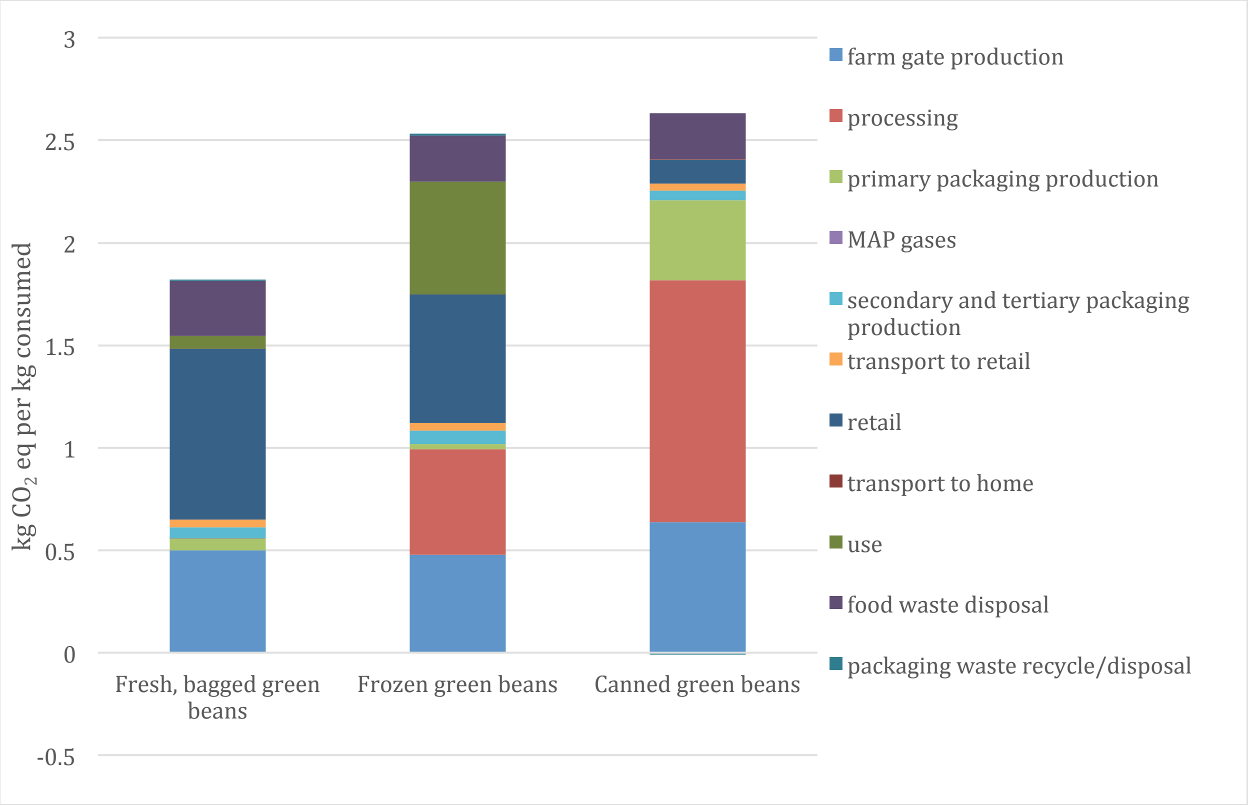

Figure 10.1. Comparison of the life cycle GHGE per kg of consumed green beans for fresh, frozen and canned beans. Consumer-level waste rates are assumed to be 24% for each scenario, whereas retail-level waste rates are 4.9%, 0.3% and 0.4% for fresh, frozen and canned, respectively. In this estimate, reductions in retail food waste do not balance the increased emission from processing and refrigeration.

Consumer waste rates are constant across the scenarios in Figures 10.1 and 10.2. The frozen bean scenario breaks even on GHGE with fresh if the consumer food waste rate decreases from 24% to 2.5%. The canned scenario is close to breaking even with fresh at zero consumer waste.

