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Life Cycle Assessment of Food Packaging and Waste

Phase 1 Internal Report: Literature Review and Case Study Descriptions

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1. 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?

These are the questions to be explored in this research project titled "Life Cycle Assessment of Food Packaging and Waste." In this Phase 1 report, we set the stage for the project with a literature review of relevant areas, an outlining of methodological approaches, and a description of the case studies to be investigated in Phase 2.

The remainder of the report proceeds as follows: the literature review establishes the area of research by first highlighting life cycle assessment efforts to quantify the environmental impacts of food production (Section 2.1), then detailing the case for concern with food waste in Section 2.2. The review then turns to life cycle assessment studies of packaging materials and systems as well as emerging sustainability efforts in food packaging (Section 2.3). This leads to the role that packaging plays in reducing food waste in Section 2.4. Finally the literature review culminates with an acknowledgement of the need to consider both food product and package as a whole system in Section 2.5, summarizing the knowledge to date of the environmental trade-off between food waste and food packaging. Section 3 provides further detail of the methodological approach that will be used in the Phase 2 study of the cases described in Section 4.

2. Literature review

2.1. 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, Ohlsson et al. 1994; Schau and Fet 2008; Roy, Orikasa et al. 2012). 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, Keoleian 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, Keoleian 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 (Gonzalez, Frostell et al. 2011; Eshel, Shepon et al. 2014; Tilman and Clark 2014). The livestock sector is responsible for 14.5 percent of all human-induced greenhouse gas emissions (GHGE) (Gerber, Steinfeld 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, Shepon 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, Audsley 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 1.

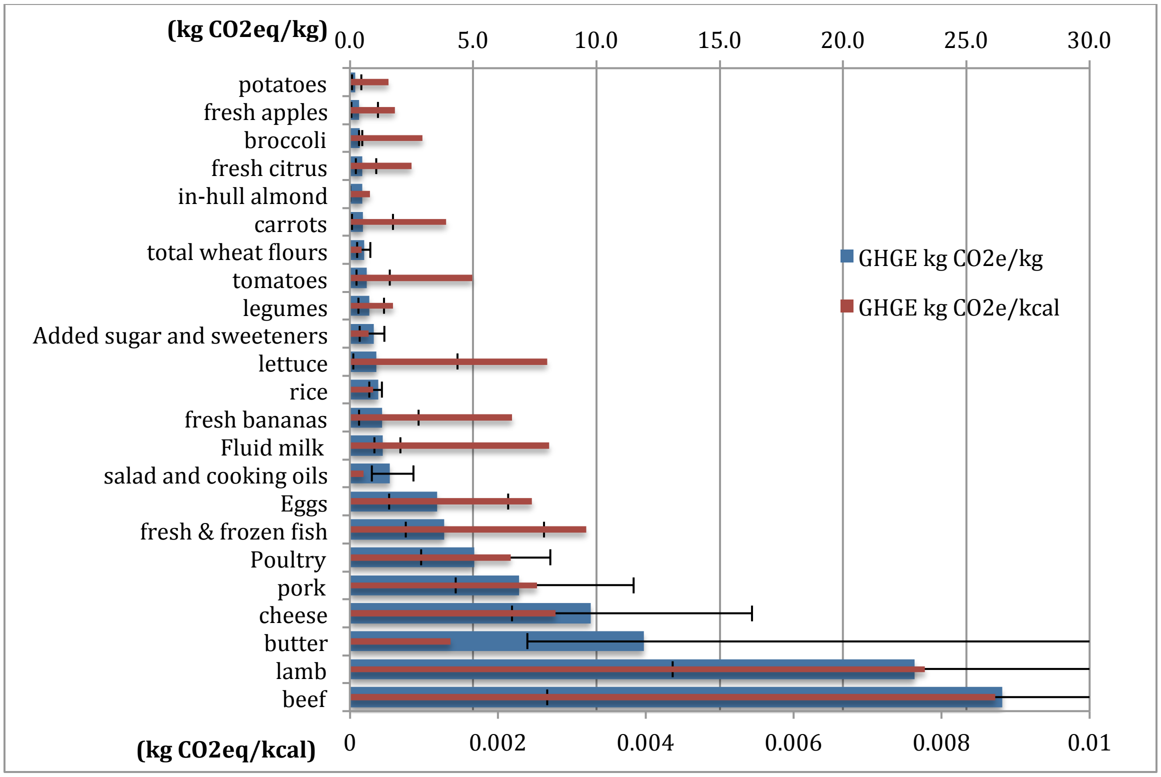


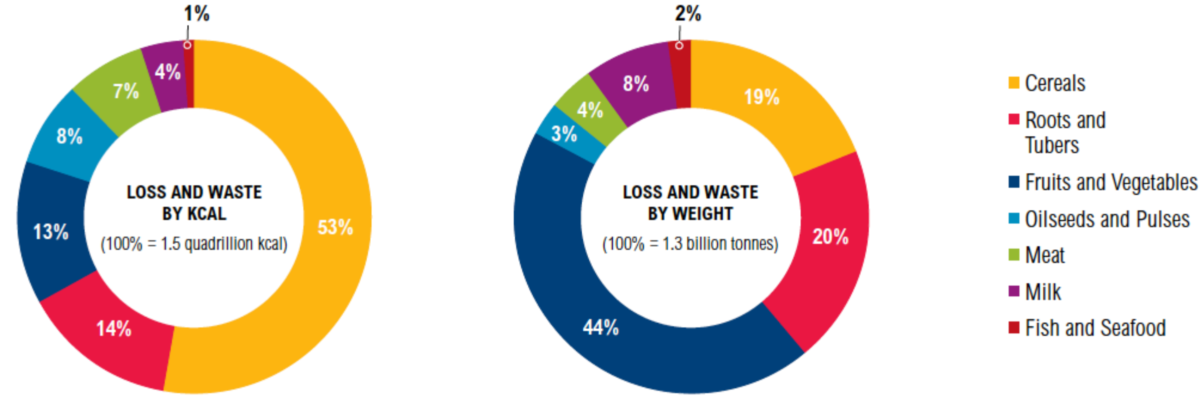
Figure 1. Example GHGE impact factors for a number of foods, on both a mass (blue bars) and food energy (red bars) basis. Data reported in (Heller and Keoleian 2014). Note that the "error bars" represent minimum and maximum values (on per kg basis) from the literature data included in the average shown 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.

2.2.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, Cederberg 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, Cederberg et al. 2011). Figure 2Figure 3 below, both from (Lipinski, Hanson 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.

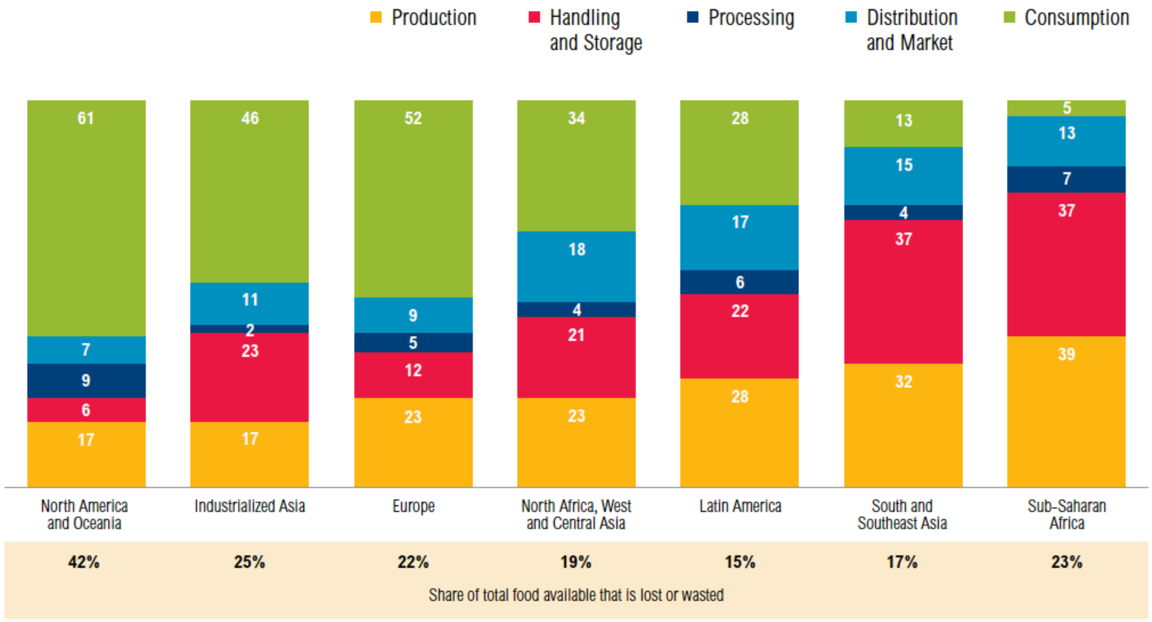


Source: WRI analysis based on FAO. 2011. *Global food losses and food waste—extent, causes and prevention*. Rome: UN FAO.

Figure 2. Share of Global Food Loss and Waste by Commodity, 2009. (Lipinski, Hanson et al.

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

The rise of what some term the "new politic" of food waste (Evans, Campbell 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, Ingle et al. 2013) and in Nordic countries (Gjerris and Gaiani 2013), as well as supply chain-wide waste in Switzerland (Beretta, Stoessel 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, Ingle et al. 2013).



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. Food Lost or Wasted By Region and Stage in Value Chain, 2009 (Percent of kcal lost and wasted). (Lipinski, Hanson 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, Farah-Wells 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, Farah-Wells et al. 2014). Since this differentiation is not made, a measure of "avoidable" food loss can not be derived from the USDA data. Figure 4 shows the composition of food loss by food group.

