U.S. Environmental Protection Agency
Office of Resource Conservation and Recovery

Evaluating the Environmental Impacts of Packaging Fresh Tomatoes Using Life-Cycle Thinking & Assessment: A Sustainable Materials Management Demonstration Project

FINAL REPORT

October 29, 2010

EPA530-R-11-005

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A Sustainable Materials Management Demonstration Project

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Prepared for:

Office of Resource Conservation and Recovery

U.S. Environmental Protection Agency

EPA Contract No. EP-W-07-003, Work Assignment 3-68

Acknowledgments

The authors, Martha Stevenson, Christopher Evans, Julia Forgie, and Louise Huttinger, would like to thank the following individuals for their contributions to this report:

- Greg Norris, Sylvatica
- Cynthia Forsch, Eco-Logic Strategies
- Kevin Grogan & Terry Coyne, Pactiv
- Helene Roberts & Hugh Mowat, Marks & Spencer
- Reggie Brown, Florida Tomato Committee
- Chad Smith, Earthbound Farms
- Niels Jungbluth, ESU Services
- Bo Weidema, Ecoinvent
- Cashion East, University of Arkansas
- Peter Arbuckle & Glenn Schaible, USDA
- Jon Dettling, Quantis
- Bryan Silberman, Produce Marketing Association
- John Bernardo, Sustainable Innovations
- Peppy, Mastronardi Produce
- Clare Broadbent, World Steel Association
- Dwight Schmidt, Fibre Box Association
- Ed Klein, TetraPak
- Gerri Walsh, Ball Corporation
- Bionaturae

We would also like to thank Deanna Lizas, Adam Brundage, and Nikhil Nadkarni at ICF International for their support on this project, and Jennifer Stephenson and Sara Hartwell at EPA's Office of Resource Conservation and Recovery for the input and guidance they provided for this study.

Executive Summary

The U.S. Environmental Protection Agency (EPA)'s report, Sustainable Materials Management: the Road Ahead, outlined a roadmap for shifting our focus from waste management to life cycle materials management. Materials management is "an approach to serving human needs by using or reusing resources most productively and sustainably throughout their life cycles" (EPA, 2009).

To promote the management of materials and products on a life-cycle basis, the report suggested that EPA "select a few materials/products for an integrated life-cycle approach, and launch demonstration projects." This demonstration project, conducted for the Office of Resource Conservation and Recovery (ORCR), evaluates *both* the direct environmental impacts of packaging options for fresh tomatoes, *and* the impact of tomato packaging decisions on the life-cycle environmental impacts of the packaged product. We use packaging to deliver a product, so why are the two analyzed separately from one another?

The goal is to demonstrate how life cycle thinking can be used as a tool to promote sustainable materials management. It considers three packaging options for fresh tomatoes:

1. "Loose", or minimally-packaged tomatoes that are transported in a corrugated container box with a General Purpose Polystyrene (GPPS) liner. Four tomatoes (2lbs) are purchased at a time by the consumer in a Polyethylene (PE) produce bag;

2. "PS Tray", where four tomatoes (2 lbs) are packaged in an Expanded Polystyrene (EPS) tray, wrapped in a Polyethylene (PE) film, and transported in bulk in corrugated container boxes; and

3. "PET Clamshell", where four (2 lbs) tomatoes are packaged in a Polyethylene Terephthalate (PET) clamshell container and transported in bulk within a corrugated container.

This report quantifies the environmental impacts associated with three different packaging options for fresh tomatoes, but also assesses the effect of different packaging options on the life-cycle impacts of growing, transporting, and retailing fresh tomatoes to consumers.

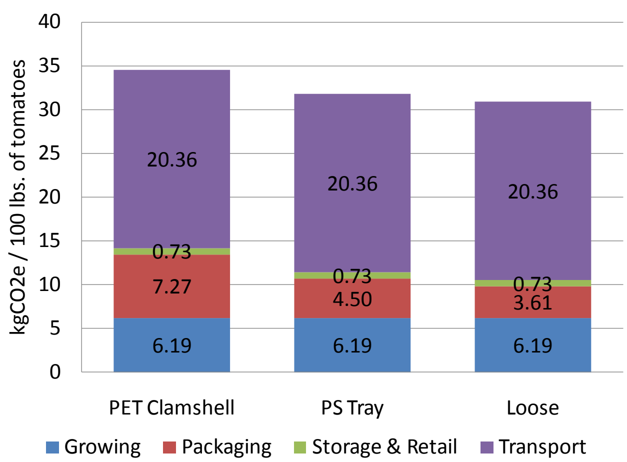
While this project uses the tools and approaches of LCA, it is not an ISO-compliant LCA and should not be used to support any claims or make any definitive choices with regards to packaging or product design. It is intended as a thought piece to expand both understanding of packaging and its relationship to the product and current biases toward considering climate change as the only impact category.

This report demonstrates how LCA can be used to answer two key questions posed by the Vision 2020 report:

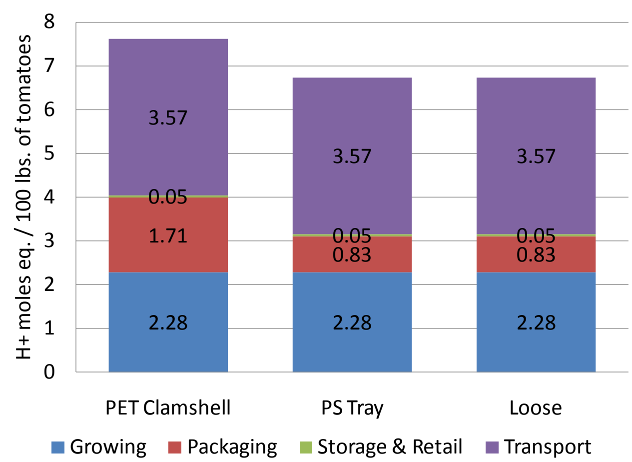
1. What are the significant environmental impacts associated with this material or product?

By collecting data on the growing, packaging, storage and retail, and transportation of 100 pounds of fresh tomatoes, we developed a preliminary life-cycle inventory (LCI) of inputs and outputs of the system to assess the global warming, acidification, respiratory effects, and smog formation environmental impacts (Exhibit ES 1).

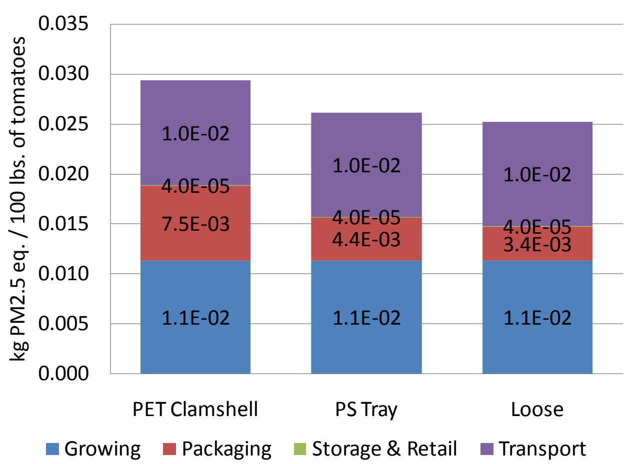
Exhibit ES 1: Environmental impacts, by life-cycle stage, of three packaging options for producing and delivering 100 pounds of fresh tomatoes from San Joaquin Valley, California, to Chicago, Illinois



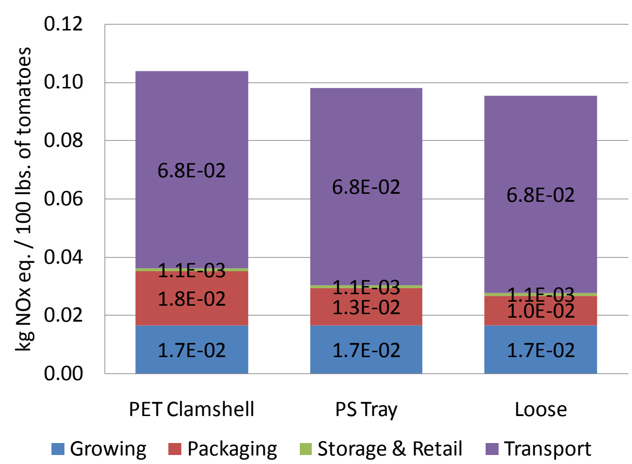
(a) global warming



(b) acidification



(c) respiratory effects



(d) smog

We found that:

- Although the difference is modest across all three packaging scenarios, the PET clamshell scenario is the most environmentally-intensive, primarily because it requires a greater amount of plastic material and because PET manufacture uses more energy per pound than the other two plastics (PE and PS).

- The contribution of transportation to global warming, acidification, respiratory effects, and smog impacts are sizable, and may dominate the impacts from other life-cycle stages at longer distances. A sensitivity analysis confirmed that the magnitude of transportation's environmental impacts across these categories varies greatly, depending on total transportation distance.

- The impacts associated with producing and transporting packaging for tomatoes are surprisingly large relative to the impacts associated with growing tomatoes, especially considering the relatively small amount of material required to package tomatoes.

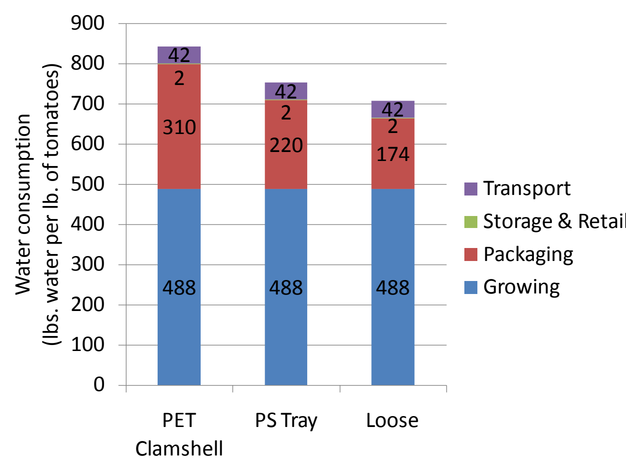
We evaluated the amount of water consumed by growing, packaging, storing and retailing, and transporting tomatoes. Since it may not be obvious, please note that the water used in transport is associated with the production of diesel for the truck. The results (Exhibit ES 2) show that:

- Irrigation of tomatoes during the growing phase dominates all three of the scenarios, although manufacturing packaging is still a significant source of water use.

- This water use is associated with the manufacturing processes of the corrugated box and the generation of hydroelectricity used as part of the electrical grid mix.

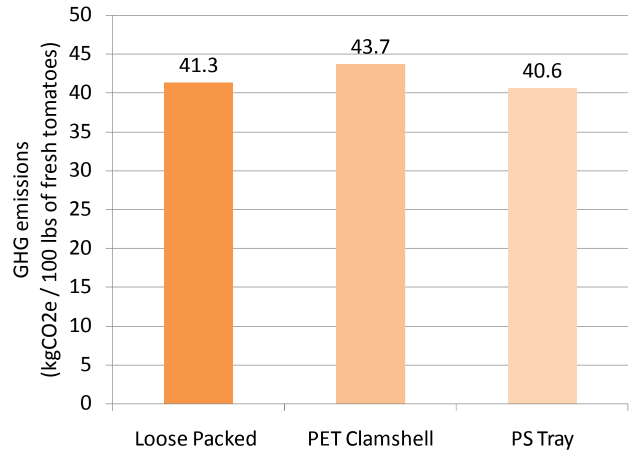
- Growing, packaging, and transporting one pound of tomatoes to the supermarket requires between 700 to 850 pounds (80-100 gallons) of water.

Exhibit ES 2: Water consumption, by life-cycle stage, of three packaging options for fresh tomatoes delivered to Chicago, Illinois



Finally, we demonstrated how LCA can be used to investigate the effect of packaging choices on the life-cycle impacts of growing, transporting, and storing and retailing tomatoes. Based on estimates of how packaging reduced fresh tomato spoilage rates, we showed how different packaging options could either increase or reduce life-cycle GHG emissions relative to loose-packed fresh tomatoes, depending on the emissions associated with producing the packaging, and the effect that packaging has on reducing spoilage before the tomatoes are sold to consumers (Exhibit ES 3). In a case where both PET clamshell and PS tray packaging reduce the spoilage of tomatoes at retail, the GHG emissions from manufacturing PET clamshell slightly increased overall GHG emissions relative to loose-packed tomatoes, while PS tray packaging slightly reduced total emissions by reducing spoilage.

Exhibit ES 3: Comparison of the effect of packaging and tomato spoilage on GHG emissions



2. If all impacts are not being addressed, what more can be done?

This demonstration project established a framework that can be improved and extended by EPA to:

- Gather further data on other impact categories, including eutrophication, carcinogens, non-carcinogens, ozone depletion, ecotoxicity, land use, and social considerations;
- Support efforts to improve LCA methodologies or other life-cycle tools that evaluate hard-to-quantify aspects of water and land use environmental impacts, and social impacts;
- Include other packaging options, such as processed tomato packaging in steel cans, glass jars, or aseptic (pouch or carton) containers;
- Extending the analysis to include other vegetables. For example, assessing carrots (a relatively hardy vegetable with a longer shelf life than tomatoes) or spinach (a vegetable with a short shelf life and number of fresh and processed packaging options, similar to tomatoes) alongside the tomato analysis. Other kinds of tomatoes, such as greenhouse-grown tomatoes could also be included.
- Evaluating other packaging-product systems outside of produce from an integrated life-cycle perspective.