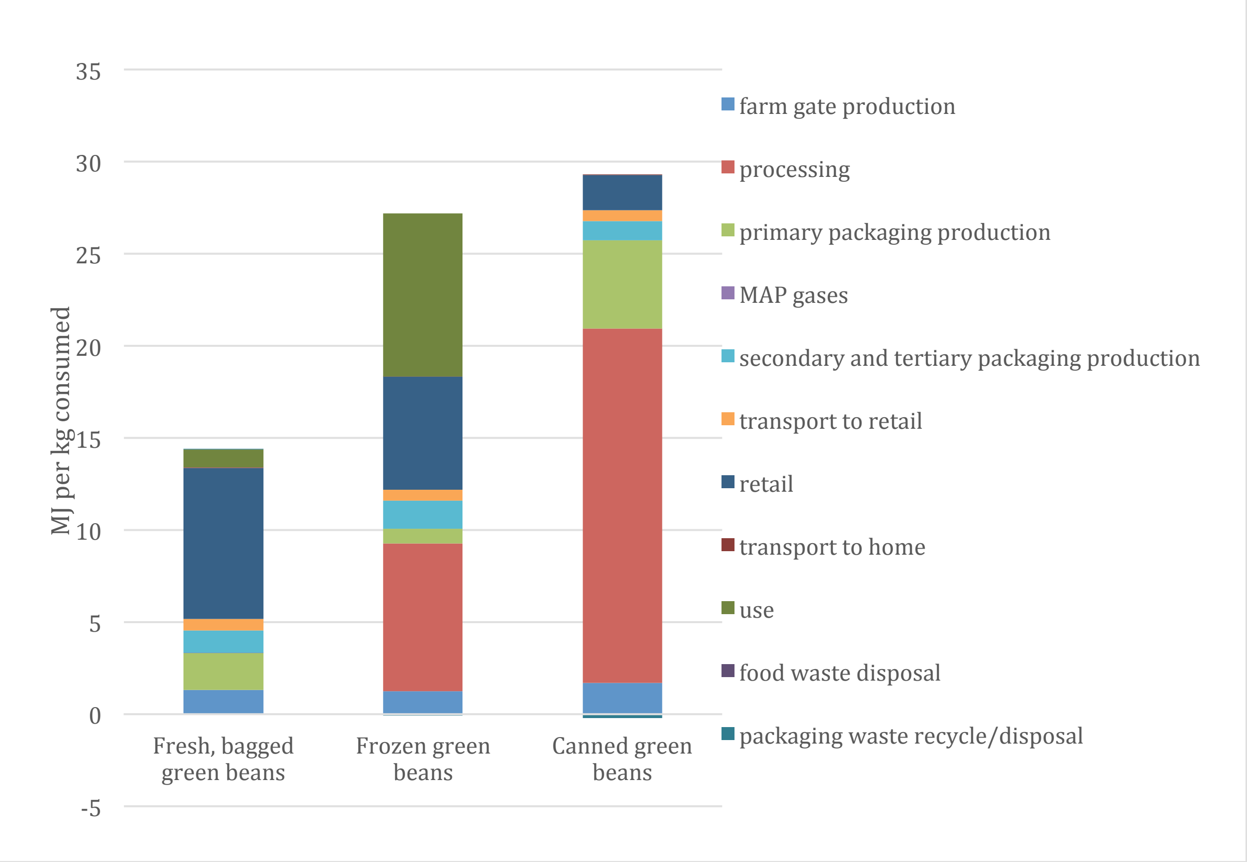

Figure 10.2. Comparison of the life cycle non-renewable energy per kg of consumed green beans for fresh, frozen and canned beans. Consumer-level waste rates are assumed to be 24% for each scenario, whereas retail-level waste rates are 4.9%, 0.3% and 0.4% for fresh, frozen and canned, respectively. In this estimate, reductions in retail food waste do not balance the increased energy due to processing and refrigeration.

Out of season consumption of green beans offers an additional comparative scenario. Here, we assume that the emissions associated with production and processing remain constant regardless of origin of production, and the only thing that varies with out-of-season consumption of fresh beans is the distance transported from farm to retail. If the transport distance (by refrigerated truck) for fresh is increased to 2028 km[2] from the default 188 km (with frozen and canned transport remaining at 188 km), the fresh bean scenario *still* represents the lowest GHGE (2.19; 2.53; 2.62 kg CO2 eq/kg for out-of season fresh, frozen and canned, respectively). Frozen GHGE break even with out-of-season fresh if consumer waste is reduced to 14.5%; canned breaks even at a consumer waste rate of 11.3%.

10.3.2. blueberries

The blueberry case follows a similar trend as that seen with green beans: reductions in retail waste are not sufficient to balance increased impacts from processing and refrigeration (Figures 10.3 and 10.4). In the blueberry case, the LAFA dataset indicates significantly greater consumer-level food waste for frozen relative to fresh: the reason for

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[2] 2028 km is a population-weighted distance from Orlando, Florida to the population center of all continental states. Florida is the largest domestic producer of fresh green beans.

this is unclear. This is not a strong driver of the trends seen in the results however: if consumer waste rates are made equal at 8%, the frozen scenario still has significantly greater GHGE (3.1 for frozen vs. 2.1 for fresh) and energy demand (28.0 for frozen vs. 19.7 for fresh).

The increased impacts for frozen blueberries are primarily driven by retail energy use, and in particular retail refrigeration energy. While the daily energy demand for the low temperature refrigeration unit is greater than horizontal, open, medium temperature unit that the fresh berries are assumed to be stored in (22.8 kWh/day vs. 15.5 kWh/day, respectively), the difference seen here is more strongly dependent on the allocation approach taken to assign this energy use to a kg of berries. In our allocation approach, retail refrigeration energy is proportional to the consumer-facing product area per kg (approximation of the fraction of total refrigeration unit occupied by product), and inversely proportional to the total annual kg sold at retail (estimate of product throughput, i.e., how long a given kg of product stays on the shelf). In this case, the throughput seems to have the strongest influence: if the total annual kg sold at retail is set equal to that for the fresh case (while keeping all other parameters as described for frozen in Table 10.6), GHGE decrease to 3.2 kg CO_2eq/kg consumed. This retail energy allocation approach is discussed in Section 6.