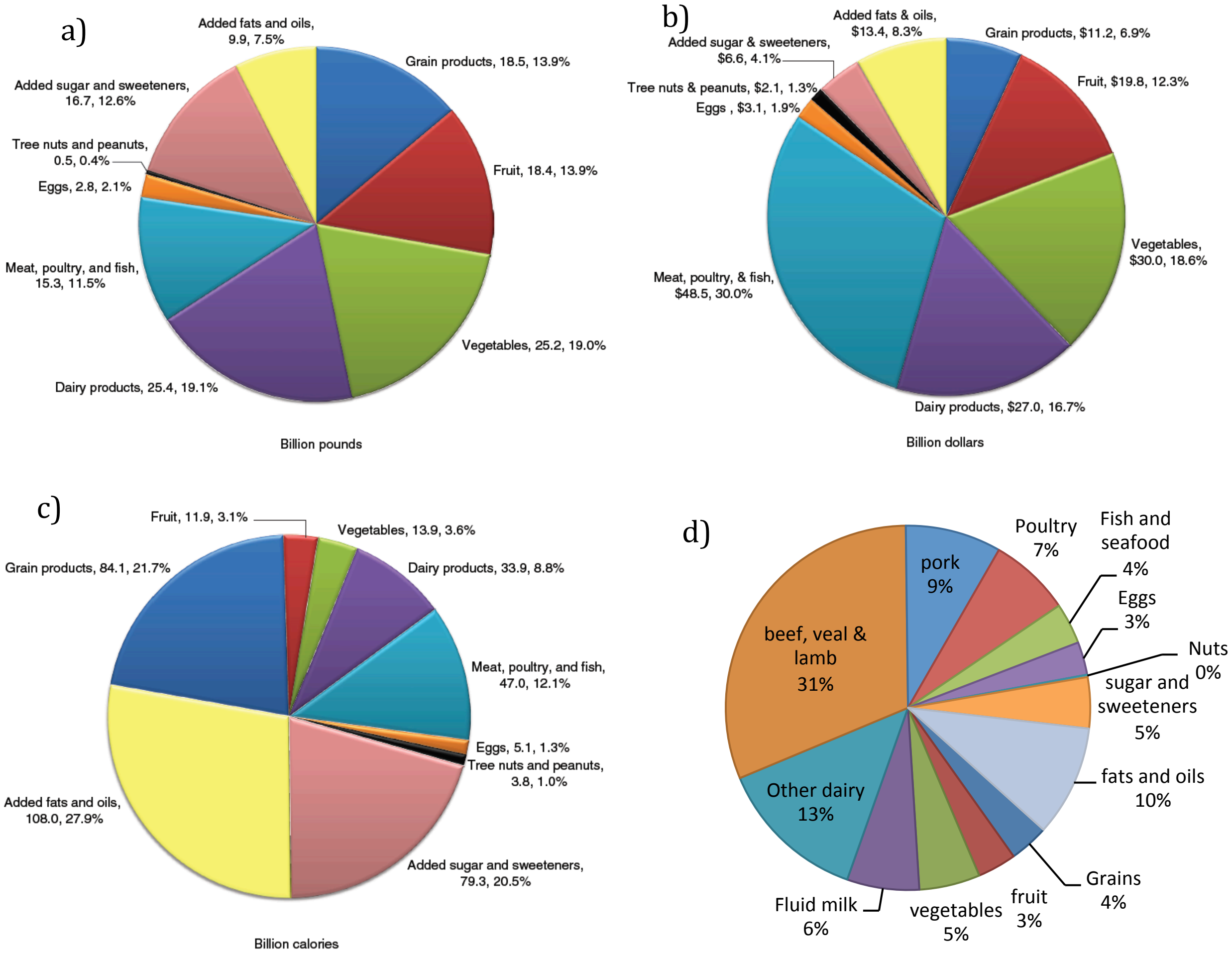


Figure 4. Estimated food loss in the U.S. by food group based on a) total amount (billion pounds); b) total value (billion dollars); c) food energy (billion Calories); and d) associated greenhouse gas emissions. Figures a, b & c from (Buzby, Farah-Wells et al. 2014), figure d from (Heller and Keoleian 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).

2.2.2. 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 1 offers a generic overview of potential sources or causes of food waste across the value chain.

Table 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, Adenso-Diaz 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, Ingle et al. 2013). 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 5 and Table 2 below offer many interesting insights into the reasons and compositions of

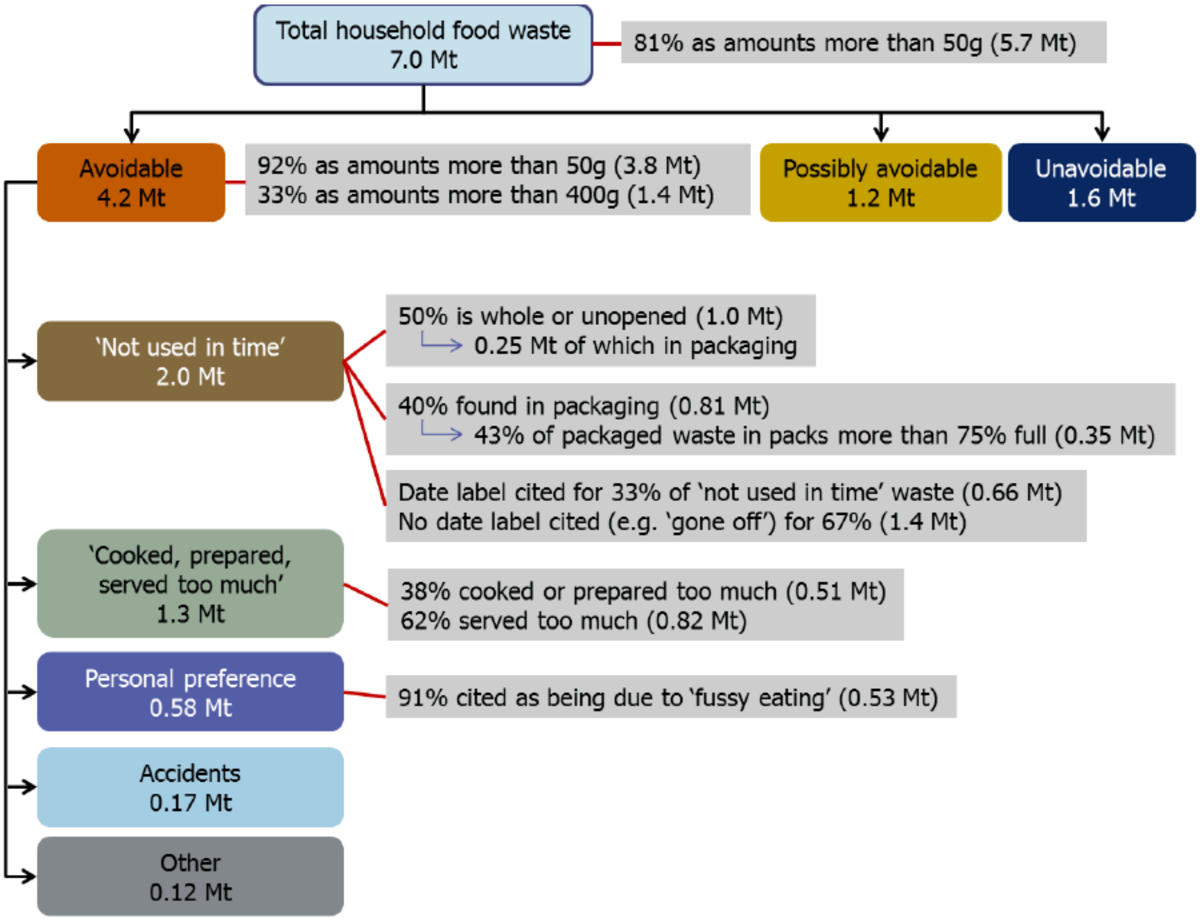


Figure 5. Breakdown of UK household food waste on the basis of reason for disposal. From (Quested and Murphy 2014).

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.

It is also worth mentioning a growing collection of recent work exploring human behavior and social demographics around food waste generation, disposal and minimization (Quested, Marsh et al. 2013; Graham-Rowe, Jessop et al. 2014; Quested and Luzecka 2014; 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, Marsh et al. 2013).

Table 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%

2.2.3. 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, De Moel et al. 2012).

On a somewhat smaller scale, Scholz, Eriksson and Strid (Scholz, Eriksson 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 4d.

2.3. 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.

2.3.1. 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 2014)), 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. 2011; Franklin Assoc. 2011; Franklin Assoc. 2011). 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, Horne et al. 2010), and reports of positive experiences are emerging from the packaging development industry (Grönman, Soukka et al. 2013).

Numerous examples of LCA studies conducted on specific food packaging configurations exist (for example, (Keoleian, Phipps et al. 2004; Madival, Auras et al. 2009; Pasqualino, Meneses et al. 2011; Siracusa, Ingrao 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, Ansems 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 6.

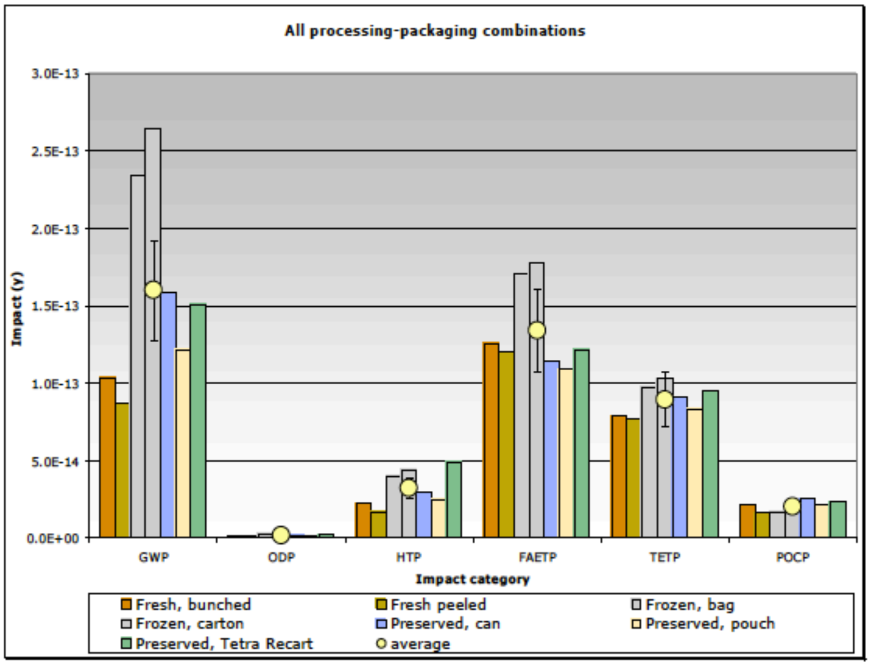


Figure 6. The normalized environmental impact of the consumption of 0.6 kg carrots for the current ratio of landfill (22%) and municipal solid waste incineration, MSWI (78%). The average value for an impact category is shown with a plus and minus 20% bar. From (Ligthart, Ansems et al. 2005). Impact categories 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, Ansems 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, Ponnak 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.

2.3.2. Packaging end-of-life disposal

Disposal options can significantly influence the overall environmental impact of packaging, as demonstrated repeatedly in example LCAs (Rigamonti, Grosso et al. 2014; Siracusa, Ingrao 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 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, Grosso 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 2.5, 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.