Since this demonstration project did not involve a full, ISO-compliant LCA of fresh tomatoes, it is subject to several caveats and limitations that would need to be addressed before making any claims or definitive choices with regards to packaging or fresh tomato production:

- Impacts associated with growing tomato transplants were not included due to data limitations
- Impacts associated with ethylene spray were not included due to data limitations.
- Losses of tomatoes at the farm were not included due to data imitations. Although Kantor et al. (1997) found evidence of losses in the growing and harvesting process, they were not able to quantify the extent of these losses.
- Scenarios where tomatoes are repacked after harvest and before wholesale were not included, even though it is understood as a standard practice. This decision was made to limit the number of permutations of the study.
- Eutrophication, human toxicity and ecotoxicity impacts were not included as we were not able to locate data on air and water emission from tomato growing process, other than those associated with combustion of fuels used to run equipment.
- U.S. data sources were used where possible but also the majority of the background data represented the European context, primarily from ecoinvent to fill data gaps.
- Environmental impacts associated with infrastructure or equipment were not included.

Overall, this demonstration project contributes to a shift toward sustainable materials management by:

1. Evaluating the environmental impacts associated with different packaging options from an integrated perspective of food production, packaging, and delivery.
2. Assessing environmental impacts from a life-cycle perspective.
3. Extending the analysis to a number of different environmental impact categories that provide information relevant to EPA efforts to reduce GHGs, reduce air pollution, conserve water, and reduce material use.
4. Applying LCA tools and thinking to characterize the material inputs and processes specific to the life-cycle of fresh tomatoes, and the environmental impacts of these activities, including both quantitative and qualitative discussions.

5. Developing approaches for collecting and compiling LCI data from existing USDA databases.

By applying the tools of LCA to evaluate the impacts of packaging options for tomatoes, this study illustrates the advantages of an LCA approach in evaluating a full range of environmental impacts that can inform multiple EPA programs and priorities. It also demonstrates how LCA can be used to assess trade-offs in environmental impacts along the life-cycle of materials and products, and to identify hot spots and areas for further investigation. This report also identifies weaknesses in the LCA tools and considers a full range of environmental issues that may not be supported by LCA tools, but are valid considerations nonetheless.

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1 Introduction

1.1 Sustainable Materials Management: Vision 2020 Report

In June 2009, the U.S. Environmental Protection Agency (EPA) released the report, Sustainable Materials Management: the Road Ahead (aka The 2020 Vision). It outlined a roadmap for shifting our focus from waste management to improved materials management, which involves understanding and reducing life-cycle impacts, using less material, reducing use of toxic chemicals, using more renewable materials, considering the substitution of services for products, and recovering more materials. This shift will impact the way that our economy uses and manages materials and products.

EPA's roadmap provides three broad recommendations:

1. Promote efforts to manage material and products on a life-cycle basis;
2. Build capacity and integrate materials management approaches in existing government programs; and
3. Accelerate the broad, public dialogue necessary to start a generation-long shift in how we mange materials and create a green, resilient, and competitive economy.

Under the first broad recommendation, the report suggests a specific course of action to "select a few materials/products for an integrated life-cycle approach, and launch demonstration projects." This report is one of two demonstration projects currently being conducted in the Office of Resource Conservation and Recovery (ORCR) to begin implementation of these recommendations. This demonstration project is focused on vegetable packaging and its relationship with the product. A parallel demonstration project is being conducted by another group on construction and demolition waste.

The Vision 2020 Report poses four questions to guide these demonstration projects:

1. What are the significant environmental impacts associated with this material or product?
2. What is currently being done to address the impacts associated with this material or product?
3. If all impacts are not being addressed, what more can we (EPA) do?
4. What strategies for improvement are advised? How should progress be measured?

This demonstration project will focus on the first and third questions proposed in the Vision Report, as its subject matter seeks to look across various sectors identified in the Vision Report.

1.2 Impacts of Packaging Materials in the Vision Report

Packaging is not included as a stand-alone sector in the Vision Report, instead the materials associated with packaging manufacture are included in their respective material-based sectors (e.g., aluminum, paper) and the activities associated with packaging are included with their respective processes (e.g., food processing and canning). For this reason, it is difficult to analyze the associated impacts of packaging materials only using the input-output economic model, which underlies the Vision Report. In order to gain a sense of the identified impacts by packaging material sector, a summary table of three packaging base materials is provided in Exhibit 1-1.

Exhibit 1-1: Summary of Direct Impacts of Selected Packaging Material Sectors from Vision Report (Rankings are out of 480 Industry Sectors)

Paper & Paperboard Making		Plastic Materials & Resins		Primary Aluminum	
Rank	**Impact Area**	**Rank**	**Impact Area**	**Rank**	**Impact Area**
1st	Marine Sedimental Ecotoxicity Potential	4th	Ozone Depletion	2nd	Ozone Depletion, Marine Aquatic Ecotoxicity Potential, Freshwater Sedimental Ecotoxicity Potential
2nd	Human Toxicity Potential	6th	Marine Sedimental Ecotoxicity Potential	7th	Marine Sedimental Ecotoxicity Potential
4th	Energy Use	10th	Material Waste	8th	Human Toxicity Potential
5th	Freshwater Sedimental Ecotoxicity Potential, Acidification Potential	11th	Human Toxicity Potential, Marine Aquatic Ecotoxicity Potential, Freshwater Sedimental Ecotoxicity	12th	Acidification Potential
6th	Marine Aquatic Ecotoxicity Potential	19th	Terrestrial Ecotoxicity Potential, Acidification Potential	14th	Photochemical Oxidation Potential
9th	Water Use	20th	Freshwater Aquatic Ecotoxicity	20th	Terrestrial Ecotoxicity Potential, Material Waste
10th	Terrestrial Ecotoxicity Potential, Photochemical Oxidation Potential				
12th	Freshwater Aquatic Ecotoxicity				
13th	Global Warming Potential				
17th	Eutrophication Potential				

1.3 Designing the Packaging Demonstration Project

The first cited life-cycle assessment (LCA) study was conducted on packaging materials in the late 1960s (Baumann, 2004). Since that time, hundreds of LCAs have been conducted looking at various packaging scenarios and their associated life cycles. These studies often do not include impacts of the product as part of the analysis. Using the principles outlined in the Vision Report (i.e., to reduce material and energy use across the whole supply chain) the project was approached from a different angle: we need to assess packaging as part of the product supply chain to understand the overall impacts and put them into context. Source reduction of packaging material has been a long-standing practice in the field of waste/material management, but when this source reduction leads to increased product damage (and typically increased overall environmental damage) it results in a net detriment to human and environmental health. We use packaging to deliver a product, so why are the two analyzed separately from one another?

In designing this demonstration project, the team wanted to analyze packaging's role in a product supply chain that generated significant environmental impacts on its own, assuming that delivering high-impact products safely to market was of utmost importance from an environmental health perspective. The Vision Report reflected that those sectors housed in the Food Products & Services division cause significant environmental burdens from production to final consumption including meat production, dairy production, restaurants (eating and drinking places), food preparation and others. Currently, several studies are being conducted in the United States on meat and dairy products. These projects include primary data collection from their specific industries and have significant budgets and longer timelines. Given that these areas were already being analyzed in a more robust manner, the vegetable supply chain was selected for this demonstration project. Please see Exhibit 1-2 for the Vegetable sector's identified impacts in the Vision Report (EPA, 2009a).

Exhibit 1-2: Vegetable Sector Impacts Identified in Vision Report

Ranking (of 480 sectors)	Impact Area
4th	Direct Water Use
6th	Direct Freshwater Aquatic Ecotoxicity, Direct Terrestrial Ecotoxicity
15th	Direct Land Use
16th	Direct Global Warming Potential
19th	Direct Material Use

2 Methodology and Project Description

This section describes the goal of this study, key details of the LCA methodology, the processes modeled, and data sources. It discusses the goal of this report within the context of the EPA's 2020 Vision Report, then describes the general LCA method that was applied to achieve this goal, and explains key methodological details, such as how fresh tomatoes—the food product evaluated in this study—were selected, definition of the functional unit for the study, and the packaging comparisons, or scenarios, assessed by this study. This section then provides an overview of the tomato growing, harvesting, packaging, and transportation processes that were modeled, and the data sources that were used to assemble the life-cycle inventory (LCI) for fresh tomatoes.

2.1 Goal of Study & Intended Application

The goal of this demonstration project is to take the recommendations from the Vision 2020 Report and apply them toward deepening our understanding of packaging's environmental impacts, positively and negatively, as related to delivery of produce. While this demonstration project utilizes the tools of LCA, it is not an ISO-compliant LCA and should not be used to support any claims or make any definitive choices with regards to packaging or product design. It is intended as a thought piece to expand both understanding of packaging and its relationship to the product and current biases toward considering climate change as the only impact category. As outlined in the report, significant data gaps were encountered during this research including limited data for some of the life cycle phases and limited emissions data for agricultural processes. For those impact areas where these data gaps generate "low-confidence," we have used the scientific literature to support a qualitative discussion rather than address them quantitatively.

2.2 Methodology and Functional Unit

Methodology

This study uses the tools of life cycle assessment (LCA), scientific literature, and expert interviews to evaluate the environmental impacts of packaging and packaging's effects on the delivery of produce. To evaluate the links between packaging and its life-cycle impacts on produce, this analysis involves two main comparisons:

1. An assessment of the life-cycle environmental impacts of different produce packaging choices compared to each other; and

2. An assessment of the environmental impacts of produce growing, transportation, and retail compared to the life cycle impacts of packaging, and the effect of different packaging options on the impacts of produce growing, transportation, and retail.

To conduct this assessment, we developed a list of candidate produce for evaluation in this analysis. In developing this list, we considered the number of packaging options available for different fruits and vegetables, the existence of a “loose packaging” option (an option with no packaging other than containers used to transport the product to the produce section in the supermarket) that could serve as a baseline for comparison, and the availability of LCI data and literature.

Based on an extensive survey of literature related to the production, packaging, and distribution of produce, we selected tomatoes as the produce type for study using LCA. Of the candidates, tomatoes offered a number of different packaging options, and a sufficient level of existing LCI data and literature was available for tomatoes compared to the other vegetables.

Functional Unit Definitions

The functional unit is the reference unit against which the environmental impacts of a product system are compared. It is necessary to select a functional unit in order to consistently compare the impacts of the different tomato packaging options and to evaluate their influence on the life-cycle impacts of producing and delivering tomatoes to the supermarket. There are a number of different characteristics that could be used to define a functional unit for tomatoes. For example, the functional unit could be defined in terms of:

- Mass or volume of tomatoes (e.g., one pound, or one cubic foot of tomatoes). This is the most common functional unit chosen today, however it is increasingly coming into question as product comparisons are being made (Schau, 2008).
- Nutritional value, a measure of the nutrient quality of different tomato products. Nutritional value functional units have been used by other studies to make comparisons across different types of foods or products (Carlsson-Kanyama et al., 2003). For example, nutritional value could be used to compare fresh tomatoes and canned or processed tomatoes.
- Quality of the tomatoes, such as their taste, color, or overall class or value. Quality is more subjective, difficult to quantify, and may vary depending upon the form and use of the product. Quality is often quantified and evaluated in studies that evaluate freshness or shelf life (e.g., Parihar, 2007).

For the purposes of this study, we defined our functional units in terms of the mass of tomatoes. Mass was selected as the basis for the functional units because we are making comparisons within one specific type of tomato (i.e., fresh slicing tomatoes), and we are most interested in evaluating the environmental impacts from the production, packaging, and distribution of tomatoes, rather than variations in quality or other characteristics. Consequently, we assume that the nutritional value and quality of tomatoes is the same within a particular type of tomato, regardless of the material used to package the tomato.

We performed two different analyses for this study, which required us to define two separate functional units:

1. One hundred pounds (100 lbs) of tomatoes delivered to supermarket. This functional unit encompasses the life-cycle environmental impacts associated with growing, packaging, and transporting tomatoes to a supermarket. We used this functional unit to compare different tomato packaging options to each other (see sections 3.1 and 3.2), and also to investigate the sensitivity of our results to the distance that tomatoes are transported for sale (see section 3.3).

2. One hundred pounds (100 lbs) of tomatoes delivered to consumer for consumption. This functional unit encompasses the same processes as the first unit, but includes the environmental impacts associated with spoilage of tomatoes at the supermarket prior to purchase by the consumer. We used this functional unit to investigate the effect that packaging can have on reducing environmental impacts from spoilage in the supermarket (see section 3.3).

Drawing from the information we gathered on tomatoes, we defined the following three packaging options for delivery of fresh tomatoes. These scenarios were used in both functional unit comparisons:

1. "Loose", or minimally-packaged tomatoes that are transported in a corrugated container box with a General Purpose Polystyrene (GPPS) liner. This box contains 25 pounds of tomatoes, approximately 50 tomatoes[1]. Polyethylene (PE) bags used by the consumer to transport tomatoes home were also included in this scenario. It was assumed that four tomatoes (2 lbs) were purchased at a time.