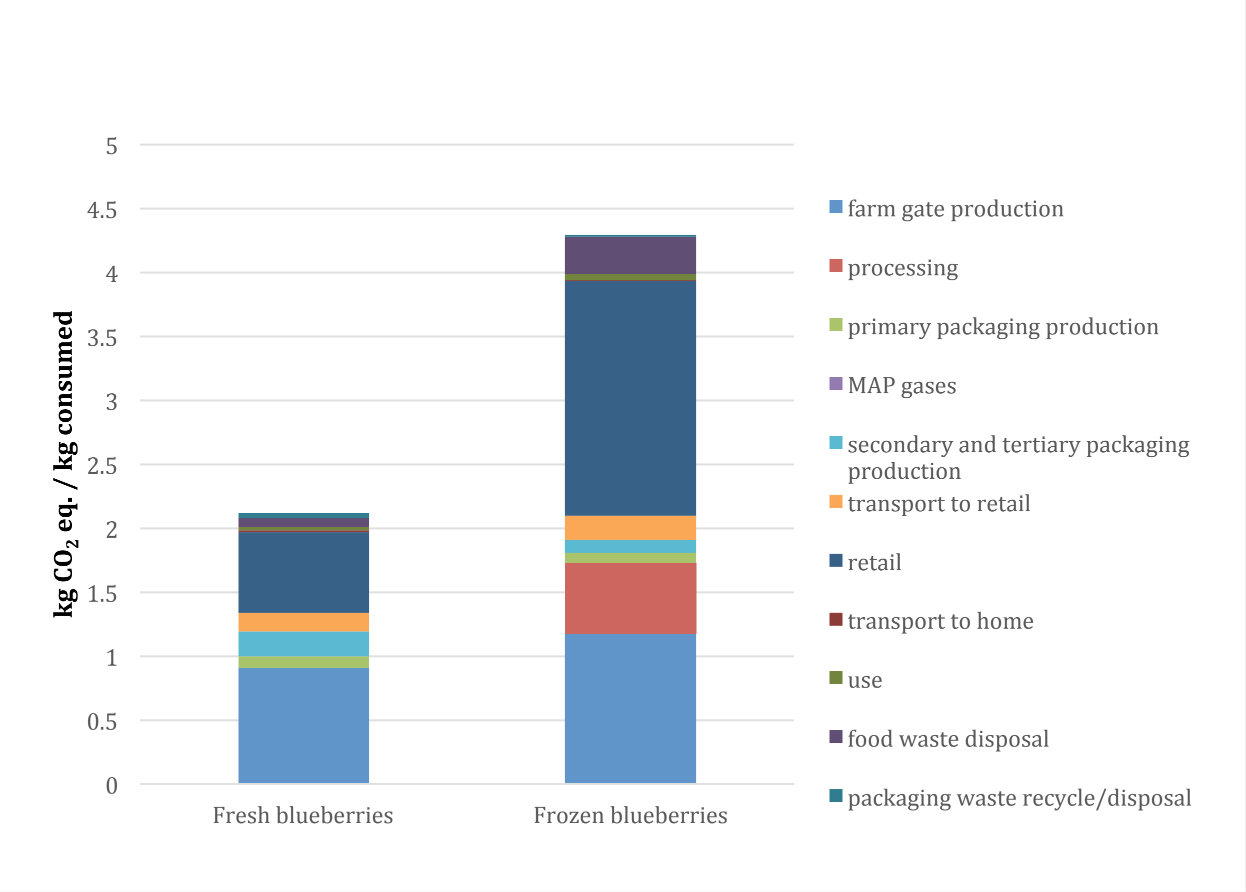

Figure 10.3. Comparison of the life cycle GHGE per kg of consumed blueberries for fresh and frozen berries. Consumer-level waste rates are assumed to be 8% and 29% and retail-level waste rates are 0.72% and 0.33% for fresh and frozen, respectively. In this estimate, reductions in retail food waste do not balance the increased emission from processing and refrigeration.