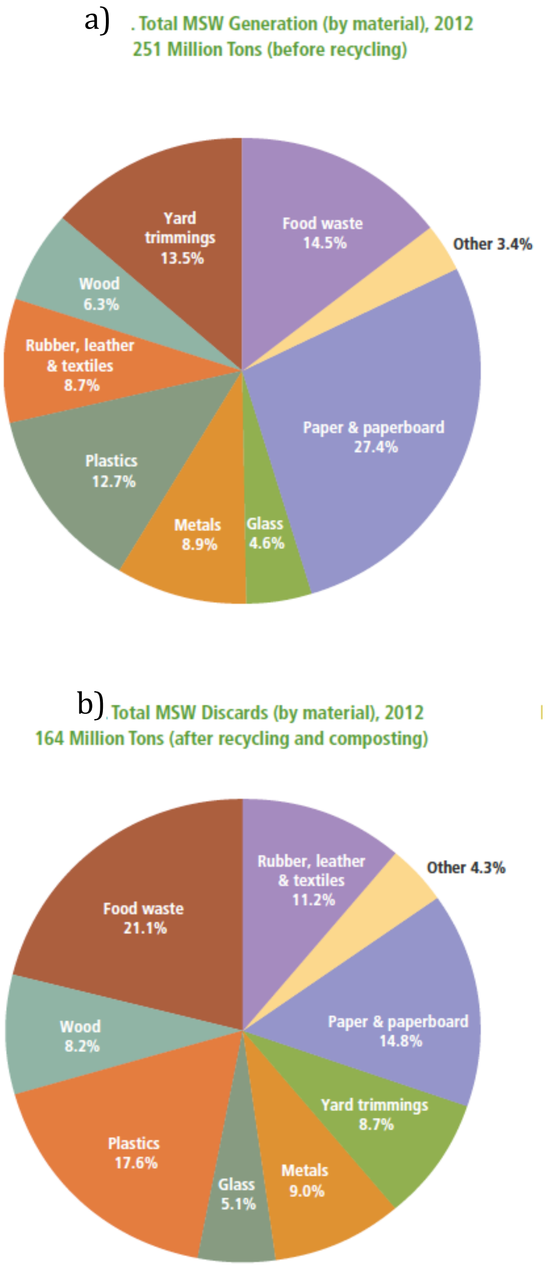


Figure 7. Composition of U.S. MSW in 2012 before (a) and after (b) recycling and composting. (US EPA 2014)

2.3.3. 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, Soukka 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 (Siracusa, Rocculi et al. 2008; Mahalik and Nambiar 2010; Barlow and Morgan 2013; 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 (Siracusa, Rocculi et al. 2008; Mensitieri, Di Maio et al. 2011). 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 (Sivertsvik, Jeksrud et al. 2002; Smith, Daifas et al. 2004; McMillin 2008; Mangaraj, Goswami et al. 2009; Sandhya 2010).

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, López-de-Dicastillo et al. 2014; Realini and Marcos 2014; Sanches-Silva, Costa 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, Ragaert 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, Ragaert et al. 2014). Heising et al (Heising, Dekker 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.

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, Guillard et al. 2013), despite recognition from various places that it is a necessary condition for properly assessing sustainability of food packaging (Williams, Wikström et al. 2008; Williams, Wikström et al. 2012; Barlow and Morgan 2013; Grönman, Soukka et al. 2013). In the following section, we briefly review opportunities for packaging to reduce food waste, and then in Section 2.5 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.

2.4.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, Soukka 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, Wikström et al. 2012).

A report from the Centre for Design at RMIT University (Australia) details opportunities to reduce food waste through packaging improvements (Verghese, Lewis 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 nonliving products but also physiological reactions for living products." (Angellier-Coussy, Guillard 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, Williams 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, Lewis 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.

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

As we saw in Section 2.2, 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 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. 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, Wikström et al. 2008) 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, Vold 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, Katajajuuri 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 8).

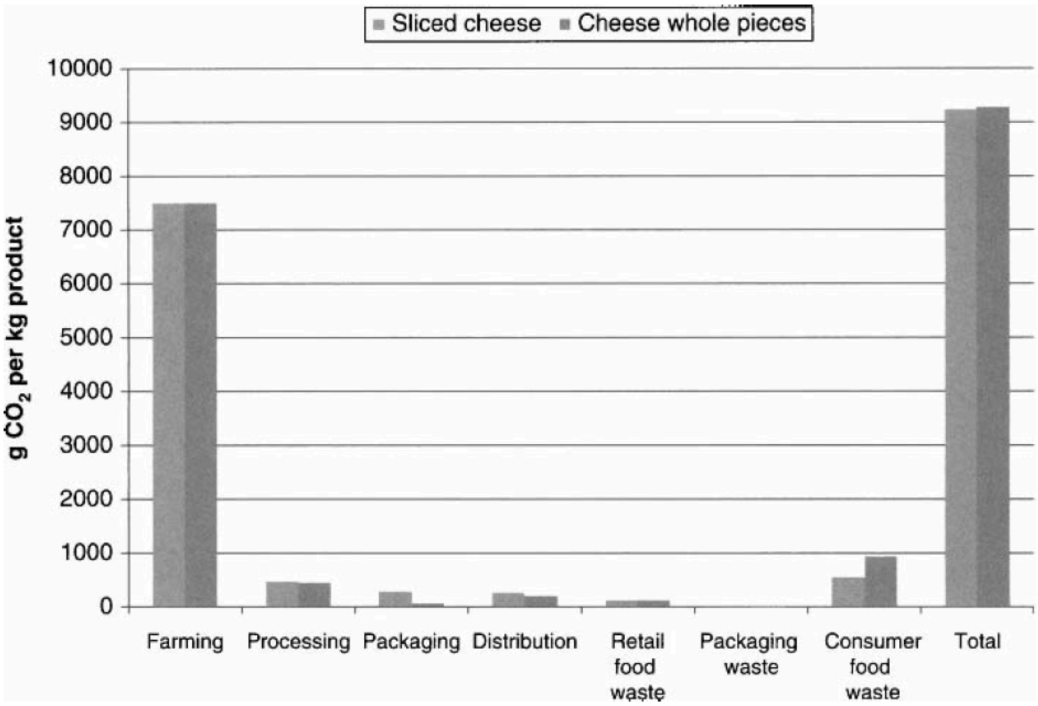


Figure 8. Greenhouse gas emissions from production, packaging and distribution of whole and sliced cheese. From (Hanssen 2012).

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 (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, Williams 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, Williams 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 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 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 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 2, Equation 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

Substituting Equation 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 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 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 5

In the plots shown in **Figure 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 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 9. This ratio, shown in Table 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.

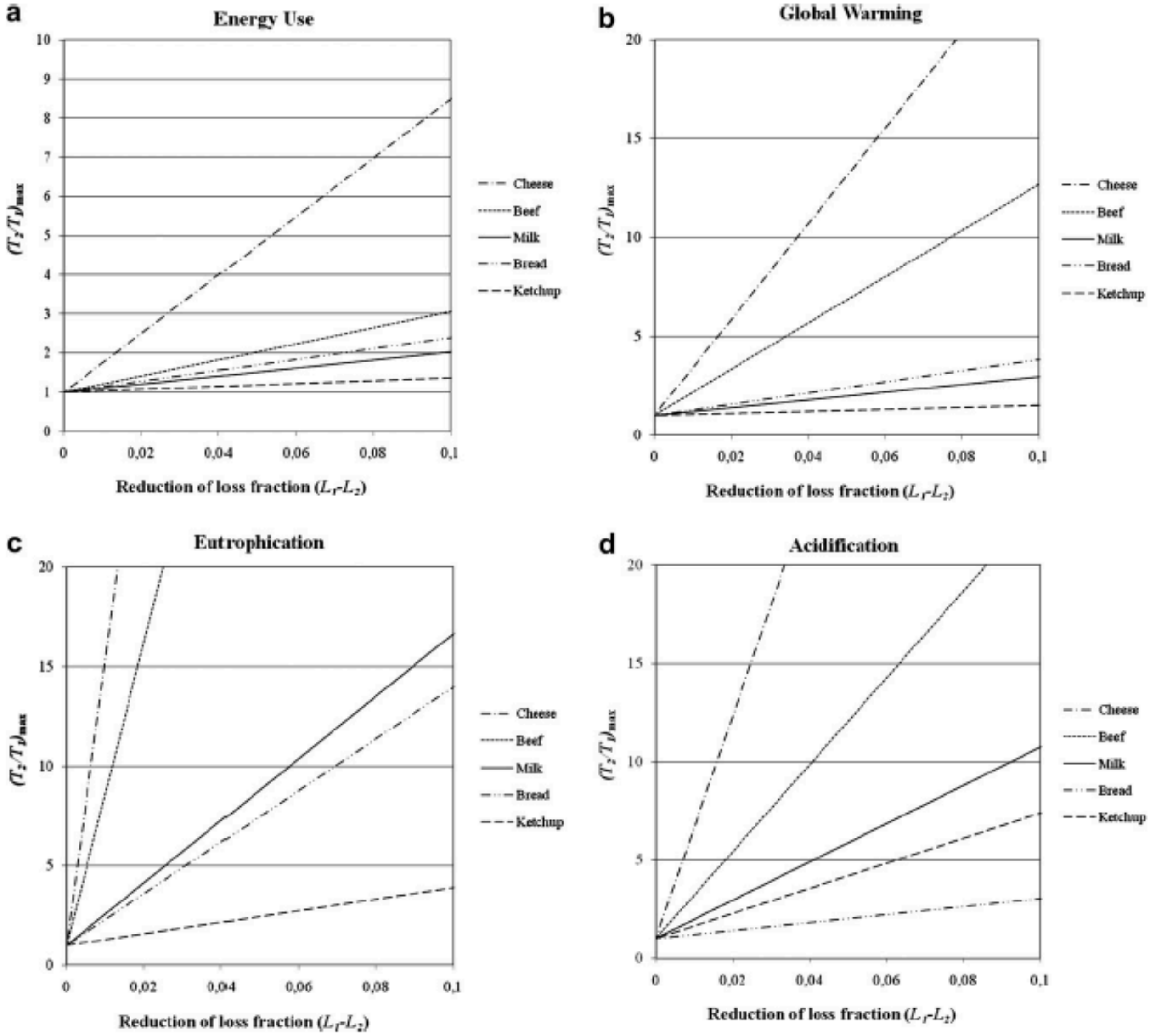


Figure 9. Plots of the maximum increase in environmental impact (P_2/P_1 in Equation 5) that still results in a net system environmental benefit, for various environmental impact indicators and a variety of food types. From (Williams and Wikström 2011). Note that the authors change variable names from previous publications (and from the above equations and descriptions) in these figures; $T_2=P_2$ and $T_1=P_1$.