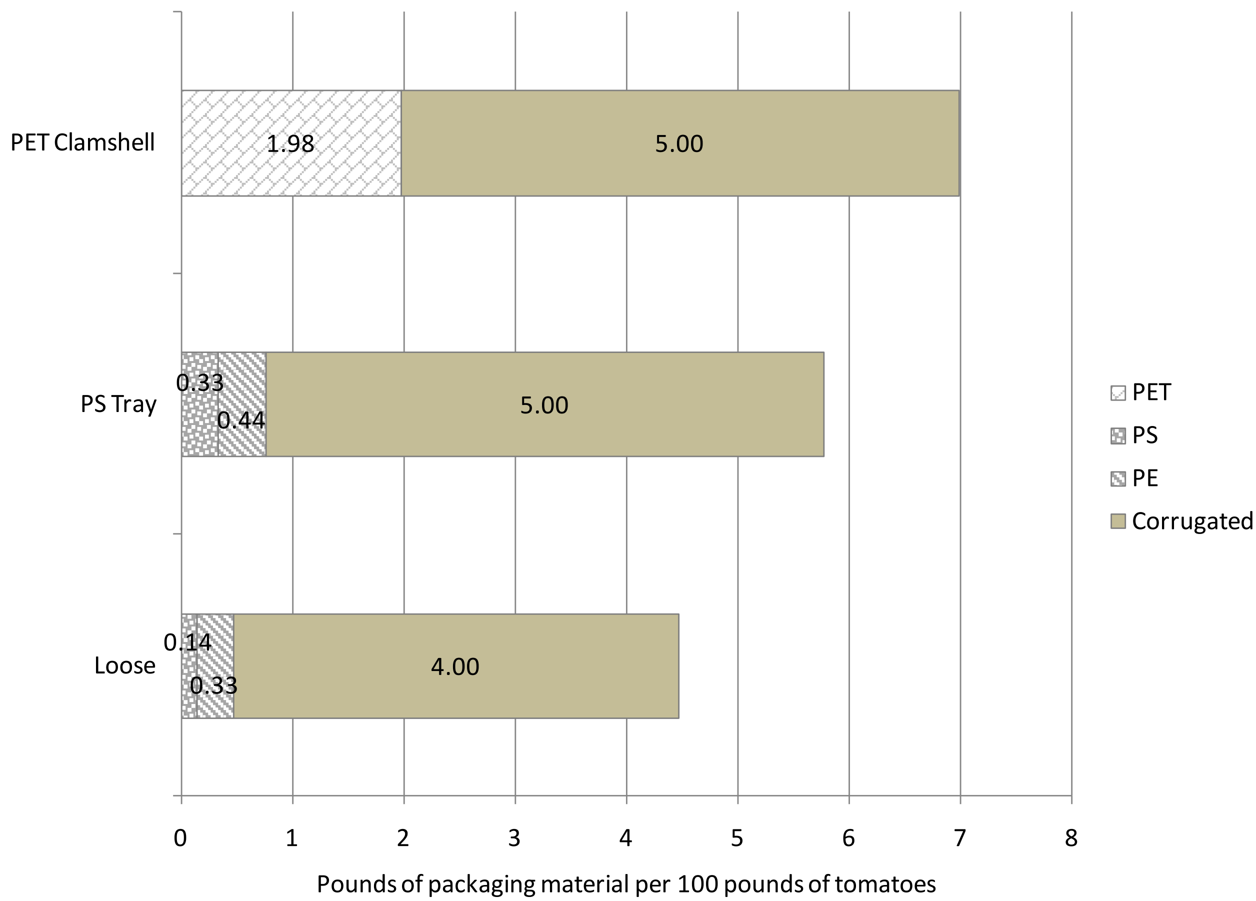
2. "PS Tray", or an Expanded Polystyrene (EPS) tray, where four tomatoes (2 lbs) are packaged in a PS tray, wrapped in a polyethylene film, and transported in bulk in corrugated container boxes. This corrugated container holds 20 pounds of tomatoes and associated packaging.

[1] Fresh slicing tomatoes can range in weight from 4oz to 2lbs. It is assumed that the average weight of a slicing tomato is 8oz for this study.

3. "PET Clamshell", or a Polyethylene Terephthalate (PET) clamshell, where four (2 lbs) tomatoes are packaged in a PET clamshell container and transported in bulk within a corrugated container that holds 20 pounds of tomatoes and associated packaging.

The material compositions of the three packaging options, or scenarios, that were developed for this analysis are shown in Exhibit 2-1 below. According to industry expert, Cynthia Forsch, "Loose" slicing tomatoes comprise 85 percent of the retail market in the United States, "PET Clamshells" make up 10 percent of the market, "PS Tray" is two percent of the market, and the remaining 3% are in other packaging formats (Forsch, 2010).

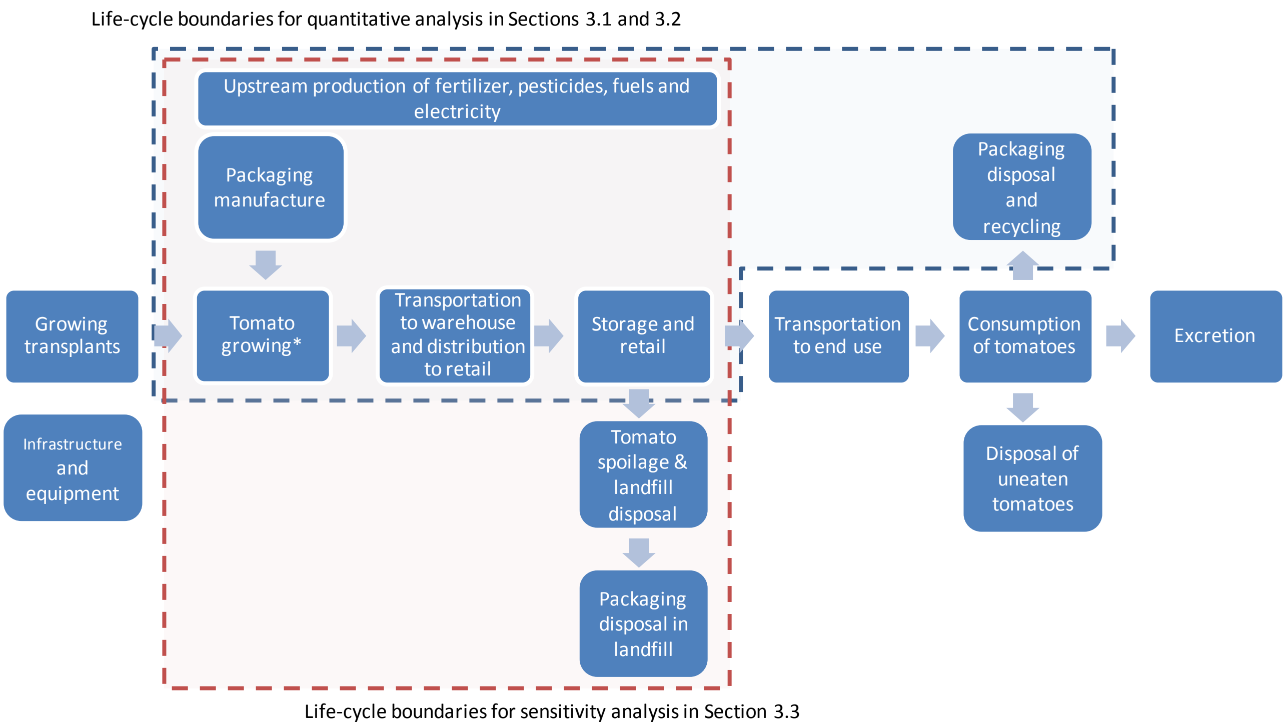
Exhibit 2-1: Composition of packaging materials in the three packaging scenarios for delivery of 100 pounds of fresh tomatoes



Life-cycle Boundary Diagram

Exhibit 2-2 provides a flow diagram of the overall process for tomatoes. The life-cycle boundaries corresponding to each of the functional units defined for this analysis are shown by the dashed lines. The outer box in blue defines the boundaries that were used to assess the qualitative environmental impacts discussed in Sections 3.1 and 3.2; the inner box in red, which encompasses “tomato spoilage” and “packaging disposal in landfill”, defines the boundaries used in the sensitivity analysis of packaging and spoilage rates provided in Section 3.3.

Exhibit 2-2: Process flow diagram of the tomato life-cycle and the life-cycle boundaries established for this analysis



* Tomato growing includes: irrigation, plowing/tillage, application of fertilizer, but does not include other air, water, and soil emissions. See Section 2.5 for details.

As shown in Exhibit 2-2, growing transplants, transportation to end use, consumption of tomatoes, disposal of uneaten tomatoes (e.g., tomatoes cores, seeds, or uneaten leftovers) and the excretion of tomatoes after consumption were not included in the assessment. Selection of the life-cycle boundaries was informed by data availability and the primary goal of the analysis, which was to focus on the environmental impacts associated with packaging and the effect of packaging on the life-cycle impacts of tomatoes.

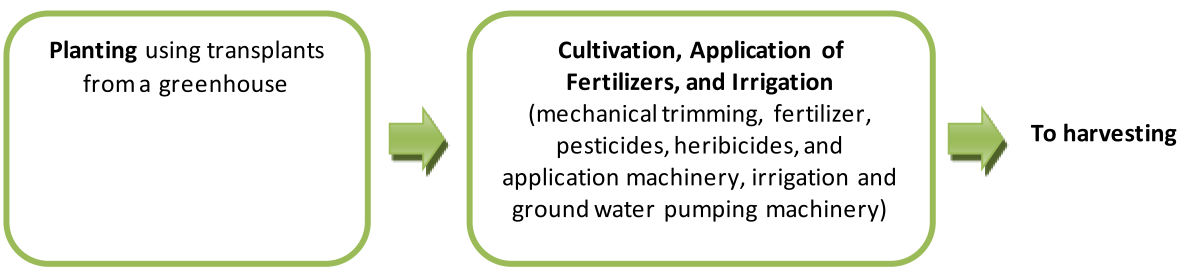
2.3 Fresh Tomato Process Description & Data Development

Process Description

USDA statistics indicate that California and Florida are the leading states for growing tomatoes in the United States. In 2007, California was responsible for 76% of the total harvested area for tomato growing in the U.S. (USDA, 2010). Since data representative of U.S.-average tomato growing practices were not available, California tomatoes, as the leader in U.S. tomato production, were chosen to represent the data inputs for the growing process in this analysis.

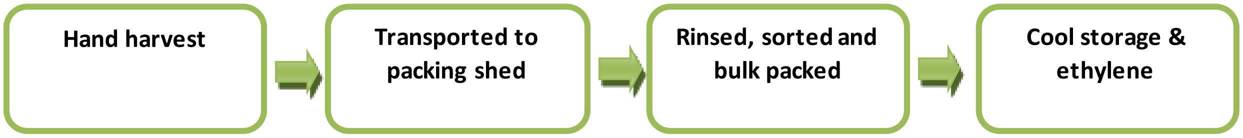
California produces both fresh and processed tomatoes. Fresh market tomatoes are juicer and harvested while immature, while processed tomatoes have a thicker skin and firmer consistency limiting damage during harvesting and transportation (CFAIC, 2009). In 2006, fresh market tomatoes had an average yield of 28,000 pounds per acre and are mostly grown in fields as bushes from transplanted plants instead of seeds to ensure protection from weeds, disease, and pests. Transplants are grown in commercial greenhouses and then transferred to the field as plug plants using a mechanical planter. Prior to planting, farms prepare the ground by tillage, which includes sub soiling, disking, rolling, land planning, and listing beds (Hartz et al., 2008). All tomato fields in California are irrigated using subsurface drip, furrow, and sprinkler irrigation methods. Fertilizers and pesticides are then mechanically applied to the crop to prevent disease and insect infestation. Exhibit 2-3 shows the steps of the growing process for fresh tomatoes in California.

Exhibit 2-3: Diagram for fresh tomato growing



Fresh tomatoes are hand harvested at the mature green and pink stages and transported from the field to the packing shed where they are rinsed and sorted. They are then put into a cool storage area where they are sprayed with ethylene before being shipped out to market. Ethylene is a naturally occurring gas produced by tomatoes that that is used to accelerate ripening and promotes earlier coloration and maturing; spraying tomatoes with ethylene prior to shipping accelerates the ripening process (LeStrange et al., 2008). Exhibit 2-4 shows the steps of the harvesting process for fresh tomatoes in California.

Exhibit 2-4: Process diagram for harvesting fresh tomatoes



After harvest, the packaging step can take many different forms. Fresh slicing tomatoes can be packed in boxes in the field and are not repacked prior to market delivery. Some fresh slicing tomatoes are packaged in the field and transported to a packing facility where they are repackaged before being distributed for sale. Fresh tomatoes are typically packaged in 20 to 25-pound containers (corrugated or reusable plastic containers "RPCs") for delivery to market. If the packaging scenario includes an interim step, typically 1,000-pound reusable plastic bins or 2,500-pound "gondolas" are used to transport tomatoes from the field to packing facilities. Once packaged, fresh tomatoes are typically sold to retail supermarkets, restaurants, or wholesale in 20-25 pound boxes (Brown, 2010).