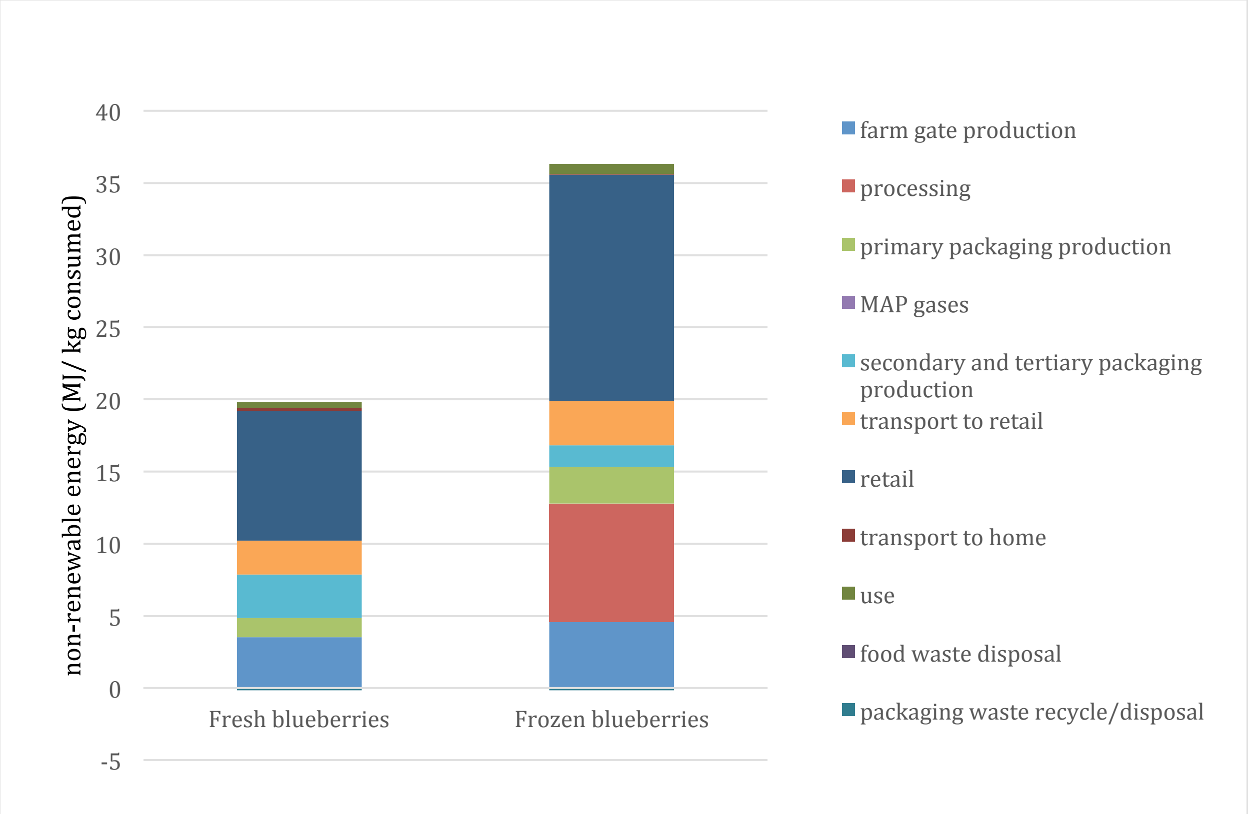

Figure 10.4. Comparison of the life cycle non-renewable energy per kg of consumed blueberries for fresh and frozen berries. Consumer-level waste rates are assumed to be 8% and 29% and retail-level waste rates are 0.72% and 0.33% for fresh and frozen, respectively. In this estimate, reductions in retail food waste do not balance the increased energy use due to processing and refrigeration.

10.4. Discussion and conclusions

The green bean and blueberry cases presented here demonstrate that while preservation methods such as freezing and canning can reduce retail-level food waste (as reported by our retail partner), and while the packaging required to maintain preservation by these techniques can represent significantly different impacts than fresh packaging, in these cases, impacts from other life cycle stages – processing and refrigeration energy demands – drive differences between fresh, frozen and canned scenarios. We demonstrate the reduction in consumer level waste that would be required for the GHGE associated with frozen green beans to break even with fresh beans. The waste reduction necessary for this break even point seems much more reasonable when comparison is made with out-of-season fresh bean production that must be transport longer distance. Of course, if beans were to require air-freight in order to meet necessary market freshness, the impacts for the fresh bean case would almost certainly be greater than frozen or canned.

We acknowledge discrepancy between identified sources of the energy demand for vegetable and fruit freezing and canning processes. The inventory data used to represent the green bean canning process was taken from a study that specifically looked at the canning of green beans by the Truitt Brothers canning operation in Oregon (Schenck, 2007). Our reconstruction of this process in SimaPro, using average US electricity grid mix and generic natural gas “heating” processes, results in canning process needs of 14.2MJ per kg beans canned (0.90 kg CO2e per kg beans canned). In addition, this report indicated a product "loss" between fresh and canned beans which further increases the impact of the canning process. An alternative, more generic source of the energy requirements for fruit and vegetable processing was found in an EnergyStar document developed by Ernest Orlando Lawrence Berkeley National Laboratory (Masanet et al., 2008). Building a process in SimaPro with energy flows given in this report resulted in canning process needs of 3.9 MJ per kg beans canned (0.29 kg CO_2eq/kg), notably lower than the Truitt Brothers example. We used the Truitt Brothers data in our case study as it was specific for green bean processing. However, if the EnergyStar data were used instead to represent green bean canning, canning would have slightly lower GHGE and energy demand (1.64 kg CO_2eq/kg, 13.4 MJ/kg) than the fresh scenario in Figures 10.1 and 10.2. Clearly, accurate data on these processing energy requirements are important for such comparisons.

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12. Other case studies pursued, lessons learned, and reasons for discontinuation

12.1. Fresh chicken in China

CPIS member WWF offered a potential case study for this project based on research they were conducting into the introduction of a cold chain into the processing and distribution of fresh chicken in China. China's meat markets have historically been "wet" markets, meaning that animal products are sold without additional processing or packaging, sometimes packed on ice. As China moves toward more of a Western style grocery retailing environment, however, there is a need/desire for more upstream processing of, for example, poultry products, resulting in the pre-packaged products now commonplace in Western markets. WWF was exploring barriers and needs in making this transition such that it resulted in reductions in energy use, food waste, and overall improvements in sustainability. At the initiation of this food waste/packaging project, it was thought that WWF's research would reveal waste rates that could be used in an LCA comparison of wet market and packaged chicken. These waste rates were not available, so pursuit of this case was discontinued.

12.2. Broccoli

Broccoli is a vegetable with a relatively high respiration rate, which requires special treatment during distribution/handling in order to maintain a marketable product. Historically, fresh broccoli heads have been shipped on ice in order to avoid excessive respiration and maintain fresh product. While some broccoli is still shipped this way, there has been a notable shift in the industry toward shrink-wrapped broccoli heads. Applying a tight-fitting film layer over the broccoli also aids in reducing respired moisture loss and allows shipment without ice. Many retailers prefer this method as it means less mess (dripping boxes) to deal with and also means a packaged product with a UPC code for easy check-out. In addition, some distributors are marketing broccoli heads sealed in modified atmosphere bags to increase shelf-life/freshness during shipping.

Conversation with Henry Dill at Pacific International Marketing (PIM), a major US broccoli supplier, offered some interesting insights to this potential comparison. According to Mr. Dill, while PIM markets broccoli both on ice and shrink wrapped per customer preference, they see no benefit from a shelf-life standpoint for the shrink-wrapped product. In fact, as a grower/distributor, PIM prefers the iced product because it can be packed and palletized in the field and then the entire pallet is "injected" with slush ice to hydro-cool the product. This greatly simplifies their post-harvest handling process, potentially leading to better/fresher product than is possible with shrink-wrapping.