3. Methodological approach to study

As laid out in the Master Agreement, the goal of this project is to conduct an LCA comparison of packaging material types that elucidates the balance between packaging type and food waste. While numerous examples of LCA comparisons of packaging configurations exist in the literature, very few specifically and explicitly consider the influence of packaging on food waste (i.e., that identify specific food waste values for each packaging configuration under consideration). The limited cases summarized in Section 2.5 use assumed food waste rates to demonstrate *potential* environmental impact savings. This study aims to fill that void by demonstrating through concrete examples the environmental trade-off between food waste and packaging, an underappreciated relationship that is of great importance to the food processing, packaging, distribution and retail industries. The remainder of this section steps through the ISO 14044 (ISO 2006) methodological framework, defining the approaches to be taken in phase 2 of this project.

3.1.Goal

The goal of the LCA study is to demonstrate the role of packaging in controlling food waste. The results will be used to build awareness both within the food packaging industry as well as with the general public. The results of the study will be externally validated, and will be communicated externally via peer-reviewed literature manuscripts and professional conferences. Validated benefits are expected to be used for marketing purposes to promote light-weight packaging as a preventer of food waste and a sustainable solution. Results *will* be used in comparative assertions to be disclosed to the public.

3.2.Scope

3.2.1. Product system and function

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

3.2.2. Functional unit

The functional unit forms the comparative basis of LCA studies and the denominator of presented results, and therefore can influence conclusions drawn from study results. Given the focus on food waste in this project, the functional unit should reflect food actually *consumed*, therefore accounting for waste at all stages. While the exact quantity represented in the functional unit may vary between case studies (e.g., it may be beneficial to define a functional unit as a “typical” serving size such as 500 g), in all cases, the functional unit will be a mass or volume of the food *consumed*. Note that, similar to most food LCAs, this mass-based functional unit does not capture a “performance” measurement of the food system. Quantifying the function or performance of foods is a perennial challenge in food LCAs (see (Heller, Keoleian et al. 2013)); assuming there are not significant nutritional differences arising between packaging configurations, a mass-based functional unit presents little problem in making comparisons between scenarios of the same food. Given nutritional differences between foods, however, caution must be exercised in comparing LCA results of different foods.

3.2.3. System boundaries

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

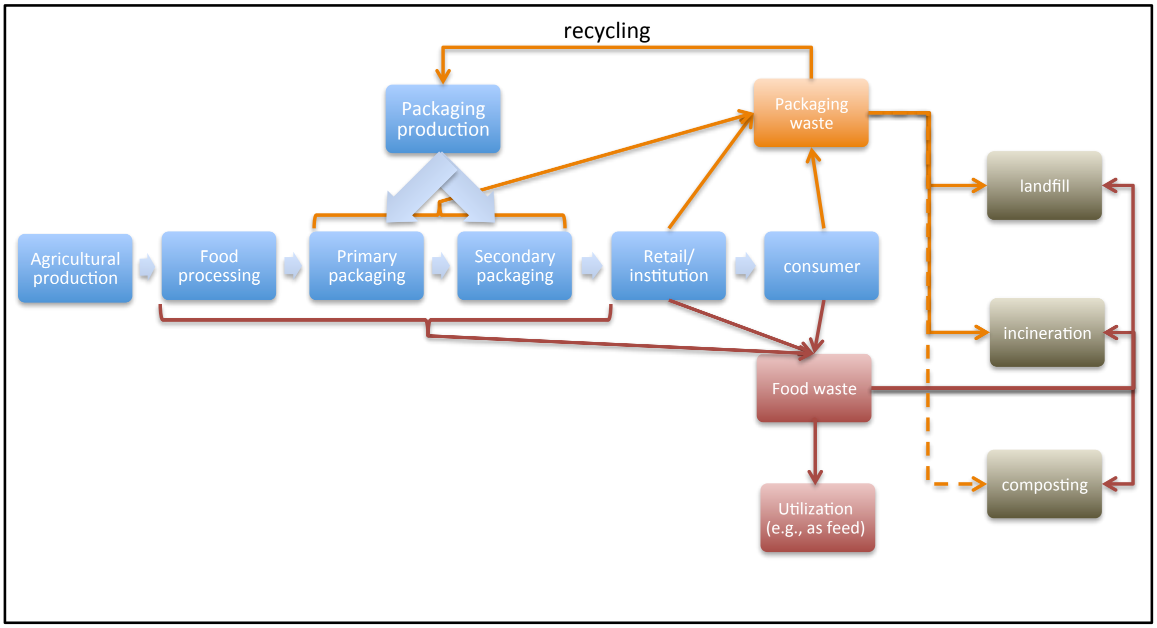


Figure 10. System diagram indicating the life cycle stages to be included in this study.

All stages of the food life cycle will be considered. Assessment of agricultural production and food processing will come from existing LCA studies of the food in question; i.e., we will not be collecting primary data for these stages. Given the intended focus of the project, food losses/waste at the agricultural production stage will not be explicitly considered. The study will instead focus on food loss/waste during processing, packaging and distribution, retail, and consumption stages. As shown in Figure 10, the environmental impacts (or credits) from alternative utilization and final disposal of food waste will be considered. Similarly, the impacts of recycling and/or disposing of packaging waste will also be included. Transportation will be accounted for between each stage, although generalized assumptions will most likely be made to reasonably represent U.S. National average transportation distances.

3.2.4. Impact categories and assessment methodology

The study will focus on the impact categories of global climate change (greenhouse gas emissions) and cumulative energy demand (CED). Inclusion of additional impact categories (e.g., eutrophication, water use, toxicity) will be dependent on data availability. The IPCC 2013 GWP 100a impact assessment method (with 100 year timeframe) will be used for global climate change, and the Cumulative Energy Demand version 1.08 (method by Ecoinvent) will be used for CED.

3.3.Modeling approach and data collection

Building on the equations presented by (Wikstrom and Williams 2010) (Equation 2, above), which focus on consumer-level food waste, we expand the relationship to explicitly consider food waste at retail and during processing/packaging/distribution. Here (in Figure 11 and following equations), B = quantity of food produced at farm gate (rather than purchased, as in Section 2.5).

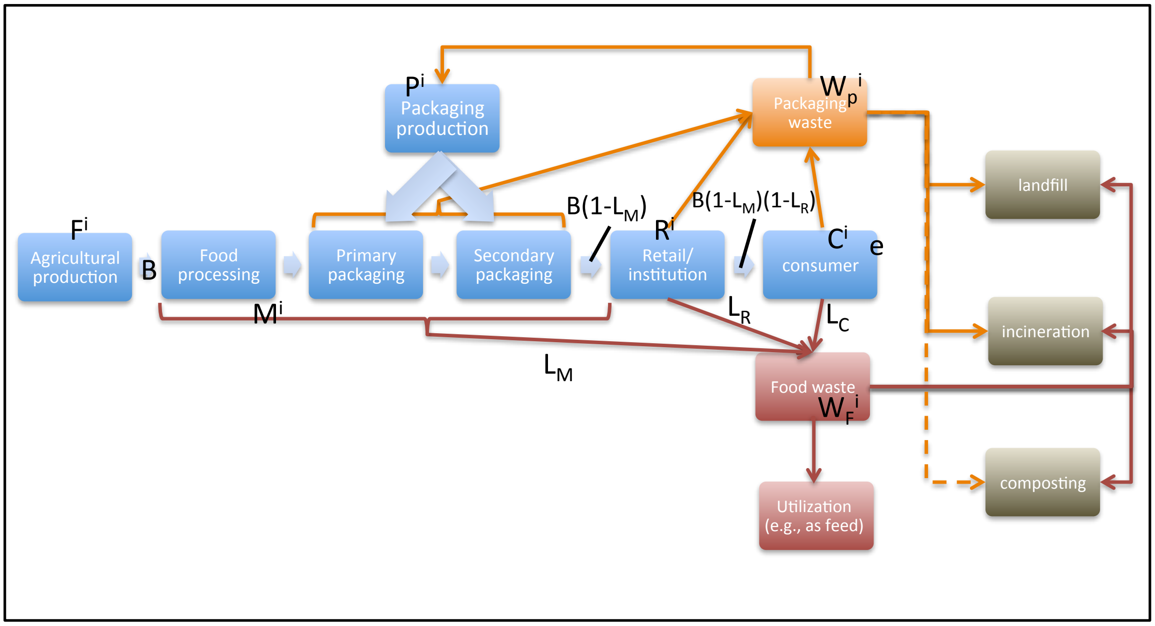


Figure 11. System diagram indicating variables used in presented equations.

Using the variable names in Figure 11, the quantity of food consumed, e, can be related to the food produced as:

$$e = B(1 - L_M)(1 - L_R)(1 - L_C)$$

Equation 6

where:

e = quantity (mass) of food consumed
B = quantity (mass) of food produced at farm gate
L_M = fraction of food loss during processing, packaging, and distribution to retail
L_R = fraction of food loss during retail
L_C = fraction of food lost at consumer level

An expression for the system environmental impact that explicitly accounts for food waste at all stages can be written as:

$$Env\ Inv = BF^i + B\left(M^i + x_p P^i\right) + B(1 - L_M)R^i + B(1 - L_M)(1 - L_R)C^i \\ + W_F^i[BL_M + B(1 - L_M)L_R + B(1 - L_M)(1 - L_R)L_C] + W_P^i B y_P$$

Equation 7

substituting B with Equation 6:

$$Env\ Inv = \frac{e}{(1-L_M)(1-L_R)(1-L_C)}\{F^i + (M^i + x_p P^i) + (1-L_M)R^i + (1-L_M)(1-L_R)C^i + W_F^i[L_M + (1-L_M)L_R + (1-L_M)(1-L_R)L_C] + W_P^i y_P\}$$

Equation 8

where:

Env Inv = total environmental inventory for the food/packaging systems
F^i = env. inventory of food production (at farm gate) per unit mass of food
M^i = env. inventory of food processing and distribution per unit mass of food
P^i = env. inventory of packaging production per unit mass of packaging
x_P = mass of packaging per unit mass of food
R^i=env. inventory of retail stage per unit mass of food
C^i=env. inventory of consumer stage (inc. transport from retail store to home) per unit mass of food
W_F^i=env. inventory of food waste disposal per unit mass of food
W_P^i=env. inventory of packaging disposal (including potential recycling) per unit mass of packaging
y_P = mass of packaging waste per unit mass of food

"Environmental inventory" in the above equations and variable descriptions refers to any environmental impact inventory of interest, such as CED or GHGE.