Life-cycle Inventory Data Development

Due to data limitations, this study focuses on developing LCI data for field grown, fresh tomatoes, as opposed to processed tomatoes. The following section discusses the data that were acquired to model the phases associated with fresh tomato production, as described in section 2.3. For a more detailed description of the process steps associated with processed tomatoes, refer to Appendix A.

For this analysis, we used California-specific data where possible, and filled data gaps with generic information from other data sources, primarily the ecoinvent database managed by the Swiss Centre for Life Cycle Inventories (2008). Exhibit 2-5 includes all California-specific raw data and inputs used for the analysis. The data are based on the total number of acres planted. Fertilizer and pesticide use data for California fresh and processed tomatoes were taken from the 2006 U.S. Agricultural Chemical Usage Survey (USDA 2007). The California Department of Water Resources estimated annual land and water use estimates, which were used to quantify total irrigation water use for both crops, were from 2001. The data in the table were scaled to provide inputs in terms of producing one kilogram (i.e., 2.205 pounds) of fresh tomatoes.

Exhibit 2-5: California Fresh Tomato specific data used as inputs for the growing process

INPUT	UNIT	DATA	SOURCE
Acres Planted	acres	41,400	USDA 2010
Acres Harvested	acres	41,000	USDA 2010
Yield	short tons	14	USDA 2010
Production	short tons	574,000	USDA 2010
FERTILIZERS- data for entire CA acres of fresh tomatoes planted			

Nitrogen	1,000 lbs	9682.8	USDA 2007
Phosphate	1,000 lbs	5116.5	USDA 2007
Potash	1,000 lbs	6432.7	USDA 2007
Sulfur	1,000 lbs	4358.6	USDA 2007
PESTICIDES- data for entire CA acres of fresh tomatoes planted			
Herbicide	1,000 lbs	24.1	USDA 2007
Insecticide	1,000 lbs	40	USDA 2007
Fungicide	1,000 lbs	310.4	USDA 2007
Other	1,000 lbs	589.7	USDA 2007
IRRIGATION WATER			
Irrigation Water Use	m3 per acre	3071.37	California Department of Water Resources 2001

We were unable to find California- or tomato-specific information on the mechanical inputs used for tilling, fertilizing, applying pesticides, and irrigating. We assumed that these tractors and agricultural machinery do not vary widely; therefore we used data inputs from Nemeck and Kagi (2007). Based on the descriptions of tomato tillage practices, three processes were chosen from the data set to represent ground preparation: plowing for sub soiling, harrowing for disking, and rolling. No data were available for the process of listing fields; therefore listing tomato fields is not included in this analysis.

Nemeck and Kagi (2007) take account for diesel fuel consumption in agricultural machinery on a per-hectare basis (2.47 acres). The following activities were considered part of the work process: preliminary work at the farm (e.g., attaching the adequate machine to the tractor); transfer to field (with an assumed distance of 1 km); field work (for a parcel of land of 1 ha surface); transfer to farm and concluding work (e.g., uncoupling the machine).

Data on the greenhouse growing of transplants and harvesting were not available. Therefore, this analysis covers the growing process from when the transplants arrive at the farm from the greenhouse up to the time right before harvest begins.

2.4 Packaging Manufacture Descriptions and Data Selection

Corrugated

Corrugated is a paper product most often made from hardwood and softwood wood chips, recycled paper, water, starches, and sizing. The process chosen for this study was corrugated from "mixed fibre" including both recycled and virgin material content. The wood chips are typically chemically pulped through the Kraft process, using heat and chemicals to separate the lignin from the fibers. After pulping, the water-laden mixture is uniformly applied to a screen and fed through a series of rollers contained in a papermaking machine. During this process, the pulp goes from containing 97% water to 3% water and is finished by winding into large reels of containerboard, the base papers for making corrugated. Single-walled corrugated, the type of corrugated typically used to construct a 20-25-pound box of tomatoes, consists of a corrugated medium affixed to two sheets of linerboard on either side. These three base papers are fed into a corrugating machine where steam is applied to "wrinkle" the center medium and starch is applied to attach the three layers together. The corrugated sheet is then printed, die-cut, folded, and glued according to box design.

Exhibit 2-6: Photograph of a cross-section of a corrugated container consisting of two linerboard sheets on either side of a corrugated linerboard medium (Oksay, 2008)

In our interviews with tomato companies and retailers, we found that some tomato growers are fully integrated and make their own boxes on-site. Others purchase their boxes from a manufacturer. There is no standard method for this industry. Exhibit 2-5 is an example of a tomato box with a liner.

Exhibit 2-7: Photograph of tomato box with liner. (Photo by Martha Stevenson)

LCI data for corrugated box manufacture and conversion were selected from the ecoinvent 2.0 database (Swiss Centre for Life Cycle Inventories, 2008) with modifications made to match electricity inputs to the U.S. electrical grid average. A study is currently being conducted by the AF&PA on U.S.-represented corrugated manufacture; however those results had not been released to the public for use in this report. There are notable differences in paper manufacture between the United States and Europe, including species and cultivation of fiber feedstocks.

Polystyrene Lining and Tray

Polystyrene is a polymer derived from natural gas and crude oil through production of ethylene and benzene. These two fractions are alkylated using a catalyst to produce ethylbenzene. The ethylbenzene is dehydrogenated to produce the styrene monomer, which is then polymerized to produce polystyrene. In this packaging study, polystyrene is used in its expanded form to produce the tray and in its general-purpose form to produce the liner in the loose tomato corrugated box (see Exhibit 2-8 for an example). Data for PS and associated conversion were used from the ecoinvent 2.0 database with modified electricity to the U.S. grid average, but originally developed by Plastics Europe (Swiss Centre for Life Cycle Inventories, 2008).

Exhibit 2-8: Tomatoes packaged in PS Tray (Photo by Martha Stevenson)

Polyethylene Bag and Overwrap

Low-Density Polyethylene is a polymer in the polyolefin family derived from steam cracking crude oil and natural gas to produce ethylene. LDPE is produced by polymerizing ethylene in high-pressure reactors using a catalyst. LDPE is typically used as a film in packaging applications through the conversion process of blown film extrusion, where the pelletized resin is heated and fed through a thin die to form a tube, continuously inflating it to form a thin tubular sheet that can be used directly, or slit to form a flat film. Data for LDPE were obtained from the U.S. LCI database and represent the U.S. context (NREL, 2009). These datasets were developed in 2007 through broad surveys of the plastics industry (FAL, 2007). Data for film extrusion conversion were used from the ecoinvent 2.0 database with modified electricity to the U.S. grid average, but originally developed by Plastics Europe (Swiss Centre for Life Cycle Inventories, 2008).

PET Clamshell

Polyethylene Terephthalate (PET) is a petroleum-based co-polymer made from the monomers ethylene glycol and terephthaltic acid, which are derived from crude oil and natural gas respectively. This plastic resin is used in many packaging applications including soda bottles, jars, and clamshells for produce. In order to produce a PET clamshell, the resin material is fed into a mold as a plastic sheet, heated to a specific temperature, and shaped into the desired form. This process is called "thermoforming." Data for PET were obtained from the U.S. LCI database and represent the U.S. context (NREL, 2009). These datasets were developed in 2007 through broad surveys of the plastics industry (FAL, 2007). Data for thermoforming were used from the ecoinvent 2.0 database with modified electricity to the U.S. grid average, but originally developed by Plastics Europe (Swiss Centre for Life Cycle Inventories, 2008).

2.5 Transportation Description and Data Selection

The transportation emissions attributed to tomatoes are determined by: (i) the mode of transportation (e.g., truck, train, ship), (ii) the distance traveled, (iii) the fuel consumption and load carried by the vehicle, and (iv) whether the transportation vessel returns empty (i.e., whether the backhaul distance needs to be attributed to the original cargo or not).

Tomatoes are typically shipped in trucks or container vans. The ideal temperature for transportation of mature, green tomatoes (i.e., tomatoes harvested prior to ripening) is between 55° to 70°F to prevent chilling damage at lower temperatures, and decay at higher temperatures. As a result, tomatoes are may be shipped in refrigerated trucks to protect tomatoes. When tomatoes are transported through areas with temperatures below freezing, the tomatoes can be protected by minimizing contact with the floors and walls of the truck and by circulating warmed interior air around the load. (University of California, 2010; USDA, 2006)

Transportation of fresh tomatoes from the field to retail in supermarket was modeled using the following assumptions:

- Tomatoes are packaged at or near the field where they are grown, then transported to a distribution or wholesale facility before retail in local supermarkets;

- Long-distance transportation in a combination truck (equivalent to a class 8b heavy-duty truck); short-distance transportation from distribution facility to supermarket in a city delivery truck (equivalent to a class 4 or 5 heavy-duty truck);
- Long-distance transportation from San Joaquin Valley, California to Chicago, Illinois, a distance of 2,155 miles;
- Short-distance transportation from distribution facility in Chicago to local supermarket, a distance of 20 miles;
- Trucks are fully-loaded with cargo;
- Backhauls are not included (i.e., we assumed that the trucks return carrying other loads, so backhaul trips do not need to be included in the analysis); and
- Although tomatoes may be refrigerated during transport when exterior air temperatures are at, or above, the recommend temperature range for transport, we did not include refrigeration estimates in the transportation of tomatoes. Refrigerated transportation will increase fuel consumption and emit small amounts of refrigerant through "fugitive" leaks in the refrigerant during transportation, and the relative impacts would increase as transportation distance increases.

We modeled truck fuel consumption and emissions using equivalent European heavy-duty truck models available from ecoinvent (Swiss Centre for Life Cycle Inventories, 2008).

2.6 End of Life

The end of life of the tomatoes was not included as part of the life cycle model. Please see section 4.4 for a discussion of tomato waste and spoilage (i.e., tomatoes are not consumed, but instead rejected as waste due to damage, spoiling, or as waste in the food preparation process) and human excrement (i.e., tomatoes are consumed by the end user for nutrition).

The end of life for the various packaging scenarios was included in the life cycle model, by including treatment of these materials through recycling, incineration with energy recovery or landfilling, based on national statistics. The proportions of waste pathways were applied using EPA's Municipal Solid Waste: Facts & Figures Report from 2008 (EPA, 2009b) and are reflected in Exhibit 2-9. One modification was made to the listed recycling rates. Corrugated is recycled at a relatively high rate in the United States including both residential and commercial combined at 77%. Because our study includes corrugated in a commercial context, we modified the average recycling rate to 95% by weight, as most supermarkets have dumpsters dedicated solely to corrugated recycling due to economic advantages.

Exhibit 2-9: End-of-life management assumptions for packaging material (EPA, 2009b)

Packaging Material	% Recycled	% Incinerated with Energy Recovery	% Landfilled
Corrugated Box	95	1	4
PET Clamshell	0	20	80
PS Liner & Tray	6.9	18.6	74.5
PE Wrap & Bag	14	17.2	68.8

2.7 Life-Cycle Impact Assessment Methodology: TRACI 3.01

The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) is a mid-point Life Cycle Impact Assessment methodology developed by EPA. The TRACI model assesses multiple impacts and includes U.S.-focused models for its assessment parameters. TRACI was selected due to the geographic scope of the project – tomato growing and delivery within the United States. Exhibit 2-10 includes a list of the TRACI impact categories, the units each category is measured in, the geographic boundary of the model and the source information for the model development. TRACI version 3.01 was used for this study.

Exhibit 2-10: Description of TRACI environmental impact categories

Impact Category	Units	Site Specificity	Source for Model Development
Global Warming	kg CO_2 eq	Global	Intergovernmental Panel on Climate Change
Ozone depletion	kg CFC-11 eq	Global	World Meteorological Organization's "Handbook for the International Treaties for the Protection of the Ozone Layer"
Human health cancer	kg benzene eq	United States	Used CalTox Version 2.2 to develop a multi-media model including 23 pathways of exposure. Only 330 chemicals characterized (Note: those chemicals represent 80% of weight of releases listed in TRI)
Human health non-cancer	kg toluene eq	United States	Used CalTox Version 2.2 to develop a multi-media model including 23 pathways of exposure. Only 330 chemicals characterized (Note: those chemicals represent 80% of weight of releases listed in TRI)
Smog formation	kg NO_x eq	U.S. east or west of the Mississippi River, U.S. census regions, states	Used model developed for California Air Resources Board to develop a U.S.-specific model for TRACI.
Human health criteria pollutants (i.e., respiratory effects)	kg PM2.5 eq	U.S. east or west of the Mississippi River, U.S. census regions, states	Model developed by Harvard School of Public Health based on emissions fate & transport, and epidemiological studies on concentration-response and translation to mortality and morbidity effects.

Acidification	H+ moles eq	U.S. east or west of the Mississippi River, U.S. census regions, states	U.S.-specific model developed for TRACI based on acidification factors for each US state and calculated into four regions. Used US National Acid Precipitation Assessment Program model.
Ecotoxicity	kg 2,4-D eq	United States	Used CalTox Version 2.2 model and developed model using concentration-to-source ratio for emissions and impact-to-concentration ratio. Only 161 chemicals characterized.
Eutrophication	kg N eq	U.S. east or west of the Mississippi River, U.S. census regions, states	U.S.-specific model developed for TRACI

Due to data gaps in the tomato LCI, we do not have confidence in the analysis of several of the impact categories and have excluded them from the study quantitatively to avoid "false positive" results, i.e. although our model provides a number for a "low-confidence" impact area, we are lacking data for the air and water emissions from the tomato growing process, so we could be missing significant additional impacts. The impacts assessed quantitatively in the report include: global warming potential, acidification, human health criteria pollutants (particulates, or respiratory effects) and smog formation.