Given this insight and the fact that our primary retail partner only markets shrink-wrapped heads and therefore side-by-side retail-level waste rate comparisons were not available, this case was discontinued despite notable effort to develop the underlying data for executing it in the LCA model.

12.3. Fresh vs. frozen fish

Fresh fish is a high value product with very limited shelf life. Freezing fish fillets offers a good method for extending shelf life, however there is a perception among consumers that frozen fish fillets are of lower quality. Advancements in freezing techniques (rapid freeze directly on the boat, for example) has eliminated much of the concern with freezing fish, and in fact, much of the fish sold fresh through a meat counter is frozen during distribution and thawed for display and sale. We were considering investigating this comparison through the lens of this project.

Fish product chains are very complex with methods varying greatly depending on source. This is further complicated by the fact that much of the fish sold today is the product of aquaculture. While sealed packaging certainly makes the marketing of frozen fish possible, it is acknowledged that it is not the packaging necessarily that extends shelf life but instead maintaining freezing temperatures. In addition, retailers may utilize the perception of differences in quality between frozen and fresh product to drive sales of fresh. This makes it challenging to consider comparable quality products.

Given the above mentioned complications and the fact that waste rates for foods sold through specialty counters such as the meat/seafood counter were not readily available from our sole retail partner, this case study was not further pursued.

12.4. Fresh pasta

Fresh, packaged pasta has developed a sizable niche market as a specialty product. Providing the necessary shelf life to successfully market these fresh pastas requires refrigeration and attention to packaging that aids in eliminating oxygen. Often, fresh pastas are packaged with an additional oxygen scavenging sachet. The Nestle-owned fresh pasta brand, Buitoni, utilizes an oxygen-absorbing film in the lidding material of its line of refrigerated pastas. This oxygen scavenging film eliminates the need for another sachet, and can extend shelf life by 50%. An alternative brand (Three Bridges) available at our retail partner uses an ultra-high barrier “Plantic eco Plastic” package based on starch technology.

We began to pursue this case by researching additional information on the two packaging technologies and gathering waste rate data from our retail partner on the two products. While differences in waste rates were observable between the two product lines (sales weighted averages circa 8.8% vs. 1.6% for Buitoni and Three Bridges, respectively, when averaged across the whole product line), there was also significant difference in total throughput. The Buitoni line had total sales that were a factor of 14 greater than the specialty (organic, gluten free, all natural, etc.) Three Bridges product line, which carried a larger price point. This introduces a complicating factor of trying to discern whether differences in waste rates at the retail level are due to differences in packaging configurations or whether they are merely due to product throughput.

We were proposing to explore methods for deconstructing the contributions to waste rates in year three of the project in order to better attribute observable differences to packaging configuration. This case was discontinued due to discontinued funding for year three of the project.

13. Project conclusions

The mapping exercise detailed in Section 7 identifies the “food-to-packaging ratio” as a useful scan-level indicator of the influence that food waste will have on overall system environmental performance. Often, estimates of this ratio can be generated without conducting a full life cycle assessment on a given product, offering a potential tool to assist in packaging design. At high food-to-packaging ratios, food waste is likely to have a strong influence on system environmental performance and investments (in terms of increased environmental impact) in packaging that result in reduced food waste are *likely* to lead to net system environmental benefit. On the other hand, very low food-to-packaging ratios (less than unity) indicate that it will be much more difficult for investments in packaging aimed at reducing food waste to lead to net reductions in environmental impact. In these instances, sustainable design efforts are likely better directed at reducing the impact of the packaging itself.

The three case studies documented in this report offer three rather different viewpoints on the food waste/ packaging interaction. The first two cases are parallel in design: both compare bulk distribution and retail of fresh vegetables (with minimal packaging) to vegetables pre-packaged in PET trays/boxes. In both the case of mushrooms and spinach, measured retail food waste rates were lower for the pre-packaged product than for the bulk product. With mushrooms, this decrease in food waste led to a net reduction in system GHGE and energy demand, despite the fact that packaging had a larger impact. In the spinach case, however, the food-to-packaging GHGE ratio is much lower (0.27 vs. 6.9 for mushrooms), and reductions in food waste were unable to balance out the increased impact of packaging, resulting in a net increase in GHGE and energy demand when going from bulk to pre-packaged spinach distribution and retailing.

The third case considers fresh vs. frozen vs. canned fruits and vegetables. Specific packaging is required to allow these preservation techniques to be marketed. The question asked in this case is whether the material and energy investments required for freezing and canning result in a net environmental benefit if retail food waste is taken into account. Pre-packaged, fresh green beans were compared with both frozen and canned green beans; the fresh beans exhibited retail-level waste rates at least a factor of ten higher than frozen or canned. Yet, system GHGE and energy demand were driven largely by processing and retail refrigeration energy requirements, resulting in greater system impacts with frozen and canned beans. Break-even scenarios were considered by assuming the frozen and canned beans also resulted in lower consumer-level food waste. Very low consumer-level waste rates were required for freezing and canning to break-even with the fresh scenario. If the fresh beans were assumed out-of-season and therefore transported a much greater distance, consumer-level waste rates still needed to be decreased in order for the preserved beans to break even, but these reductions were more reasonable. A similar comparison was made between fresh and frozen blueberries. Frozen had lower retail-level waste rates, but GHGE and energy demand were still greater than the fresh scenario. These results are very sensitive to processing energy demand and trends could change with more accurate data.