As mentioned earlier, inventories/impacts for agricultural production and food processing will draw from existing LCA studies. The manufacture of packaging materials will also rely on existing databases and LCA studies, and lean heavily on data from the life cycle inventories of plastics prepared by Franklin & Associates for the American Chemistry Council (Franklin Assoc. 2006; Franklin Assoc. 2011; Franklin Assoc. 2011). Retail impacts will be dependent on product refrigeration/freezing needs and store overhead, allocated based on typical shelf space occupancy. Impacts at the consumer stage will be limited to transportation from retail to home and storage (i.e., refrigeration) in the home. Preparation (cooking) and dish cleaning impacts will not be included.

The impact of food waste and packaging waste disposal will be modeled based on the particular scenario, but likely will use national average distributions between landfill, incineration, composting, or other dominant disposal methods. Common recycling rates for the packaging materials in question will also be used, and additional impacts of recycling efforts, along with reductions of virgin material in packaging production, will be included.

Data on food loss rates and quantities of packaging per unit of food will be gathered from multiple sources including food manufacturers, packaging material suppliers, retailers, industry organizations, and scholarly and industry literature. Given the difficulty in establishing robust estimates of food waste at the consumer level, especially for a given product/package configuration, the differentiating food loss rates between scenarios will focus mainly on the retail and distribution (and potentially, processing and packaging) stages.

4. Case studies

The following three case studies will be examined in Phase 2 of this project. These cases have been chosen based on their relevance to the food industry, their anticipated ability to demonstrate interesting aspects of the food waste/packaging trade-off, and the relative availability of data. Details of the anticipated scenarios and information gathered to date for each case is provided below.

4.1.Modified atmosphere beef packaging

Beef production has one of the largest associated GHGEs (as well as other quantifiable environmental impacts) of all foods available in the marketplace, primarily because of the high feed-to-food conversion rates (amount of feedstuffs invested per unit of human edible food yielded) for beef and high levels of enteric methane emissions from live cattle. Thus, it is likely that any packaging alternative that results in decreased food waste (presumably through extended shelf life) will result in net environmental benefits. As is indicated in Section 2.5, coarse estimates suggest that beef packaging capable of reducing beef waste by 10% could have upwards of three times the GHGE and 1.5 times the energy use of current packaging and still result in a net environmental benefit for the system.

We will evaluate this behavior through a life cycle assessment comparison of the following (note that the same retail cut will be examined in all scenarios):

- fresh beef (retail cut to be determined) in typical tray and overwrap

  Typical cut-to-order beef and sometimes even case-ready beef is supplied in a expanded polystyrene tray with an absorbent "soaker pad" (polyolefin-covered cellulose) and an overwrap of plasticized PVC or EVA/LDPE, often treated with anti-fog agents. The overwrap is not sealed. Typical shelf life for whole muscle in these air-permeable overwraps is 5-7 days, with 3-7 days of display life (Delmore 2009).
- fresh beef in a high oxygen modified atmosphere package

  Packaging fresh beef in a modified atmosphere of 70-80% O_2 with the balance CO_2 has been demonstrated to lead to extended shelf life. CO_2 in the packaging headspace leads to inhibition of microbial growth while the high O_2 concentration encourages myoglobin oxygenation, and therefore the bright red color deemed desirable by consumers (Limbo, Torri et al. 2010). Typical packaging materials for MAP are expanded polystyrene or thermoformed rigid plastic tray with a hermetically sealed barrier film, often of PA/PE or PVDC/EVA co-polymers. Typical shelf lives for whole muscle, high O_2 MAP is 12-16 days, with 3-4 days of display life (Delmore 2009). An additional notable difference is that most MAP of retail cuts will be prepared in centralized processing facilities (rather than at individual stores), potentially introducing efficiencies and making recovery and rendering of trimmings and other scraps much more practical.

There are, however, several disadvantages with high-O_2 MAP. It has been shown to increase the breaking strength of individual beef muscle fibers. The high-O_2 concentration can also lead to a warmed-over flavor, premature browning and retardation of the tenderization process (Lagerstedt, Ahnström et al. 2011).

- <u>fresh beef in vacuum packaging</u>

  Vacuum packaging of meats has been a known means of extending shelf-life for many decades and is currently the most common method of delivering beef primals and sub-primals to processors, butchers and retailers. Vacuum packaging has not seen much usage for retail cuts, however, because myoglobin in the absence of oxygen takes on a purple color, which differs from the bright red expected by consumers. It is worth noting that the color change is reversible – the meat will again return to its bright red color on exposure to O_2 – and it does not affect the taste or quality of the beef: it is merely an aesthetic concern. An additional concern is that the vacuum promotes release of juices from the meat, and these fluids accumulate in the surface folds of the evacuated bag, which is both unattractive to consumers and may be susceptible to bacterial growth. Retailers in Europe and other parts of the world have been successfully marketing vacuum packaged meats for years, and consumer education is beginning to introduce market openings in the U.S. Wegman's food retail chain, located in New England states, has a successful line of vacuum packed retail beef cuts. Like MAP products, vacuum packaging of retail cuts will likely occur in centralized processing facilities.

  Flexible vacuum pack materials are typically multi-layer co-extrusions containing PET as an outside strength layer, PA for good O_2 barrier, and inner layers of LDPE, ionomer or EVA copolymer for moisture barrier and heat-sealing (Robertson 2012). Reports of shelf life with vacuum packaging vary, but are significantly greater than permeable overwrap and hi O_2 MAP: one assessment placed the typical shelf life of vacuum packed beef at 28 days (Kameník, Saláková et al. 2014).

- <u>Fresh beef in vacuum skin pack</u>

  Vacuum skin pack (VSP) methods applied to fresh meat are a relatively new alternative packaging configuration in which the product is placed on a tray and wrapped in a film under vacuum and at elevated temperature. The heat causes the wrapping film to soften and tightly cover the product, forming a "skin." All vacuum packaging avoids the negative impacts on meat quality that can occur in high O_2 MAP, and VSP results in lower purge loss (meat juices) than conventional vacuum packaging. VSP beef still exhibits the same purple color as conventional vacuum packaging. Numerous coextruded layer combinations can be used for the top web material (as well as bottom tray material) in VSP, but typically incorporate EVOH as a gas barrier.

Information on dominant packaging materials and typical quantities per unit of product will be developed with the assistance of established contacts at Sealed Air/Cryovac. We are developing contacts within major grocery chains (Meijer, Wegman's, Kroger, etc) to assist with defining typical food waste rates, or in the very least to assist with understanding the relationship between shelf life and food waste so that waste rates can be modeled from literature-provided shelf life values.

It is assumed that all products are the same prior to packaging/distribution; therefore, the same generic beef production model will be used throughout. We will consider LCA studies of U.S. beef by BASF conducted for the National Cattlemen's Beef Association (Battagliese, Andrade et al. 2013); an LCA study of Northern Great Plains beef production (Lupo, Clay et al. 2013); an LCA of beef production strategies in Upper Midwestern U.S. (Pelletier, Pirog et al. 2010); Eschel's report of environmental impact of animal-based foods in the US (Eshel, Shepon et al. 2014); and a variety of LCA-based studies of beef from the rest of the world. The primary food waste source under focus in this case will be losses due to spoilage or other unsalable qualities during distribution and retail.

4.2.Fresh and frozen fish

The safe distribution and marketing of fresh fish poses a particular challenge in the contemporary retail market because of its high perishability and limited shelf life. The rate of fish spoilage can vary greatly by species, but depends principally on the chemical composition of the fish, its microbial flora, and subsequent handling, processing and storage (Robertson 2012). Maintaining chill temperatures is critical, but packaging technology can assist in slowing spoilage and reducing loss.

For this case study, we will focus on analyzing farm-raised Atlantic salmon due to its increasing relevance in the seafood industry. Demand for salmon in the U.S. and throughout the world has grown steadily in recent decades, driven mainly by income growth and urbanization, along with a widespread shift in preferences towards healthy eating and sushi-type food products (FAO Globefish 2015). This is highlighted by the fact that in 2013, the U.S. per capita consumption of salmon rose to 2.7 lbs. per year (47% increase since 2008), placing it second for most consumed type of seafood in the U.S. (National Fisheries Institute 2015)

In the U.S. in 2012, Maine produced about 12,000 tons of salmon valued at $78 million and Washington State produced about 8,000 tons valued at $52 million (NOAA 2013). Atlantic salmon accounts for over 95% of the farmed salmon produced in the U.S (Burden and Huntrods 2012).

Globally, Chile, Canada, and Norway are the leading producers of farmed salmon. In 2014, the total imports of Atlantic salmon to the U.S. (fresh, frozen and fillets) were 539 million pounds, valued at about $2.4 billion, with over half of imports coming from Chile (USDA ERS 2015).

With a global average farm-to-gate GHG emission intensity of 2.2 t CO_2-e/t, farmed salmon has lower emissions than other meat sources such as beef and pork, but in contrast it generates 50% more emissions than U.S. poultry and 27% more than the global average for capture fisheries (Pelletier, Tyedmers et al. 2009). In addition, its high perishability and geographically unique production needs make it a distribution challenge, and therefore an interesting case study for this project.

With this in consideration, a life cycle assessment between the following packaging options for distributing Atlantic salmon will be conducted, with a focus placed on food waste occurring throughout the distribution chain. The packaging scenarios listed below will each be conducted for farmed salmon from different locations (Chile, Norway, Canada, U.S.) to demonstrate how packaging/distribution methods interface with production practices and locations to influence overall environmental impact.

- <u>Fresh salmon fillets sold in typical tray and overwrap</u>
  As stated before, fish is one of the most perishable foods and begins to spoil immediately after harvest. Short-term preservation by chilling is typically carried out using ordinary water ice (Paine 1992). Salmon fillets at chill temperature (2°C) have a reported shelf life on the order of 11 days (Sivertsvik, Jeksrud et al. 2002). Because of this limited shelf life, fresh fish is often air-freighted, adding significantly to its carbon footprint.

  This scenario will consist of fresh salmon fillets sold out of a fish case or pre-packaged in expanded polystyrene trays with an absorbent pad and film overwrap. Such packaging does not extend shelf life, but does keep the product clean, reduces odor, and makes self-service possible (Paine 1992). Sub-scenarios of fillets sold wrapped in waxed paper or novel “eco-friendly” alternative wrap will also be considered.