Global Warming

Global warming potential is an indicator for a product or system's contribution to climate change. The ability of chemicals to retain heat on the earth (radiative forcing) is combined with the expected lifetime of these chemicals in the atmosphere and expressed in CO_2 equivalents. TRACI includes the Intergovernmental Panel on Climate Change's (IPCC's) 2001 Global Warming Potentials with a 100-year time perspective.

Acidification

Acidification is the potential of a chemical emission to acidify ecosystems and thus disrupt the chemical equilibrium of the ecosystem, including loss of species biodiversity and loss of soil productivity. The main causes of acidification include coal-fired power plants, fuel combustion, and livestock growing.

Human Health – Criteria Air Pollutants (i.e., Respiratory Effects)

Particulate matter is a complex mixture of organic and inorganic substances of varying dimensions, which suspend in air. Given the complexity and variety in terms of chemical composition of particulate matter, their characterization and quantification in air is typically performed on the basis of physical measures. The TRACI methodology normalizes particulate emissions to kg PM2.5 equivalents. Impacts to human health from particulates can include asthma, lung cancer, cardiovascular issues, and premature death. Fuel combustion is a primary contributor to particulate emissions.

Smog Formation

Smog Formation is the potential of ozone creation at ground level (i.e. tropospheric ozone) through photochemical transformation of ozone precursor emissions. The main ozone precursor compounds are nitrogen oxides (NOx) and non-methane volatile organic compounds (NMVOC). Fuel combustion is a significant contributor to smog formation. Similar to criteria air pollutants, smog can cause irritation to the respiratory system and induce asthma.

2.8 Life-Cycle Impact Assessment Methodology: Water

Water consumption was assessed using a single-issue impact assessment method provided in the SimaPro software. The methodology is titled “Water v1.01” and was developed in 2008. It is essentially a counting metric, meaning that it only counts inputs of water from different sources to the modeled processes and does not characterize them toward specific impacts (e.g., removing water from critical habitat or quality of water after use). The result is a total volume of “blue” water (i.e., water removed from surface or groundwater) delivered to a process, where information is present in the inventory data.

2.9 Data Quality Assessment

As described in the fresh tomato and packaging material process descriptions in sections 2.3 and 2.4, an LCI was compiled from public sources for use in this report. The data are specific to the U.S. context and thus the geographic and temporal representation is considered high, however due to significant gaps, the data are not complete. Other than the combustion of fuels in on-farm machinery, no air or water emissions from the tomato growing stage were included in the dataset. A data gap this significant would not be accepted for an ISO peer-reviewed LCA. Overall, while this data development represents an innovative approach toward working in a constrained and data poor U.S. environment, the quality is considered moderate to low for the eutrophication, carcinogenic, non-carcinogenics, ecotoxicity, ozone depletion indicators, and GHG emissions from nitrous oxide (N_2O) released by application of synthetic fertilizers to tomato fields.

Data for PET and LDPE were obtained from the U.S. LCI database and also represent the U.S. context (NREL, 2009). These datasets were developed in 2007 through broad surveys of the plastics industry. This data quality is considered to be high. (FAL, 2007)

Data for PS and plastic conversion were used from the ecoinvent 2.0 database with modified electricity to the U.S. grid average, but originally developed by Plastics Europe (Swiss Centre for Life Cycle Inventories, 2008). The geographic representation of this data is low-quality; however the technological representation is on par with U.S. operations.

Data for on-farm processing, corrugated manufacture, transportation, and storage were taken from the ecoinvent 2.0 data and the DK food database (Nielsen et al., 2007; Swiss Centre for Life Cycle Inventories, 2008). Data quality with regards to completeness is considered high, however due to the geographic and technological differences the overall data quality is considered moderate.

2.10 Caveats and Limitations to the Model

A list of various assumptions and limitations to the life cycle model for the various scenarios has been included below as a reference for the reader. Additional work on this demonstration project would provide an opportunity to address some of these limitations.

- Impacts associated with growing tomato transplants and infrastructure were not included due to data limitations.
- Impacts associated with ethylene spray were not included due to data limitations.
- Losses of tomatoes at the farm were not included due to data imitations. Although Kantor et al. (1997) found evidence of losses in the growing and harvesting process, they were not able to quantify the extent of these losses.
- Scenarios where tomatoes are repacked after harvest and before wholesale were not included, even though it is understood as a standard practice. This decision was made to limit the number of permutations of the study.
- Although tomatoes may be refrigerated during transport when exterior air temperatures are at, or above, the recommended temperature range for transport, we did not include refrigeration estimates in the transportation of tomatoes. Refrigerated transportation will increase fuel consumption and emit small amounts of refrigerant through "fugitive" leaks in the refrigerant during transportation, and the relative impacts would increase as transportation distance increases.
- Since the effects of packaging on environmental impacts from transportation to end use, consumption, disposal of uneaten tomatoes (e.g., tomatoes cores, seeds, or uneaten leftovers), and excretion are minimal, these were excluded from the study.

- Eutrophication, human toxicity and ecotoxicity impacts were not included as we were not able to locate data on air and water emission from tomato growing process, other than those associated with combustion of fuels used to run equipment.
- Used U.S. data sources where possible but also incorporated European data, primarily from ecoinvent to fill data gaps.
- Environmental impacts associated with infrastructure or equipment were not included.

3 Quantitative Results & Discussion

3.1 Results from TRACI

Exhibit 3-1 compares the environmental impacts of the three packaging options for fresh tomatoes grown in San Joaquin Valley, California and delivered to retail in Chicago, Illinois. These results include the environmental impacts from growing the tomatoes in the field, harvest, packaging, transportation to wholesale in Chicago, and distribution to retail in a Chicago supermarket, but are subject to the data limitations described in section 2.10. The packaging scenarios are the only aspect that varies in the results shown in Exhibit 3-1. Data on the absolute environmental impacts for the three packaging options are provided in Exhibit 3-2.

Packaging fresh tomatoes in PET clamshells has the greatest impact across the four environmental impact categories (global warming, acidification, respiratory effects, and smog). The environmental impacts from packaging fresh tomatoes in PS trays with PE wrapping are five to ten percent lower, and eight to 15 percent lower for loose tomatoes transported in corrugated containers, across the categories shown in Exhibit 3-1. The ranking of the packaging options is similar across the four environmental impact categories in Exhibit 3-1 because these categories are all influenced primarily by the combustion of fuels.

The PET clamshell scenario is the most intensive, primarily because it requires a greater amount of plastic material and because PET manufacture uses more energy per pound than the other two plastics (PE and PS). But it is important to note that the difference between all three packaging options is somewhat modest.

Exhibit 3-1: Relative comparison of environmental impacts of three packaging options for fresh tomatoes delivered to from San Joaquin Valley, California to Chicago, Illinois

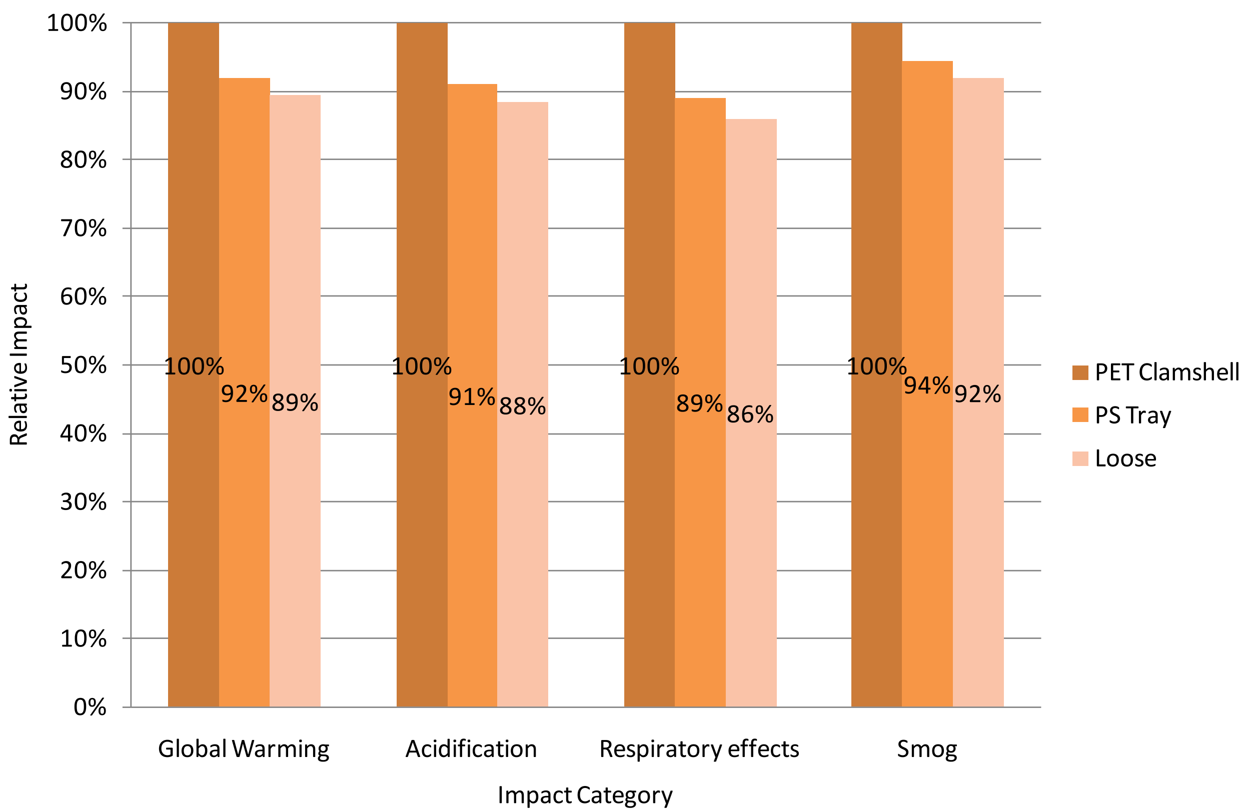
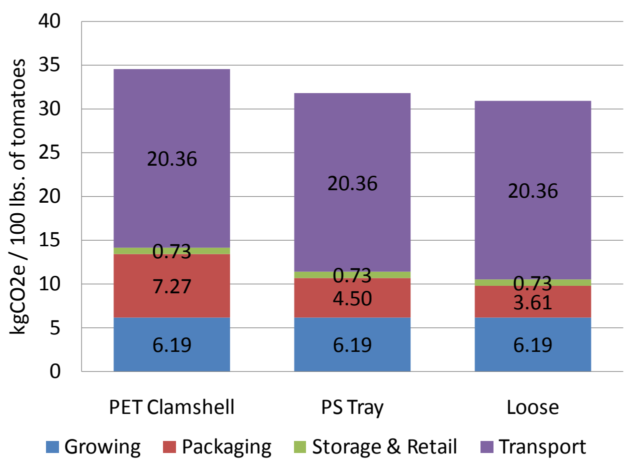


Exhibit 3-2: Environmental impacts of three packaging options for fresh tomatoes delivered to Chicago, Illinois

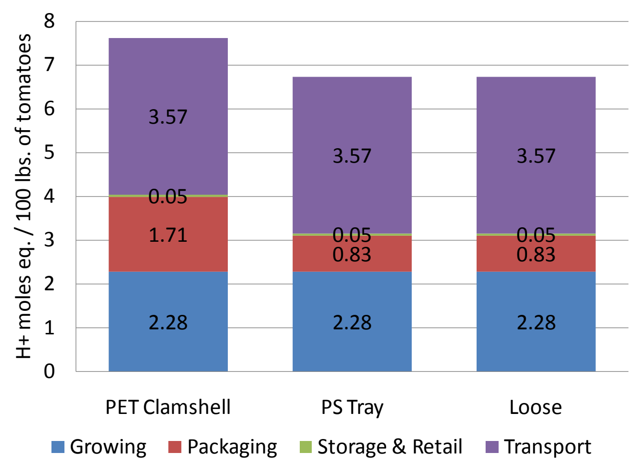
Impact category	**Unit per 100 lbs. of tomatoes**	**PET Clamshell**	**PS Tray**	**Loose**
Global Warming	kg CO2 eq	34.5	31.8	30.9
Acidification	H+ moles eq	7.62	6.94	6.73
Respiratory effects	kg PM2.5 eq	0.0294	0.0262	0.0252
Smog	kg NOx eq	0.104	0.0980	0.0954

Exhibit 3-3 summarizes the contribution of each life-cycle stage (i.e., growing, packaging, storage and retail, and transportation) to global warming, acidification, respiratory effects, and smog impacts across the three packaging scenarios. These graphs include environmental impacts from growing the tomatoes in the field, harvest, packaging manufacture, transportation to wholesale in Chicago, and distribution to retail in a Chicago supermarket.