In conclusion, this project has demonstrated the opportunities, both theoretically and in empirically based case studies, for packaging to contribute to reduced food waste and for such waste reductions to lead to net environmental benefits. The project has also demonstrated, however, that the environmental balance between food waste and food packaging can be delicate, and careful assessment and quality waste rate data are needed in order to demonstrate a net environmental benefit in these tenuous cases. The detailed cases explored in this project lie close to the balancing point, making them interesting case studies. Surely there are other food/packaging combinations where the food-to-packaging ratio is much higher (beef, for instance) and opportunities for food waste reduction to result in system environmental benefit much more certain. As a fully designed system at the interface between food and the end user, the opportunities for packaging to further influence food waste can not and should not be overlooked.

14. Recommendations for future research

A major barrier in better understanding the impacts of food waste and packaging's role in moderating this waste is access to quality data on food waste rates for specific products. Over the course of this project, we were able to access food waste rates for specific products from a few retailers, thus allowing development of case studies grounded in empirical food waste data at the retail level, at least. However, identifying meaningful comparisons – foods that can be considered identical or interchangeable that are offered in multiple packaging configurations – among the products offered a given retailer proved to be very challenging. This is especially true when attempting to identify comparisons where there is a logical reason for assuming that differences in retail-level waste rates are due to differences in packaging configuration. An observation made over the course of this project is that in the current marketplace, design decisions on packaging configuration appear to be driven to a far greater extent by consumer perception/appeal than by the ability to moderate food waste. This represents a potential opportunity for the packaging industry. However, being smart about such design will require a better understanding and better feedback on waste rates. It seems that this may be possible at the retail level if the cooperative will existed among retailers: inventory data logging is sophisticated enough at this stage that aggregation of waste rate data for specific products across multiple retail enterprises (and large number of storefronts, regional markets, etc.) should be possible. It would require careful development/design such that sensitive sales data were not shared amongst competitors and waste rates were available only in an aggregate fashion that hid individual retailer identity. Given the current concern around food waste, however, and the need to intervene at multiple levels, there *may* be opportunity for such a data gathering effort to materialize.

Consumer-level food waste is an extremely tenuous problem in that it represents the majority of the food waste in the US, but it is also very difficult to accurately measure, characterize and understand in a way that would allow smart, product-specific design aimed at moderating consumer-level food waste to occur and to be monitored. Further research in this area is desperately needed in order to better direct efforts by the food packaging industry toward design and innovation that can aid in reducing consumer food waste, both by extending shelf life, but also by “scripting” consumer behaviors. This area – better understanding consumer behavior surrounding food waste and how packaging attributes can influence this behavior – perhaps shows the most promise of leading to positive change.

Case studies such as the ones presented in this report would greatly benefit from more integrated involvement by the food manufacturing, distribution, and retailing industry. Great effort went in to gathering data on packaging materials, quantities per food unit, likely distribution networks, and typical retail display practices, with the net result being data that is likely to be of only moderate quality. Much of this information is likely to be easily at hand, and of a very specific and therefore higher quality nature, among manufacturers and other food industry stakeholders. Buy-in through involvement in the research process also increases the likelihood that the results of the research will be noted and integrated into design efforts and business practices. Future research in this or similar areas should be conducted with careful attention and effort placed on building cooperative relationships and participation among the full ‘life cycle’ of food industry stakeholders.

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SUPPORTING INFORMATION

Mapping the Influence of Food Waste in Food Packaging Environmental Performance Assessments

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number of pages: 12
number of figures: 1
number of tables: 4

Contents:

Table S1. Data sources and impact factors for packaging material production and transformation.

process	Dataset origin	GHGE (kg CO_2eq/kg)	CED (MJ/kg)
General purpose polystyrene	USLCI	3.1	94.7
High density polyethylene resin (virgin)	USLCI	1.8	72.7
Recycled postconsumer HDPE pellet	USLCI	0.6	8.4
Low density polyethylene resin	USLCI	2.2	80.1
Linear low density polyethylene resin	USLCI	1.9	74.2
Polypropylene resin	USLCI	1.9	74.0
Polyvinyl chloride resin	USLCI	2.2	54.4
Ethylvinylacetate foil (proxy for Ethylene vinyl alcohol)	Ecoinvent 3	2.9	88.2
Ethylene vinyl acetate copolymer	Ecoinvent 3	2.2	76.5
Polyvinylidenechloride, granulate	Ecoinvent 3	5.1	80.3
Recycled postconsumer PET flake	USLCI	0.8	11.5
Polyethylene terephthalate resin (virgin)	USLCI*	2.7	71.1
Steel, low-alloyed, hot rolled	Ecoinvent 3	1.9	21.7
Corrugated board box	Ecoinvent 3	1.1	16.3
Kraft paper, bleached (used for all other paper beyond corrugated)	Ecoinvent 3	1.6	23.5
Rough green lumber, softwood, at sawmill (used for palletwood)	USLCI	0.1	1.3
Blow moulding	Ecoinvent 3	1.4	21.6
Calendaring, rigid sheets	Ecoinvent 3	0.4	6.9
Extrusion, plastic film	Ecoinvent 3	0.6	8.7
Injection moulding	Ecoinvent 3	1.3	22.2
Polymer foaming	Ecoinvent 3	0.9	10.8
Thermoforming, with calendering	Ecoinvent 3	0.9	14.7

*the "dummy" ethylene glycol manufacturing process included in the Ecoinvent 3 version of this process was replaced with "ethylene glycol, at plant" from the USLCI dataset.