- <u>Frozen salmon fillets, individually shrink wrapped</u>.
  Given the short shelf life of fresh fish, freezing offers significant advantages including greatly extended shelf life and the ability to sea transport. It can, however, be perceived by consumers as being of lower quality. When dealing with frozen seafood, an efficient packaging system is critical to mitigate the detrimental quality changes that can occur during frozen storage. Hence, choosing appropriate packaging materials and methods are essential in terms of maintaining product quality.
  Low water vapor permeability is an important characteristic needed in the packaging materials (Jiang and Lee 2004). A broad selection of materials have been used for various frozen foods, but for this case, we will focus on the use of plastic films such as polyethylene (PE), and polypropylene (PP). These materials are used as liners and as single- or double-wall bags. The bags either are prefabricated or are formed from roll stock on a filling machine (Jiang and Lee 2004).
  Shrink-wrap materials are particularly important because of their ability to adhere close to the product. Shrink-wrap bags require evacuation of entrapped air before shrinking. Additionally, some of these bags can withstand boiling water, which allows the package to be used for end-cooking of the product before serving (Jiang and Lee 2004). Individually shrink-wrapped fillets often are aggregated into an additional bag for retail sale.

- Hypothetical case of fresh fillets in high CO_2, low O_2 modified atmosphere packaging
  Even though modified atmosphere packaging is a well-established packaging method for many flesh foods in Europe and some other parts of the world, it is currently prohibited for use with fresh fish in the U.S. due to the possibility of toxin-producing microorganisms propagating under low oxygen, low temperature conditions. Despite this current limitation, we will conduct a hypothetical case to determine the potential benefits of this packaging alternative.
  Significant research on proper gas mixtures and microbial growth under MAP for fresh salmon fillets have been conducted, and have found that with careful handling and processing procedures, low temperatures, and high CO_2, microbial growth can be inhibited significantly to safe levels after 28 days (Milne and Powell 2014). Other studies suggest that by using MAP with a CO_2 concentration of 90% and a gas-to-product ratio of 2.5 could extend shelf life up to 22 days (Fernández, Aspe et al. 2009).
  The materials that are used to contain the product are crucial to the success of MAP. The typical materials consist of a semi-rigid base tray (PVC/PE) sealed with a thinner film barrier (Inns 1987).
  The greatest limitation for MAP is temperature control. The rates of deterioration for fish products are heavily affected by temperature, for which it is important to take into consideration the changes that might take place due to gas mixture requirements (Inns 1987). Because of this, it is important to maintain a tightly controlled supply chain and ensure that proper quality control practices and testing methods are applied.

- Hypothetical fresh fillet in VSP
  Vacuum skin packaging of fish follows the same procedure and uses similar materials as that of other meats (see beef description, above) and is seeing increasing market penetration in Europe (McCarthy 2011). Again, vacuum skin modified atmosphere packaging of fish/seafood is not permitted in the US. Existing contacts with INCIPEN will be utilized to supplement literature-based data on shelf life with real experiences from European retailers. As with modified atmosphere packaging, vacuum packs are leak proof and odor free and offer merchandising advantages.

Numerous LCA-based studies of salmon aquaculture exist in the literature. Pelletier et al. report LCA results of farmed Atlantic salmon in Norway, Chile, the UK and British Columbia, and found that GHGE vary from 1.8 kg CO_2 eq/kg in Norway to 3.3 kg CO_2 eq/kg in the UK, with a weighted global average of 2.2 kg CO_2 eq/kg (Pelletier, Tyedmers et al. 2009). The large majority of GHGEs are due to feed production. Ziegler, et al. report on the GHGE of Nowegian seafood, including fresh and frozen farmed salmon, and find very little difference between fresh and frozen when both are trucked, but air-freight of fresh salmon is 5.5 times as impactful (Ziegler, Winther et al. 2013). Additional LCA studies of salmon aquaculture (Ayer and Tyedmers 2009; Buchspies, Jungbluth et al. 2011; Parker 2012) as well as salmonid feeds (Papatryphon, Petit et al. 2004; Boissy, Aubin et al. 2011) will also be considered. Land-based, closed containment Atlantic salmon systems, currently in scale-up demonstration in Nova Scotia (Gardner Pinfold 2014), hold the potential to bring salmon farming closer to consumer populations, thus reducing the need for impactful transport. We will also consider the possibility of including this sub-scenario in our study.

4.3.Salad mixes

Fresh-cut salad mixes have been increasing in popularity over the past thirty years since Fresh Express and Dole founded the bagged salad industry in the late 1980s. Per capita consumption of head (iceberg) lettuce has steadily declined since 1980, while sales of leaf and romaine lettuces have increased over the same period (USDA 2011), due in part by growing popularity of ready-to-eat packaged salad greens. With the average shelf life of salad greens around nine days, significant losses can occur at the retail and consumer level due to poor temperature control, improper refrigeration and handling or simply from product not selling or being consumed in a timely manner (McKellar, Odumeru et al. 2004). According to the USDA's loss adjusted food availability dataset, 30% of head lettuce and 35% of romaine and leaf lettuce is lost at the retail and consumer level (USDA ERS 2013). Ready-to-eat packaged salad mixes come in a variety of types and formulations in today's market and are popular with consumers due to their convenience and ease of use. However, as mentioned in Section 2.5 (see Table 3), the ratio of environmental impacts associated with the product to that of the package for lettuce products is relatively low. Thus, within the framework employed in this study, large reductions in food losses would be required to compensate for an increase in packaging in order to result in net environmental benefit. It is anticipated that this case will demonstrate a situation where additional packaging may *not* be warranted on environmental grounds, even when food losses are accounted for. Thus, this case is valuable to demonstrate that the relationship between packaging and waste is indeed a trade-off and must be evaluated on a case-by-case basis. However, it is important to note that packaged salads offer numerous other advantages that will not be captured in the "functional unit" used in this study.

There are several main packaging types for minimally processed salad mixes that will be analyzed in this study. Minimally processed salad mixes are defined in this study as greens that have been altered from their original form but still remain in a fresh state. Processes can include washing, cutting, treatments with sanitizing agents, and storage under refrigerated conditions. This includes fresh-cut greens such as lettuce, spinach, kale, and arugula. The exact salad mix to be studied will be determined through conversations with our contacts at Dole and others. It is important to note that ideal storage conditions for ready-to-eat cut salads of, for example, iceberg lettuce differ from those of 'tender greens,' that are harvested small and not further cut. We intend to consider the same salad mix throughout, but to account for differences in packaging needs, may have to consider two mix types in parallel. We will show the relationship between food loss and food packaging through a life cycle assessment that compares the following main package systems for salad mixes:

- Bulk Salad Mix:

A bulk salad case will be used as a baseline scenario. Bulk salad mixes include any greens that are sold from a bulk container at retail, where the customer selects a weight of greens to purchase by placing the greens in a polyethylene produce bag.

- Fresh Cut Salad Mix in Modified Atmosphere Flexible Packaging:
  Cut salads in MAP bags can take the form of preformed bags, roll stock, and standup pouches. MAP packaging helps keep the salad greens at an ideal temperature of around 32° F and close to 100% humidity (Hunt Ashby, 1987). Most commonly used are plastic film bags composed of polyolefins with varying levels of gas permeability, which increase carbon dioxide levels to help prolong shelf life (McKellar, Odumeru et al. 2004). Specific packaging and gas mixtures will be determined through industry contacts. Typical shelf life for greens in MAP is 7-10 days, whereas in air, nearly double the shelf life in air. MAP packaging can also have undesirable side effects such as the bleaching of color or development of off-tastes (Lee, Osborn et al. 2015).

- Fresh Cut Salad Mix in Rigid Packaging: This packaging option consists rigid tray or container, such as a PET clamshell with a snap-on lid or a polymeric peel-off lidding film, or both. These films are most likely a blend of LLDPE, LDPE, or OPP with EVA copolymer. The polyolefin resins provide excellent strength and moisture barriers, while EVA copolymers provide higher oxygen permeability (Robertson 2012). The lid and peel-off film provide different advantages for the consumer, with the lid providing greater protection and rigidity, and the peel-off film offering better tamper resistance, and in special cases, resealability. These packages often do not contain modified atmospheres. The rigidity of the packages can be important during transport when salad mixes are transported in boxes on pallets, which often result in damages to bagged salad mixes.
  In packaging without modified atmosphere, the main concern of the package is to avoid anoxic conditions and condensation of water vapor inside the package. Perforation or incomplete sealing of the plastic packaging allows some escape of trapped moisture, thereby avoiding condensation. Even a very small hole in a polymeric package can affect the package atmosphere significantly (Robertson 2012).

These case studies will be developed with the assistance of contacts at Dole, Cryovac and others in determining typical packaging materials and quantities of packaging per unit of salad mix. Contacts within grocery chains will be utilized to gain further information on shelf life and waste rates of salad mixes and greens. Contacts within specialty grocers, such as Oryana Food Co-Op in Traverse City, MI, will be used to determine typical waste rates and average purchase quantities for bulk salad greens.

LCA studies of salad crop production (i Canals, Muñoz et al. 2008; Gunady, Biswas et al. 2012; Romero-Gámez, Audsley et al. 2014) will be used to construct a generic salad crop production model, utilizing the assumption that all products are the same prior to packaging and distribution. We will focus on food losses from spoilage and damage during distribution and retail.

5. References

Alter, H. (1989). "The Origins of Municipal Solid Waste: the Relations Between Residues From Packaging Materials and Food." Waste Management & Research **7**(1): 103-114.

Andersson, K., T. Ohlsson, et al. (1994). "Life cycle assessment (LCA) of food products and production systems." Trends in Food Science & Technology **5**(5): 134-138.

Angellier-Coussy, H., V. Guillard, et al. (2013). "Role of packaging in the smorgasbord of action for sustainable food consumption." Agro FOOD Industry Hi Tech **24**: 3.

Ayer, N. W. and P. H. Tyedmers (2009). "Assessing alternative aquaculture technologies: life cycle assessment of salmonid culture systems in Canada." Journal of Cleaner Production **17**(3): 362-373.

Barlow, C. and D. Morgan (2013). "Polymer film packaging for food: An environmental assessment." Resources, Conservation and Recycling **78**: 74-80.

Battagliese, T., J. Andrade, et al. (2013). More Sustainable Beef Optimization Project: Phase 1 Final Rport. BASF.

Beretta, C., F. Stoessel, et al. (2013). "Quantifying food losses and the potential for reduction in Switzerland." Waste management **33**(3): 764-773.

Boissy, J., J. Aubin, et al. (2011). "Environmental impacts of plant-based salmonid diets at feed and farm scales." Aquaculture **321**(1): 61-70.