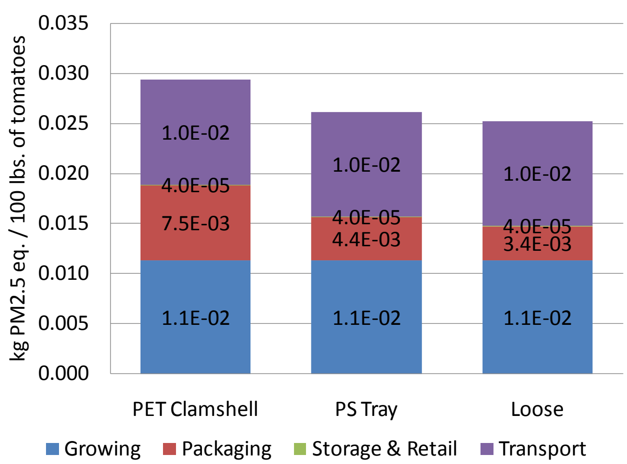
Exhibit 3-3: Environmental impacts, by life-cycle stage, of three packaging options for 100 pounds of fresh tomatoes delivered to Chicago, Illinois



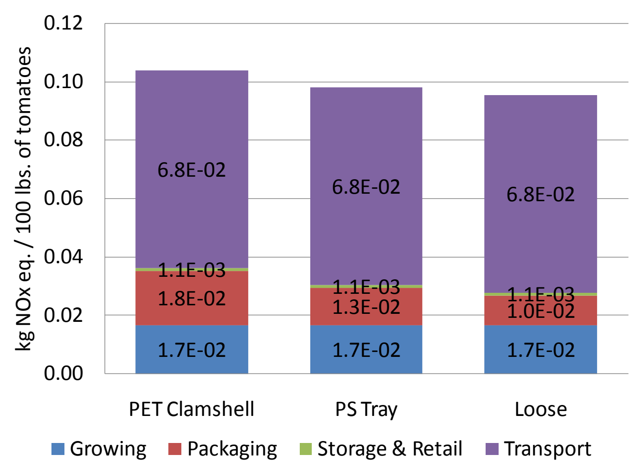
(a) global warming



(b) acidification



(c) respiratory effects



(d) smog

Note change in units on the vertical axis of each graph.

The impact from packaging is surprisingly high across these four impact categories, given the relatively small amount of packaging material used in the packaging of 100 pounds of tomatoes (i.e. 4.5 to 7 pounds of packaging material per 100 pounds tomatoes, depending upon the packaging scenario). This may be a result of the categories assessed, which are driven primarily by emissions from the combustion of fuels used for process heat and electricity in the manufacturing processes. Similar to the results shown in Exhibit 3-1 and Exhibit 3-2, the environmental impacts associated with PET clamshell packaging are the largest of the three packaging scenarios.

Transportation of the tomatoes and packaging from San Joaquin Valley to Chicago contributes to over 50% of the total impact in most categories across the three packaging scenarios. The impacts associated with tomato growing are slightly larger than packaging. Impacts associated with cool storage of the tomatoes after harvest and at the retail store contribute to a very small fraction of the total environmental impact.

Exhibit 3-4 reflects the comparison between the impacts of growing, transport, and storage of the tomatoes to manufacturing the packaging and transporting to retail. The embodied impacts associated with the tomato are typically three times those impacts associated with the packaging. These results are well-supported in the Industry Council for Packaging and the Environment (INCPEN) report “Table for One: The Energy Costs to Feed One Person” where primary and transport packaging comprise 10% of the energy burden for one person’s weekly consumption of food (INCPEN, 2009). These results suggest that we should prioritize activities toward decreasing the impacts of food production, consider sustainable consumption of food, and holistically approach the relationship between packaging and product.

Exhibit 3-6 presents the results for GHG emissions emitted from growing, packaging, storing, transporting (from San Joaquin Valley, California to Chicago, Illinois), and disposing of or recycling the packaging of 100 pounds of loose, fresh tomatoes. The results are presented for each stage of the life-cycle, with each bar comprised by the GHG emissions of the activities within a given life-cycle stage. Presenting the results in this way allows for a clear representation of the major sources of emissions, primarily in the transportation stage, but also in the growing and packaging stages.

Exhibit 3-4: Comparison of environmental impacts of manufacturing and transportation of three different packaging materials relative to growing and transporting fresh tomatoes from San Joaquin Valley, California to Chicago, Illinois

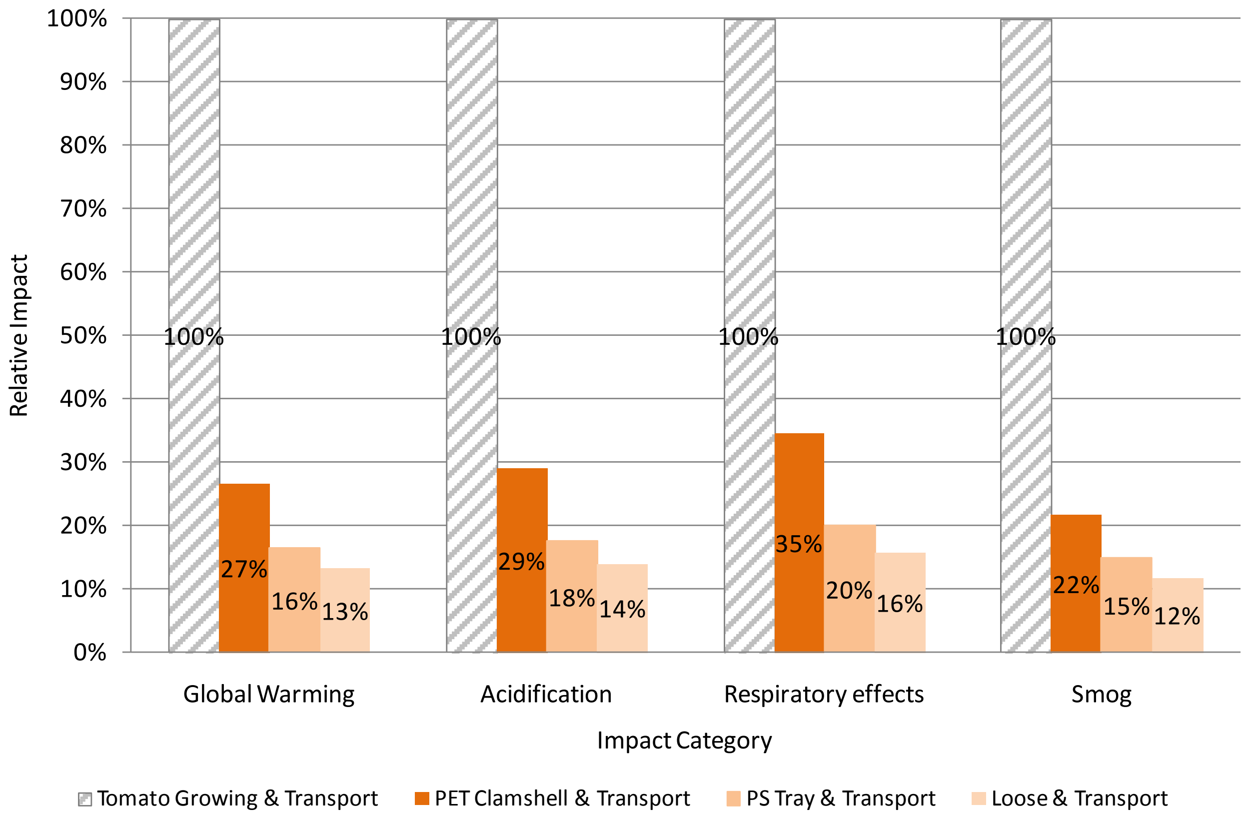
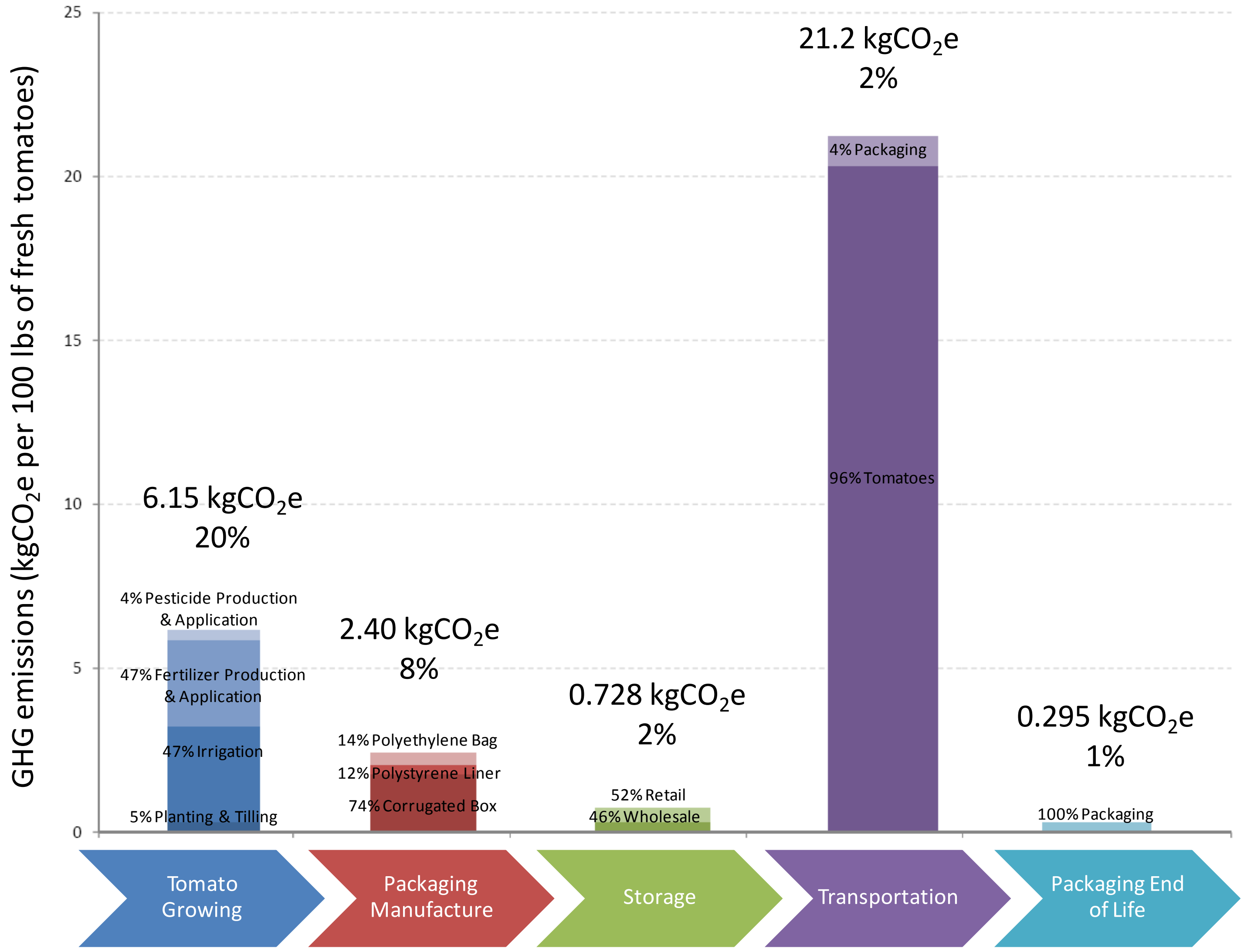


Exhibit 3-5: Environmental impacts of three packaging options for fresh tomatoes delivered to Chicago, Illinois

Impact category	Unit per 100 lbs of tomatoes	Tomatoes & Transport	PET Clamshell & Transport	PS Tray & Transport	Loose & Transport
Global Warming	kg CO2 eq	27.3	7.27	4.50	3.61
Acidification	H+ moles eq	5.90	1.71	1.03	0.828
Respiratory effects	kg PM2.5 eq	0.0218	0.00754	0.00435	0.00343
Eutrophication	kg N eq	0.0124	0.0158	0.01022	0.00734

Exhibit 3-6: GHG emissions from growing, packaging, retail and storage, transportation from San Joaquin Valley, California to Chicago Illinois, and packaging end of life for loose, fresh tomatoes