Table S2: Data sources and impact factors for distribution transport processes.

process	Dataset origin	GHGE (kg CO_2eq/tkm)	CED (MJ/tkm)
1 tkm Transport, freight, lorry, unspecified	Ecoinvent 3	0.139	2.270
Refrigerated transport	Above, with modifications described in text	0.143	2.344

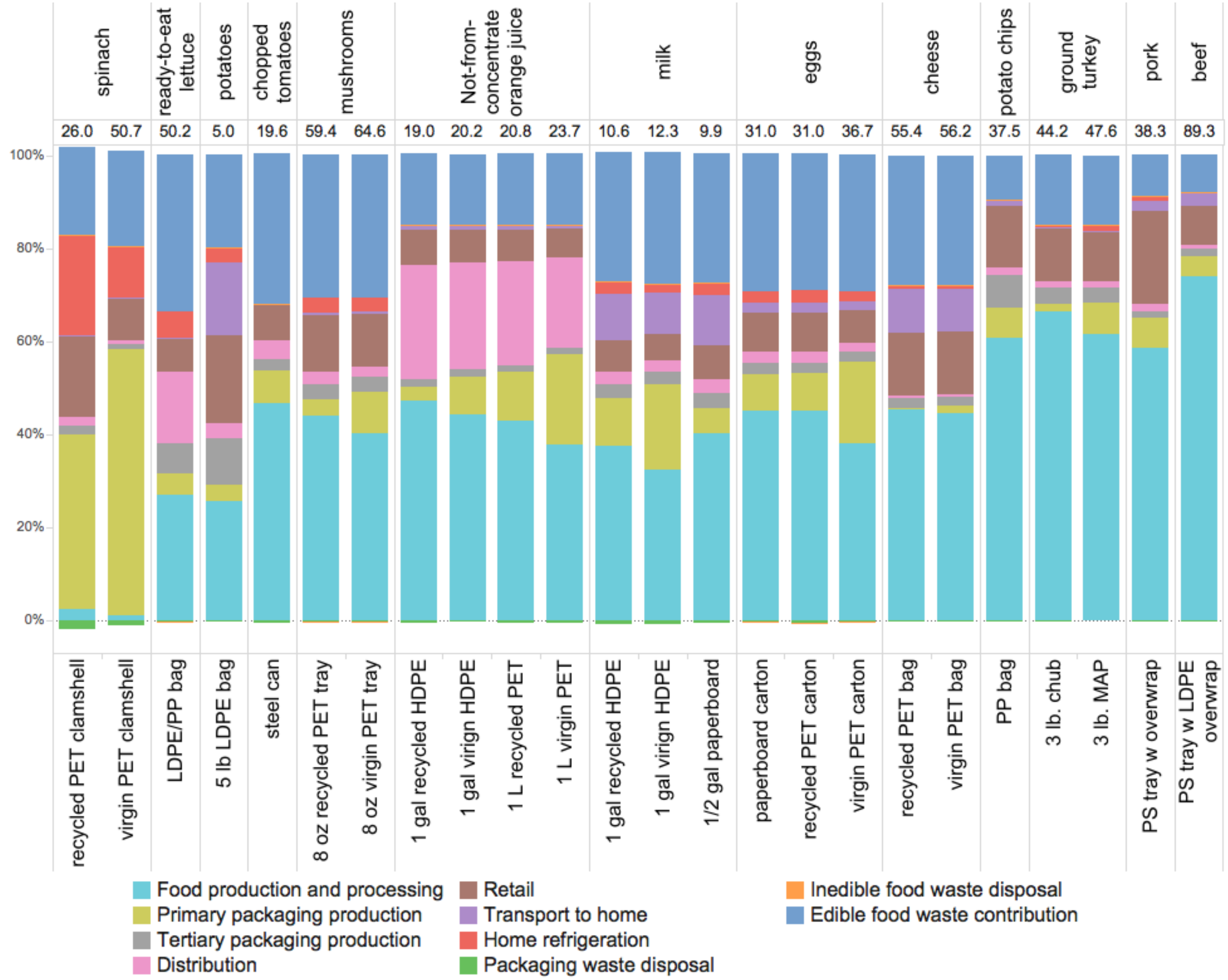

Figure S1. Distribution of non-renewable energy demand across life cycle stages for the food/package combinations in Table 1. Values above bars represent total energy demand in MJ (kg consumed)$^{-1}$. Note that "edible food waste contribution" includes emissions associated with edible retail- and consumer-level food waste accumulated throughout the life cycle: production, packaging, distribution, retail, refrigeration, and disposal.

Table S3. Food waste rates for food categories examined in study, comparing empirical values based on sales and waste data from a US retailer (averaging multiple products in each food category) and values available through USDA's Loss Adjusted Food Availability dataset.

Food category	**USDA LAFA waste rates**[a]		**Waste rate data from retail Partner**[b]	
	Retail	consumer	number of specific products (separate UPC IDs) averaged[c]	sales weighted average[d]
Spinach	14%	9%	3	0.87%
Lettuce	14%	24%	3	1.24%[e]
Tomatoes, chopped, canned	6%	28%	4	0.19%
Mushrooms	13%	21%	3	2.65%
Potatoes	7%	16%	5	0.42%
Potato chips	6%	4%	5	0.23%
Orange Juice	6%	10%	14	0.62%
Eggs	9%	23%	5	0.0005%
Cheese	11%	6%	8	3.42%
Milk	12%	20%	21	0.39%
Ground turkey	4%	12%[f]	2	2.64%
Pork	4%	5%[f]	6	3.86%
Beef	4%	4%[f]	9	2.80%

[a] from USDA Loss Adjusted Food Availability (LAFA) data, presented as food "loss" rates

[b] based on sales and "throwaway" tracking from an anonymous US retail chain, averaged over 2 years of sales at circa 200 storefronts.