BSR (2013). Analysis of U.S. Food Waste Among Food Manufacturers, Retailers, and Wholesalers. Food Waste Reduction Alliance: http://www.kbcsandbox3.com/fw/wp-content/uploads/2013/06/FWRA_BSR_Tier2_FINAL.pdf.

BSR (2014). Analysis of U.S. Food Waste Among Food Manufacturers, Retailers, and Restaurants. Food Waste Reduction Alliance: http://www.foodwastealliance.org/wp-content/uploads/2014/11/FWRA_BSR_Tier3_FINAL.pdf.

Buchspies, B., N. Jungbluth, et al. (2011). Life cycle assessment of high-sea fish and salmon aquaculture. ESU-Services Ltd. Switzerland.

Burden, D. and D. Huntrods. (2012). "Salmon Profile." Retrieved March, 2015, from http://www.agmrc.org/commodities__products/aquaculture/salmon-profile/.

Buzby, J. C., H. Farah-Wells, et al. (2014). "The estimated amount, value, and calories of postharvest food losses at the retail and consumer levels in the United States." USDA-ERS Economic Information Bulletin(121).

Conscious Brands (2009). The Carbon Footprint of Canterbury Naturals Down Home Chicken Noodle Soup™ and a Canned Soup Alternative: A Comparative Analysis.

Cox, J. and P. Downing (2007). Food Behavior Consumer Research: Quantitative Phase, WRAP.

De Azeredo, H. M. (2013). "Antimicrobial nanostructures in food packaging." Trends in Food Science & Technology **30**(1): 56-69.

Delmore, R. J. (2009). Beef Shelf-life: http://www.beefresearch.org/CMDocs/BeefResearch/Beef Shelf-life.pdf.

Eshel, G., A. Shepon, et al. (2014). "Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States." Proceedings of the National Academy of Sciences **111**(33): 11996-12001.

European Council (1994). Directive 94/62/EC on packaging and packaging waste European Parliament and the Council of the European Union. Brussels.

Evans, D., H. Campbell, et al., Eds. (2013). Waste Matters: New Perspectives on Food and Society Hoboken, New Jersey, Wiley-Blackwell.

FAO (2013). Food wastage footprint: Impacts on natural resources Summary Report. Natural Resources Management and Environment Department, Food and Agriculture Organization of the United Nations: http://www.fao.org/nr/sustainability/food-loss-and-waste/en/.

FAO (2014). Food wastage footprint: Full-cost accounting final report. Natural Resources Management and Environment Department, Food and Agriculture Organization of the United Nations: http://www.fao.org/3/a-i3991e.pdf.

FAO. (2015). "Animal Production and Health." 2015, from http://www.fao.org/ag/againfo/themes/en/Environment.html.

FAO Globefish. (2015). "Salmon " Globefish.org March 2015. Retrieved March, 2015, from http://globefish.org/salmon-march-2015.html.

Fernández, K., E. Aspe, et al. (2009). "Shelf-life extension on fillets of Atlantic Salmon (Salmo salar) using natural additives, superchilling and modified atmosphere packaging." Food Control **20**: 1036-1042.

Franklin Assoc. (2006). Life Cyle Inventory of Polystyrene Foam, Bleached Paperboard, and Corrugated Paperboard foodservice Products: http://plastics.americanchemistry.com/LifeCycle-Inventory-of-Polystyrene-Foam-Bleached-and-Corrugated-Paperboard-Foodservice-Products.

Franklin Assoc. (2008). LCI Summary for Six Tuna Packaging Systems: http://plastics.americanchemistry.com/Education-Resources/Publications - Resource-EnvironmentalProfileAnalyses.

Franklin Assoc. (2011). Cradle-to-Gate Life Cycle Inventory of Nine Plastic Resins and Four Polyurethane Precursors: http://plastics.americanchemistry.com/LifeCycle-Inventory-of-9-Plastics-Resins-and-4-Polyurethane-Precursors-APPS-Only.

Franklin Assoc. (2011). LIFE CYCLE INVENTORY OF 100% POSTCONSUMER HDPE AND PET RECYCLED RESIN FROM POSTCONSUMER CONTAINERS AND PACKAGING http://plastics.americanchemistry.com/Education-Resources/Publications/Life-Cycle-Inventory-of-Postconsumer-HDPE-and-PET-Recycled-Resin.pdf.

Franklin Assoc. (2011). Life Cycle Inventory of Plastic Fabrication Processes: Injection Molding and Thermoforming: http://plastics.americanchemistry.com/Education-Resources/Publications/LCI-of-Plastic-Fabrication-Processes-Injection-Molding-and-Thermoforming.pdf.

Gardner Pinfold (2014). Feasibility of Land-Based Closed-Containment Atlantic Salmon Operations in Nova Scotia: http://medwayriversalmonassociation.org/aquaculture/Closed-Containment-FINAL.pdf.

Gerber, P. J., H. Steinfeld, et al. (2013). Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities, Food and Agriculture Organization of the United Nations (FAO).

Gjerris, M. and S. Gaiani (2013). "Household food waste in Nordic countries: Estimations and ethical implications." Etikk i praksis **1**(1).

Gómez-Estaca, J., C. López-de-Dicastillo, et al. (2014). "Advances in antioxidant active food packaging." Trends in Food Science & Technology **35**(1): 42-51.

Gonzalez, A. D., B. Frostell, et al. (2011). "Protein efficiency per unit energy and per unit greenhouse gas emissions: Potential contribution of diet choices to climate change mitigation." Food Policy **36**(5): 562-570.

Graham-Rowe, E., D. C. Jessop, et al. (2014). "Identifying motivations and barriers to minimising household food waste." Resources, Conservation and Recycling **84**: 15-23.

Grönman, K., R. Soukka, et al. (2013). "Framework for sustainable food packaging design." Packaging Technology and Science **26**(4): 187-200.

Gunady, M. G., W. Biswas, et al. (2012). "Evaluating the global warming potential of the fresh produce supply chain for strawberries, romaine/cos lettuces (Lactuca sativa), and button mushrooms (Agaricus bisporus) in Western Australia using life cycle assessment (LCA)." Journal of Cleaner Production **28**: 81-87.

Gustavsson, J., C. Cederberg, et al. (2011). "Global food losses and food waste." Food and Agriculture Organization of the United Nations, Rom.

Hanssen, M., H., Svanes, E., Schakenda, V., O J (2012). Life Cycle Assesment as a tool in Food Waste Reduction and Packaging Optimization - Packaging Innovation and Optimimization in a life cycle perspective. Life Cycle Assessment Handbook. A Guide for Environmental Sustainable Products. M. A. Curran, Scrivener Publishing LLC: 345-368.

Hanssen, O. J. and H. Moller (2013). Food Wastage in Norway 2013: Status and Trends 2009-13. Ostfoldforskning: http://www.fao.org/fsnforum/cfs-hlpe/sites/cfs-hlpe/files/resources/Food Waste in Norway 2013 - Status and trends 2009-13.pdf.

Heising, J. K., M. Dekker, et al. (2014). "Monitoring the quality of perishable foods: opportunities for intelligent packaging." Critical Reviews in Food Science and Nutrition **54**(5): 645-654.

Heller, M. C. and G. A. Keoleian (2014). "Greenhouse Gas Emission Estimates of U.S. Dietary Choices and Food Loss." Journal of Industrial Ecology **DOI: 10.1111/jiec.12174**.

Heller, M. C., G. A. Keoleian, et al. (2013). "Toward a Life Cycle-Based, Diet-level Framework for Food Environmental Impact and Nutritional Quality Assessment: A Critical Review." Environmental Science & Technology **47**(22): 12632-12647.

i Canals, L. M., I. Muñoz, et al. (2008). Life Cycle Assessment (LCA) of Domestic vs. Imported Vegetables. Case Studies on Broccoli, Salad Crops and Green Beans. CES working paper 01/08 Centre for Environmental Strategy, University of Surrey, Guildford (Surrey) GU2 7XH, United Kingdom.

Inns, R. (1987). Modified Atmosphere Packaging. Modern Processing, Packaging and Distribution Systems for Food. F. A. Paine. Boston, MA, Springer eBooks: 36-51.

ISO (2006). Environmental management - life cycle assessment - requirements and guidelines. International Organization for Standardization.

Jiang, S.-T. and T.-C. Lee (2004). Freezing Seafood and Seafood Products: Principles and Applications. Handbook of Frozen Foods. K. D. Murrell, Y. H. Hui, W.-K. Nipet al. New York, CRC Press: 245-280.

Kameník, J., A. Saláková, et al. (2014). "Vacuum skin packaging and its effect on selected properties of beef and pork meat." European Food Research and Technology **239**(3): 395-402.

Keoleian, G. A., A. W. Phipps, et al. (2004). "Life cycle environmental performance and improvement of a yogurt product delivery system." Packaging Technology and Science **17**(2): 85-103.

Kummu, M., H. De Moel, et al. (2012). "Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use." Science of The Total Environment **438**: 477-489.

Lagerstedt, Å., M. L. Ahnström, et al. (2011). "Vacuum skin pack of beef—A consumer friendly alternative." Meat science **88**(3): 391-396.

Lee, P., S. Osborn, et al. (2015). Reducing food waste by extending product life. WRAP: http://www.wrap.org.uk/sites/files/wrap/Product Life Report Final_0.pdf.

Ligthart, T. N., A. M. M. Ansems, et al. (2005). Eco-efficiency and nutrtional aspects of different product-packaging systems: an integrated approach towards sustainability. TNO (Netherlands Organization for Applied Scientific Research). The Netherlands: http://www.apeal.org/uploads/Library/22-11-2005_TNO Study - exec summary.pdf.

Limbo, S., L. Torri, et al. (2010). "Evaluation and predictive modeling of shelf life of minced beef stored in high-oxygen modified atmosphere packaging at different temperatures." Meat science **84**(1): 129-136.

Lipinski, B., C. Hanson, et al. (2013). Reducing Food Loss and Waste. World Resources Institute. Washington, DC: http://www.worldresourcesreport.org.

Lupo, C. D., D. E. Clay, et al. (2013). "Life-Cycle Assessment of the Beef Cattle Production System for the Northern Great Plains, USA." Journal of Environmental Quality **42**(5): 1386-1394.

Madival, S., R. Auras, et al. (2009). "Assessment of the environmental profile of PLA, PET and PS clamshell containers using LCA methodology." Journal of Cleaner Production **17**(13): 1183-1194.

Mahalik, N. P. and A. N. Nambiar (2010). "Trends in food packaging and manufacturing systems and technology." Trends in Food Science & Technology **21**(3): 117-128.