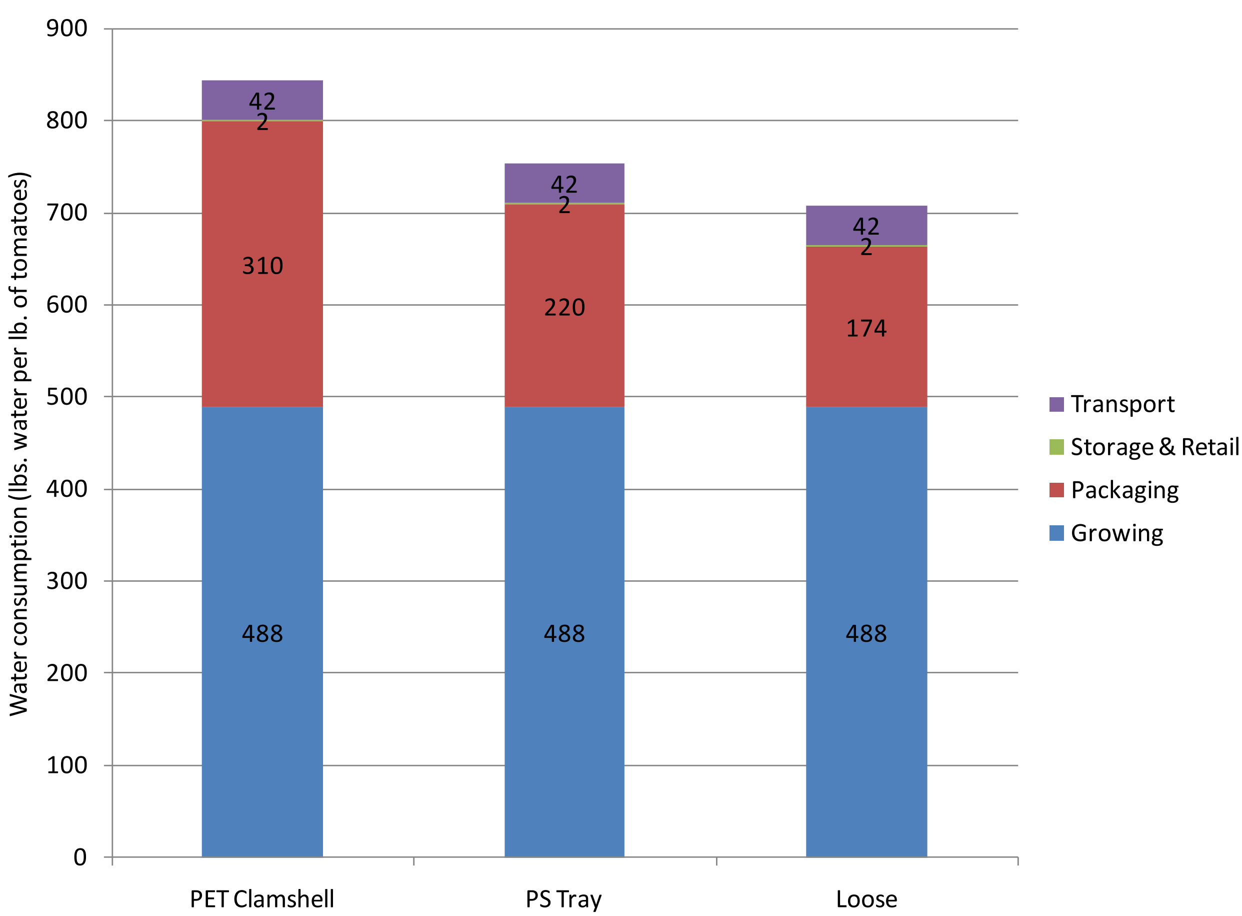


3.2 Results for Water Consumption

Exhibit 3-7 reflects the total amount of water consumed for the three different packaging scenarios of 100 pounds of tomatoes delivered to Chicago, Illinois. The water used during irrigation of tomatoes during the growing phase dominates all three of the scenarios. However, the packaging is still a significant source of water use. This water use is associated with the manufacturing processes of the corrugated box and the hydroelectricity used as part of the electrical grid mix. Transportation (fuel production) and storage contribute small amounts to the overall water use.

Overall, producing one pound of tomatoes requires nearly 500 pounds (58.5 gallons) of water in the growing cycle, 175 to 300 pounds (21-37 gallons) of water for packaging, and 45 pounds (5.3 gallons) of water in storage and transportation.

Exhibit 3-7: Water consumption, by life-cycle stage, of three packaging options for fresh tomatoes delivered to Chicago, Illinois



3.3 Sensitivity Analyses

Impact of Packaging on Spoilage and Shelf Life

Spoilage and shelf-life affect the life-cycle environmental impacts of producing and consuming tomatoes. A high spoilage rate influences the growing phase life cycle impacts because a large quantity of tomatoes must be produced to supply the consumer with a given quantity. For example, Oilver Wyman (2008) states that up to one in seven truckloads of perishables delivered to a store will be thrown out—equivalent to a spoilage rate of 15 percent. Pydynkowski et al. (2008) estimate that the amount of “shrink”, or spoilage, in a given store can be as high as 10 percent. In a recent study by Cuellar et al., (2010), the authors found that over 32% of fresh vegetables are wasted in the United States, based on a 1997 USDA paper (Kantor, 1997). As a result, they concluded that the embedded energy in wasted food accounts for 2% of annual energy use in the United States. Given the high rates of spoilage and the reduction potential from packaging, this impact should be incorporated into full vegetable LCAs.

It is impossible to completely avoid food spoilage and waste, but a goal of this study was to investigate the role that packaging can play a role in reducing spoilage by protecting produce from damage and by extending the shelf life of fruits and vegetables in retail and in consumers’ homes.

For example, Exhibit 3-8 below summarizes estimates of the shelf life of loose tomatoes relative to different types of packaging, including Modified Atmosphere Packaging (MAP) filled with nitrogen (N_2) or carbon dioxide (CO_2), and canned tomatoes. Depending on the estimate, MAP packaging can double or triple the shelf life of tomatoes; canning tomatoes allows for much longer storage times, although direct comparisons between processed tomatoes and fresh tomatoes are difficult due to the different functions of these food products. Note that we did not examine the effect of different gas mixture atmospheres for the PS tray and PE wrap packaging scenario in this analysis. However, the PET Clamshell and PS Tray examples would be considered “passive” MAP. Since fruits and vegetables continue to respire after they are packaged, the CO2 to O2 ratio changes within the wrapped packaging to create a modified atmosphere, limiting presence of O2, without actively changing the gaseous mixture.

Although comprehensive information on the effect of packaging on spoilage rates was not available, we did find evidence that packaging can reduce spoilage in fresh tomatoes. For instance, Marks & Spencer, a grocery store chain based in the UK, indicated that loose tomatoes suffer from a 5.5 percent spoilage rate, while clamshell tomatoes have only 4.4 percent spoilage (Marks & Spencer, 2010).

However, estimates of tomato spoilage as well as shelf life rates vary widely. U.S.-based estimates suggest much higher rates of spoilage in retail: in a study of food loss rates across multiple food products, the USDA found that loose tomatoes have an average spoilage rate of 13.2 percent in retail stores. Food waste in the home is even higher. According to the study, an additional 29 percent of tomatoes brought home from the supermarket are discarded as waste (Buzby, et al., 2009). Exhibit 3-9 presents these varying spoilage rates.

Exhibit 3-8: Estimated shelf life of tomatoes across different packaging options

Material	Type	Description	Shelf life	Source
Plastic	MAP	Not specified	2 weeks	Hui et al. (2004)
Plastic	MAP	N2 atmosphere	3 weeks	Parihar, 2007
Plastic	MAP	CO2 atmosphere	1 week	Parihar, 2007
		Ambient air	1 week	Parihar, 2007
None	Fresh	Refrigerator storage	1 week	Boyer, 2009
Metal	Canned	Opened, refrigerator storage	3-5 days	Boyer, 2009; Northampton County Cooperative Extension (2009)
Metal	Canned	Unopened, pantry storage	1 year	Boyer, 2009; Northampton County Cooperative Extension (2009)

Exhibit 3-9: Spoilage rates for loose tomatoes and PET clamshell-packaged tomatoes

Source	Loose		PET Clamshell	
	Retail	Home	Retail	Home
Marks & Spencer	5.5%	--	4.4%	--
USDA	13.2%	29%	--	--

Spoilage rates have been incorporated to some extent in other tomato LCAs. For example, Andersson and Ohlsson (1999) assumed a five percent product loss in the consumer-use phase for tomato ketchup. To investigate the impact that changes in spoilage rates would have on the overall environmental impact of providing tomatoes to the consumer, we conducted a sensitivity analysis of the global-warming impacts of providing 100 pounds of tomatoes to the consumer at the store.

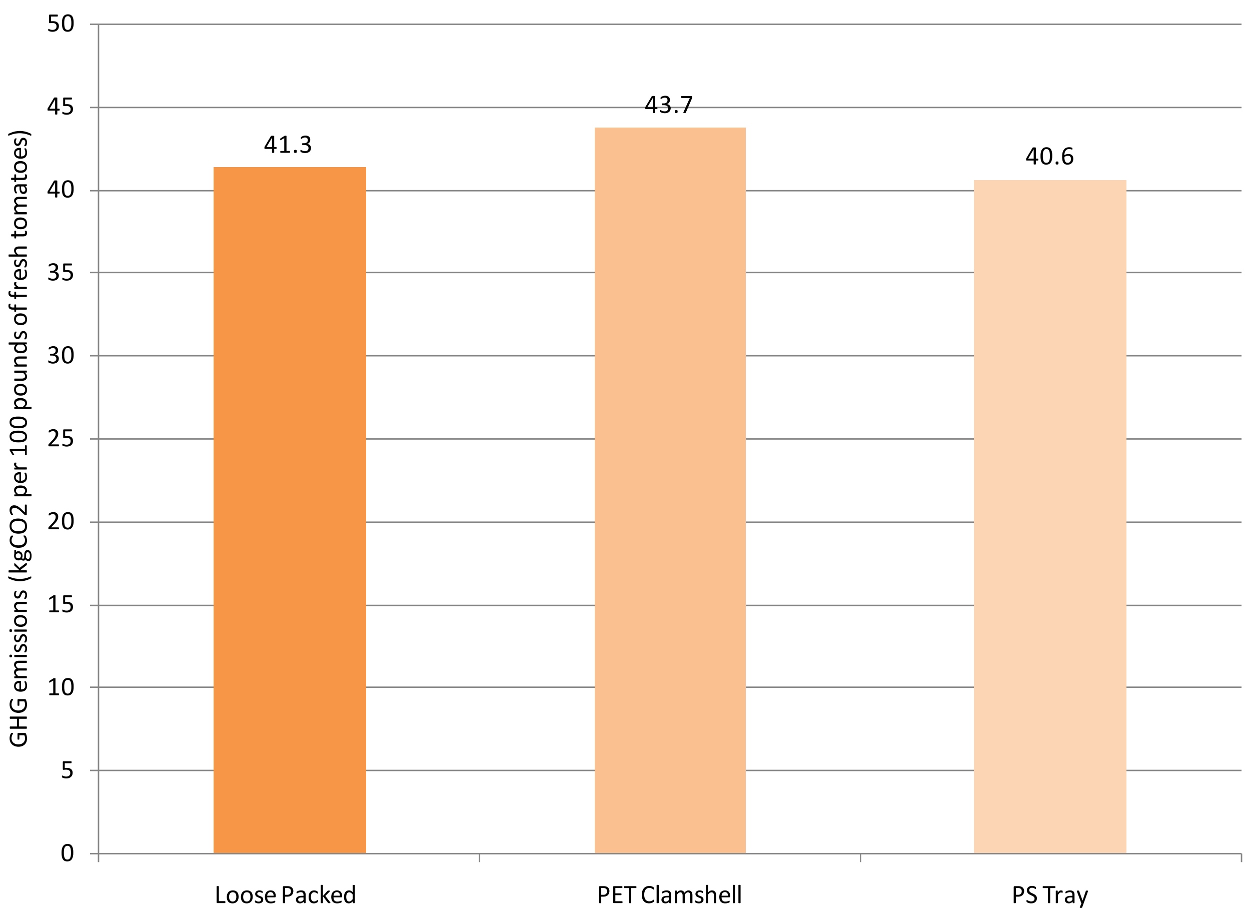
For this analysis, we assumed that, on average 13.2 percent of fresh, loose tomatoes are discarded at the supermarket as waste, based on data from Buzby et al. (2009). As a result, in order to provide a consumer with 100 pounds of fresh tomatoes, the supermarket must stock 115 pounds of tomatoes, since 13.2 percent of the 115 pounds will spoil (i.e., approximately 15 pounds of tomatoes).

Next, we compared the global warming impacts of growing, packaging, and transporting tomatoes in either PS trays or PET clamshell, assuming that these packaging options reduce the amount of spoilage at retail by 2%, based on the estimates provided by Marks & Spencer (2010). As a result, supermarkets will need to stock 113 pounds of tomatoes to provide the consumer with 100 pounds.

In all cases, we assumed that spoiled tomatoes and their associated packaging are sent to landfill at end of life. We included estimates of methane generation in landfills (Barlaz, 1998), but we assumed that carbon dioxide emissions from tomatoes are carbon-neutral (i.e., carbon dioxide emissions from tomatoes are end-of-life are balanced by their uptake of carbon dioxide as they are grown). We included landfill gas capture at the U.S. national average, based on data from the U.S. GHG Inventory (EPA, 2010), but assumed that this gas was flared and did not include an electricity generation offset for energy recovery from captured landfill gas.

As shown in Exhibit 3-10, while packaging with PET clamshell reduces spoilage, the additional GHG emissions associated with producing and transporting the additional packaging are higher than for loose packed tomatoes. In contrast, packaging tomatoes in PS trays decreases spoilage, and the overall GHG emissions—including the production and transportation of the additional packaging—are slightly reduced relative to loose tomatoes.