[c] number of individual products of given food category included in estimates

[d] Average retail-level waste rate, weighted by the total sales of each product in the given category

[e] ready-to-eat romaine lettuce

[f] corrected for cooking losses (see methods in article)

Sensitivity Analysis

Table S4 offers the effect on total system GHGE and CED due to 20% perturbations in a full suite of modeling parameters for two cases: spinach in PET clamshell (a low FTP case) and ground turkey in MAP packaging (a high FTP case). Differing responses to positive and negative perturbations are due to parameters that enter into the model calculations as divisors. The parameter, "average retail price of product" influences the model through economic allocation of retail non-refrigeration energy use and retail-to-home transport.

Table S4. Sensitivity of total system GHGE and non-renewable CED for the 'spinach in PET clamshell' and 'ground turkey in MAP packaging' case to a ±20% change in model parameters.

	Spinach in PET clamshell				Ground turkey in MAP packaging			
Parameter change	+20%	-20%	+20%	-20%	+20%	-20%	+20%	-20%
Model parameter	Change in system GHGE		Change in system CED		Change in system GHGE		Change in system CED	
Agricultural production impact per kg	1.85%	-1.85%	0.65%	-0.65%	18%	-18%	13%	-13%
consumer-level food waste rate	8.44%	-7.43%	6.72%	-5.93%	3.10%	-2.90%	2.80%	-2.70%
retail-level food waste rate	2.09%	-2.02%	1.45%	-1.39%	0.80%	-0.78%	0.72%	-0.71%
weight of primary packaging	7.25%	-7.25%	8.92%	-8.92%	0.33%	-0.33%	1.60%	-1.60%
weight of tertiary packaging	0.24%	-0.24%	0.32%	-0.32%	0.35%	-0.35%	0.75%	-0.73%
transport distance to retail	0.28%	-0.28%	0.43%	-0.43%	0.13%	-0.13%	0.34%	-0.34%
total annual product sold nationally	-2.00%	3.01%	-1.04%	1.58%	-0.09%	0.14%	-0.05%	0.09%
total grocery sales, all products	-0.08%	-0.07%	-0.11%	-0.10%	-0.86%	1.30%	-2.00%	3.10%
average retail price of product	2.18%	-2.18%	3.21%	-3.21%	1.00%	-1.00%	2.40%	-2.40%
total display area (TDA) of retail refrigeration unit	-0.12%	0.18%	-0.06%	0.10%	-0.02%	0.03%	-0.02%	0.03%
product consumer facing area	2.42%	-2.42%	1.28%	-1.28%	0.13%	-0.13%	0.11%	-0.11%
days in home refrigerator	3.46%	-3.46%	5.03%	-5.03%	0.13%	-0.13%	0.30%	-0.30%
annual household refrigeration energy demand	3.46%	-3.46%	5.03%	-5.03%	0.13%	-0.13%	0.30%	-0.30%
home refrigerator volume	-2.88%	4.32%	-4.19%	6.29%	-0.11%	0.16%	-0.25%	0.37%
product volume	3.46%	-3.46%	5.03%	-5.03%	0.13%	-0.13%	0.30%	-0.30%
food composting rate	-0.10%	0.10%	0.01%	-0.01%	-0.02%	0.02%	0.00%	0.00%
PET recycling rate	-0.24%	0.24%	0.14%	-0.14%	-	-	-	-
PP recycling rate	-	-	-	-	0.00%	0.00%	0.00%	0.00%
corrugated cardboard recycling rate	-0.10%	0.19%	0.01%	-0.02%	-0.14%	0.28%	0.03%	-0.05%

Meta analysis contributing to Figure 2 (main text):

Figure 2 in the main text was developed out of a literature survey of the food LCA literature, drawing from a large variety of publicly available sources. A much larger collection of food GHGE data gathered from the literature was filtered to contain only scenarios that included packaging in the overall life cycle (excluding, e.g., studies for which the scope was only farm-gate). The citations listed below are those remaining after this filter, and are the sources for the data in Figure 2. The boundary conditions for these studies do not necessarily reflect the system boundaries for the current study (as presented in Figure 1) nor were any of the LCA data corrected or adjusted to reflect U.S. conditions.

All GHGE factors, reported per life cycle stage, were corrected to a functional unit (relative basis) of 1 kg consumed food. For animal-based foods, this correction was to 1 kg boneless, edible weight. The Food To Packaging (FTP) ratio data presented in Figure 2 was calculated as follows:

$$FTP = \frac{(agricultural\ production\ stage\ GHGE) + (processing\ stage\ GHGE)}{(packaging\ production\ stage\ GHGE)}$$

Note that waste disposal stages (either food waste or packaging waste) were not included in the FTP ratio.

It is important to recognize that the food LCA scenarios contained in this review represent a wide variety of food types, production methods and locations, and packaging configurations. Our intention in presenting the data in this manner is to communicate the potential range and variability of this parameter that may be relevant to considering food waste impacts in designing sustainable packaging solutions.

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