Mangaraj, S., T. Goswami, et al. (2009). "Applications of plastic films for modified atmosphere packaging of fruits and vegetables: a review." Food Engineering Reviews **1**(2): 133-158.

Marsh, K. and B. Bugusu (2007). "Food packaging—roles, materials, and environmental issues." Journal of food science **72**(3): R39-R55.

McCarthy, C. (2011). Skin Packaging in the Retail Market. Irish Sea Fisheries Board: http://www.bim.ie/media/bim/content/publications/Report on Skin Packaging in the Retail Market.pdf.

McKellar, R. C., J. Odumeru, et al. (2004). "Influence of a commercial warm chlorinated water treatment and packaging on the shelf-life of ready-to-use lettuce." Food Research International **37**: 343-354.

McMillin, K. W. (2008). "Where is MAP going? A review and future potential of modified atmosphere packaging for meat." Meat science **80**(1): 43-65.

Mena, C., B. Adenso-Diaz, et al. (2011). "The causes of food waste in the supplier–retailer interface: evidences from the UK and Spain." Resources, Conservation and Recycling **55**(6): 648-658.

Mensitieri, G., E. Di Maio, et al. (2011). "Processing and shelf life issues of selected food packaging materials and structures from renewable resources." Trends in Food Science & Technology **22**(2): 72-80.

Milne, D. and S. M. Powell (2014). "Limited microbial growth in Atlantic salmon packed in a modified atmosphere." Food Control **42**: 29-33.

National Fisheries Institute. (2015). "Top 10 Consumed Seafoods." Retrieved March, 2015, from http://www.aboutseafood.com/about/about-seafood/top-10-consumed-seafoods.

NOAA. (2013). "Atlantic Salmon (farmed)." Fishwatch - U.S. Seafood Facts, from http://www.fishwatch.gov/seafood_profiles/species/salmon/species_pages/atlantic_salmon_farmed.htm.

Paine, F. A. (1992). Fresh and Chilled Foods: Meat, Poultry, Fish, Dairy Products and Eggs. A Handbook of Food Packaging. Boston, MA, Springer eBooks**:** 205-230.

Papatryphon, E., J. Petit, et al. (2004). "Environmental impact assessment of salmonid feeds using life cycle assessment (LCA)." AMBIO: A Journal of the Human Environment **33**(6): 316-323.

Parker, R. (2012). Review of life cycle assessment research on products derived from fisheries and aquaculture. Sea Fish Industry Authority: http://www.seafish.org.uk/media/583639/seafish_lca_review_report_final.pdf.

Pasqualino, J., M. Meneses, et al. (2011). "The carbon footprint and energy consumption of beverage packaging selection and disposal." Journal of food Engineering **103**(4): 357-365.

Pelletier, N., R. Pirog, et al. (2010). "Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States." Agricultural Systems **103**(6): 380-389.

Pelletier, N. and P. Tyedmers (2010). "Forecasting potential global environmental costs of livestock production 2000–2050." Proceedings of the National Academy of Sciences **107**(43): 18371-18374.

Pelletier, N., P. Tyedmers, et al. (2009). "Not all salmon are created equal: life cycle assessment (LCA) of global salmon farming systems." Environmental science & technology **43**: 8730-8736.

Poovarodom, N., C. Ponnak, et al. (2012). "Comparative carbon footprint of packaging systems for tuna products." Packaging Technology and Science **25**(5): 249-257.

Quested, T., R. Ingle, et al. (2013). "Household food and drink waste in the United Kingdom 2012." WRAP, London.

Quested, T. and P. Luzecka (2014). Household food and drink waste: A people focus. WRAP: http://www.wrap.org.uk/sites/files/wrap/People-focused report v6_5 full.pdf.

Quested, T., E. Marsh, et al. (2013). "Spaghetti soup: the complex world of food waste behaviours." Resources, Conservation and Recycling **79**: 43-51.

Quested, T. and L. Murphy (2014). Household food and drink waste: A product focus. WRAP: http://www.wrap.org.uk/sites/files/wrap/Product-focused report v5_3.pdf.

Realini, C. E. and B. Marcos (2014). "Active and intelligent packaging systems for a modern society." Meat science **98**(3): 404-419.

Rigamonti, L., M. Grosso, et al. (2014). "Environmental evaluation of plastic waste management scenarios." Resources, Conservation and Recycling **85**: 42-53.

Robertson, G. L. (2012). Food packaging: principles and practice, CRC press.

Robertson, G. L. (2013). "Food Packaging: Principles and Practice."

Romero-Gámez, M., E. Audsley, et al. (2014). "Life cycle assessment of cultivating lettuce and escarole in Spain." Journal of Cleaner Production **73**: 193-203.

Roy, P., T. Orikasa, et al. (2012). "Life cycle of meats: An opportunity to abate the greenhouse gas emission from meat industry in Japan." Journal of Environmental Management **93**(1): 218-224.

Sanches-Silva, A., D. Costa, et al. (2014). "Trends in the use of natural antioxidants in active food packaging: a review." Food Additives & Contaminants: Part A **31**(3): 374-395.

Sandhya (2010). "Modified atmosphere packaging of fresh produce: Current status and future needs." LWT - Food Science and Technology **43**(3): 381-392.

Schau, E. M. and A. M. Fet (2008). "LCA studies of food products as background for environmental product declarations." International Journal of Life Cycle Assessment **13**(3): 255-264.

Schenck, R. and D. Huizenga, Eds. (2014). Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector. LCA Food 2014. San Francisco, CA, American Center fo Life Cycle Assessment.

Scholz, K., M. Eriksson, et al. (2015). "Carbon footprint of supermarket food waste." Resources, Conservation and Recycling **94**(0): 56-65.

Schott, A. B. S. and T. Andersson (2015). "Food waste minimization from a life-cycle perspective." Journal of environmental management **147**: 219-226.

Silvenius, F., J.-M. Katajajuuri, et al. (2011). Role of packaging in LCA of food products. Towards Life Cycle Sustainability Management, Springer**:** 359-370.

Siracusa, V., C. Ingrao, et al. (2014). "Environmental assessment of a multilayer polymer bag for food packaging and preservation: An LCA approach." Food Research International **62**: 151-161.

Siracusa, V., P. Rocculi, et al. (2008). "Biodegradable polymers for food packaging: a review." Trends in Food Science & Technology **19**(12): 634-643.

Sivertsvik, M., W. K. Jeksrud, et al. (2002). "A review of modified atmosphere packaging of fish and fishery products–significance of microbial growth, activities and safety." International Journal of Food Science & Technology **37**(2): 107-127.

Smith, J. P., D. P. Daifas, et al. (2004). "Shelf life and safety concerns of bakery products—a review." Critical Reviews in Food Science and Nutrition **44**(1): 19-55.

Svanes, E., M. Vold, et al. (2010). "Sustainable Packaging Design: a Holistic Methodology for Packaging Design." Packaging and Technology and Science **23**: 161-175.

Swiss Center for Life Cycle Inventories. (2014). "Ecoinvent Database version 3.0." Simapro 7.1.6 Life Cycle Assessment Software, 2013, from http://www.ecoinvent.org/home/.

Tilman, D. and M. Clark (2014). "Global diets link environmental sustainability and human health." Nature **515**(7528): 518-522.

Tucker, C. and T. Farrelly (2015). "Household food waste: the implications of consumer choice in food from purchase to disposal." Local Environment(ahead-of-print): 1-25.

US EPA (2014). Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012. United States Environmental Protection Agency Solid Waste and Emergency Response. Washington, DC: http://www.epa.gov/solidwaste/nonhaz/municipal/pubs/2012_msw_fs.pdf.

USDA (2011). Vegetables and melons yearbook data, May 2011.

USDA ERS. (2013). "Loss-adjusted food availability documentation." Retrieved January, 2014, from http://www.ers.usda.gov/data-products/food-availability-(per-capita)-data-system/loss-adjusted-food-availability-documentation.aspx - .UssZpmRDveY.

USDA ERS. (2015). "Aquaculture Data." Retrieved 2015, March, from http://www.ers.usda.gov/data-products/aquaculture-data.aspx.

Vanderroost, M., P. Ragaert, et al. (2014). "Intelligent food packaging: The next generation." Trends in Food Science & Technology **39**(1): 47-62.

Verghese, K., R. Horne, et al. (2010). "PIQET: the design and development of an online 'streamlined' LCA tool for sustainable packaging design decision support." The International Journal of Life Cycle Assessment **15**(6): 608-620.

Verghese, K., H. Lewis, et al. (2013). The role of packaging in minimising food waste in the supply chain of the future: Final report. Centre for Design, RMIT University: http://www.chep.com/foodwaste/.

Wikstrom, F. and H. Williams (2010). "Potential Environmental Gains from Reducing Food Losses Through Development of New Packaging – A Life-Cycle Model." Packaging Technology and Science **23**: 403-411.

Wikström, F. and H. Williams (2010). "Potential environmental gains from reducing food losses through development of new packaging–a life-cycle model." Packaging Technology and Science **23**(7): 403-411.

Wikström, F., H. Williams, et al. (2013). "The influence of packaging attributes on consumer behaviour in food-packaging life cycle assessment studies - A neglected topic." Journal of Cleaner Production **73**: 100-108.

Williams, A., E. Audsley, et al. (2006). "Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities: Defra project report IS0205." Zu finden in: http://randd. defra. gov. uk/Default. aspx.

Williams, H. and F. Wikström (2011). "Environmental impact of packaging and food losses in a life cycle perspective: A comparative analysis of five food items." Journal of Cleaner Production **19**: 43-48.

Williams, H., F. Wikström, et al. (2008). "A life cycle perspective on environmental effects of customer focused packaging development." Journal of Cleaner Production **16**(7): 853-859.

Williams, H., F. Wikström, et al. (2008). "A life cycle perspective on environmental effects of customer focused packaging development." Journal of Cleaner Production **16**: 853-859.

Williams, H., F. Wikström, et al. (2012). "Reasons for household food waste with special attention to packaging." Journal of Cleaner Production **24**: 141-148.

WPO (2008). Market Statistics and Future Trends in Global Packaging. World Packaging Organization. PIRA International Ltda.: http://www.worldpackaging.org.

Yates, M. R. and C. Y. Barlow (2013). "Life cycle assessments of biodegradable, commercial biopolymers—A critical review." Resources, Conservation and Recycling **78**: 54-66.

Ziegler, F., U. Winther, et al. (2013). "The carbon footprint of Norwegian seafood products on the global seafood market." Journal of Industrial Ecology **17**(1): 103-116.

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