Exhibit 3-10: Comparison of the effect of packaging and tomato spoilage on GHG emissions. Results include GHG emissions from: growing tomatoes, manufacturing packaging, transporting packaged tomatoes from San Joaquin Valley, California to Chicago, Illinois, supermarket retail, and end-of-life of spoiled tomatoes and packaging



This sensitivity analysis shows that the effect of different packaging options on tomatoes is relatively modest from a life-cycle perspective. Even so, the high rates of spoilage and food waste in the United States suggests that a large portion of the environmental impacts associated with producing and distributing tomatoes may be lost as waste in retail and in the home. As a result, further investigation into options to reducing spoilage and food waste—including the role that packaging can play in reducing spoilage by protecting produce and extending shelf life—is warranted.

Additionally, it is important to note that the results of this analysis were based on very limited data on the rates of spoilage in supermarkets, and the factors that contribute to spoilage of fresh produce. This analysis does provide, however, an example of how adopting a life-cycle perspective can be used to consider the upstream and downstream impacts of packaging decisions on fresh food products. Further research and data development on similar effects of packaging on tomatoes or other types of food products could be used to extend this analysis more broadly.

Transportation

Since emissions from the combustion of fuels in transporting tomatoes from San Joaquin Valley to Chicago accounted for a majority of the environmental impacts of growing, packaging, and delivering fresh tomatoes to the super market, we conducted a sensitivity analysis of transportation distance to determine the effect that distance has on overall environmental impacts.

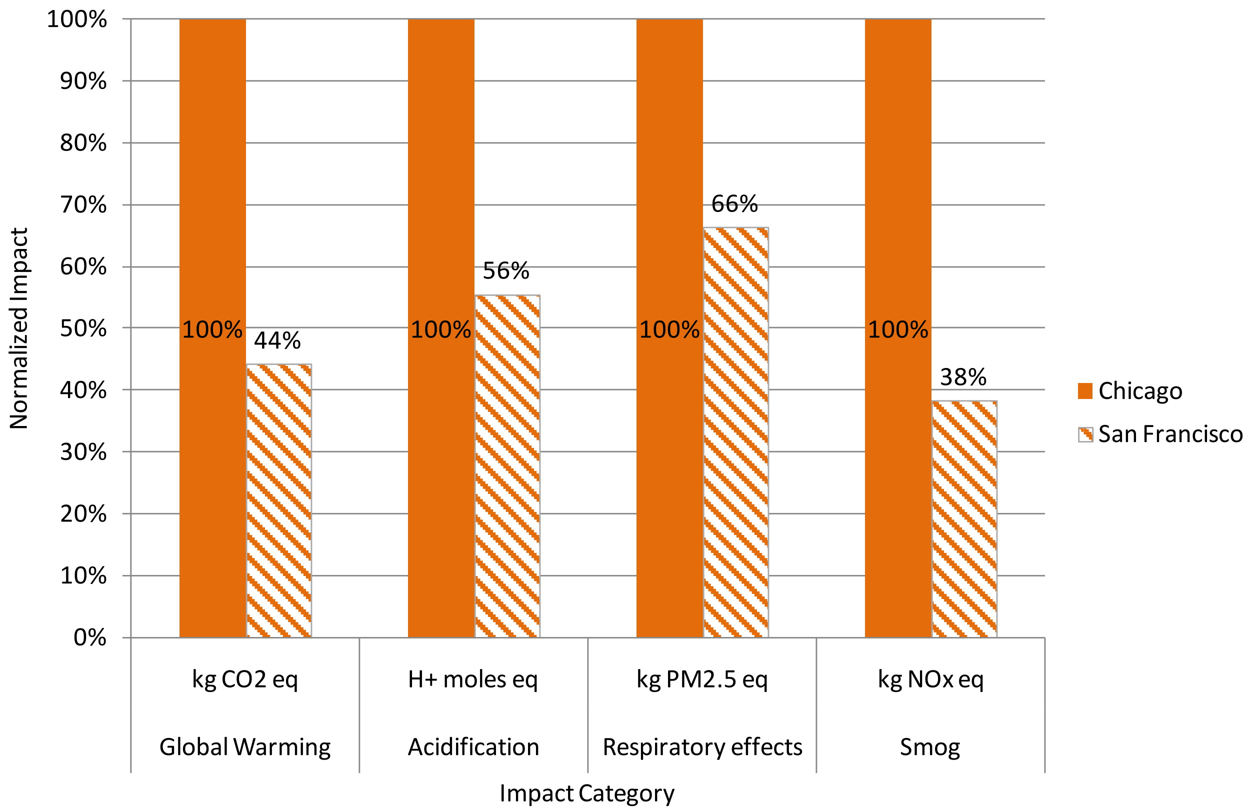
The quantitative results described in sections 3.1 and 3.2 assume transportation from San Joaquin Valley in California to Chicago, Illinois (a total distance of 2,175 miles). We developed a separate scenario for transportation from San Joaquin Valley to San Francisco (total distance of 60 miles) to evaluate the effect of transportation distance on overall environmental impacts. Both transportation scenarios are summarized in Exhibit 3-11 below.

Exhibit 3-11: Transportation scenarios investigated in sensitivity analysis

Scenario	Trip Leg	Departure	Destination	Mode	Distance (miles)
A (default)	1	San Joaquin Valley	Chicago, Wholesale	Combination truck	2,155
	2	Chicago, Wholesale	Chicago, Supermarket	City delivery truck	20
B	1	San Joaquin Valley	San Francisco, Wholesale	Combination truck	40
	2	San Francisco, Wholesale	San Francisco, Supermarket	City delivery truck	20

Exhibit 3-12 summarizes the overall results of the sensitivity analysis. The exhibit shows that the global warming, acidification, respiratory effects, and smog impacts are very sensitive to the distance over which tomatoes are transported. Tomatoes that are grown in San Joaquin Valley and delivered to San Francisco have roughly two-fifths of the smog-forming impact, half of the global warming and acidification impacts, and two-thirds of the respiratory effect impacts of tomatoes delivered to Chicago.

Exhibit 3-12: Relative (i.e., normalized) environmental impacts of growing, packaging, storing, and transporting 100 lbs of tomatoes from San Joaquin Valley to Chicago (Scenario A) or San Francisco (Scenario B) in PET clamshell packaging



The results in Exhibit 3-12 are for tomatoes in PET clamshell packaging, but the relative results are the same across the other fresh tomato packaging options included in this analysis (i.e., tomatoes packaged in PS trays with PE film, and loose tomatoes).

The results of this sensitivity analysis can be compared across the three packaging types and two transportation scenarios to yield insights into the relative sensitivity of the analysis to transportation distance and packaging type. Our analysis, however, is also subject to the following caveats and limitations:

- Although tomatoes may be refrigerated during transport when exterior air temperatures are at, or above, the recommended temperature range for transport, we did not include refrigeration or cooling in transportation of tomatoes. Refrigerated transportation will increase fuel consumption and emit small amounts of refrigerant through "fugitive" leaks in the refrigerant during transportation. Including refrigerated transportation would increase the impacts across the four categories assessed in this analysis, and the relative impacts would increase as transportation distance increases.

- We assumed that tomatoes would be packaged on-site after harvest. To simplify the data requirements and complexity of the analysis, we assumed that tomatoes were packaged on-site, or close to the field where the tomatoes are grown. We did not include transportation for the packaging materials to the tomato growing site. Transportation of packaging materials to the farm or packaging site will not have a major impact on relative comparisons between the three different packaging options as long as the transportation modes and distances are roughly the same for each of the packaging types.

- We modeled truck fuel consumption and emissions using equivalent European heavy-duty truck models available from ecoinvent (Swiss Centre for Life Cycle Inventories, 2008). Equivalently sized European heavy-duty trucks have different rates of fuel consumption and air pollutant emissions than trucks in the United States. Information on U.S. heavy-duty trucks could be used to improve the accuracy of our estimates, but the relative comparisons across packaging types and transportation scenarios are valid since they are calculated consistently across the same set of data.

These results are well supported from other fresh produce studies including a case study on apples, runner beans and watercress which reflects that transportation, and especially air-freight transport, dominate the life cycles of over-seas production of produce. This study also reflects that the electricity requiring phases including grading, packing storage, agro-chemical production and transport dominate local production of produce (Sim, 2007). Broadly this can be interpreted to suggest that when specific crops are in season, the environmental burden is lower by purchasing locally. When crops are out of season, the energy-consuming activities of production and shipping should be done where the best energy profile is achieved either through grid mix or fuel mix/intensity of transport.

4 Qualitative Discussion

While life cycle assessment is a sound methodology for comparisons, it is limited in application by data availability and impact assessment method accuracy. In the spirit of the Sustainable Materials Management report, the project team wanted to assess more than those impact categories supported by a quantitative analysis. Both scientific journal articles and personal interviews were conducted to support the following sections, which discuss other environmental and social considerations that are not measurable due to data gaps and methodological limitations.

4.1 Water Use

The previous section discussed the water used primarily in irrigation and electricity generation. This water is tracked through metering on pipes delivering water to the field or to the manufacturing facility. Information on water including source, quantity, and quality is often missing from LCI data (Mila I Canals, 2009). Life Cycle Impact Assessment (LCIA) methods for water consumption are under development, but are not in wide use. LCA currently does not have the capability to capture regional water issues because LCI data tend to be "site-independent," meaning data sets are not fixed to a geographic location. Water flows associated with the natural water cycle, including precipitation and evapotranspiration, are not included in LCA, but are critical to agricultural processes. As an example, the vegetable sector ranked 4th in water use in the Vision 2020 Report (EPA, 2009a). This is seen as a significant data gap and any robust assessment of water issues with regard to agricultural processes would need to include an in-depth study of the impacts of the process on the natural water cycle and site-dependent linkage of water from specified sources with local water issues.

4.2 Land Use

EPA's report on Sustainable Materials Management (EPA, 2009a) found that the vegetables sector ranked as the 15th-highest sector in land use impacts, distinguishing it as an important impact category associated with the production of vegetables, including tomatoes. In this analysis, we have considered the land area planted with tomatoes—both nationally, and in California—and yield data from fresh and processed tomatoes, but we have not quantitatively evaluated the environmental impacts associated with land use, competition for land use, or land use changes.

A thorough evaluation of land use impacts is difficult due to both methodological and data-availability limitations. A number of methods for quantifying the environmental impacts of land use in LCA have been proposed (see Finnveden et al., 2009 for a list of recent publications), but a common framework has not been established in the field of LCA. A key methodological issue is that there are a number of different land-use aspects associated with land-use activities, inputs from land, outputs to land, and the associated effects on the natural environment, resources, and human society (Udo de Haes, 2006; Finnveden et al., 2009). While certain aspects, such as the surface area required for agricultural activities, are compatible with current LCA methods, other aspects are harder to integrate, or may be appropriately addressed through other life-cycle approaches (Udo de Haes, 2006). Additionally, land use impacts will depend upon site-specific conditions and use characteristics, making it difficult to generalize environmental impacts from land use changes in LCA studies.

In addition to the methodological issues associated with quantifying land use impacts, we were unable to locate sufficient data that would allow a more thorough evaluation of land use impacts associated with tomato production. Further research and methodological development is needed in order to extend the EPA's identification of land use as an important impact category for agricultural products, such as tomatoes and other vegetables.

4.3 Other Environmental Impacts

As data on emissions to air, water and soil were not readily available for tomato production, with the exception of fuels combusted in on-site equipment, several environmental impacts were not analyzed. Eutrophication, the nutrient loading of ecosystems changing species balance and viability, is a significant environmental issue that was not addressed in the quantitative analysis. One of the significant causes of eutrophication is the application of fertilizer in agricultural systems. According to estimates used for modeling nitrogen emissions from agricultural systems, agricultural processes (both crop and animal production combined) are responsible for up to 87% of ammonia (NH_3) emissions globally and 47 percent of nitrous oxide (N_2O) emissions globally (Brentrup, 2000). These emissions are difficult to track due to their variability influenced by soil type, climatic conditions, and agricultural management practices. Accurate measurements would require both considerable time and financial resources, and so models are typically used for estimation rather than actual measurements.

To investigate the sensitivity of our GHG emission results at the growing stage, we conducted a screening analysis using the Carbon Trust's Footprint Expert Crop Calculator (Carbon Trust Footprinting Company, 2008); a tool that calculates the GHG footprint of agricultural crops in accordance with IPCC guidelines for national GHG inventories (IPCC, 2006). The analysis showed that N_2O emissions from applying synthetic fertilizer to tomato fields could increase GHG emissions at the fresh tomato growing stage by 30 percent, or a 1.8 $kgCO_2e$ per 100 pounds of fresh tomatoes (in addition to our current estimate of 6.2 $kgCO_2e$ per 100 pounds of fresh tomatoes). This is obviously a significant data gap that would need to be addressed before the results of this study could be used to support decision-making with regards to packaging or tomato production.

Another missing impact, commonly included in LCA studies, is human and eco-toxicity. Again, this assessment was removed from the analysis due to limits in the emissions to air and water inventory data. Pesticides, herbicides, and fungicides are all used in the tomato production processes. Given the generality of the USDA data, specific chemicals were not disclosed in the available data. Another complicating factor is that toxicants tend to be used in smaller quantities and are not reported well in LCI data, which typically consider mass material and energy flows of systems. If specific data were obtained on the pesticides, herbicides, and fungicides used in the tomato growing process, a risk assessment could be conducted to estimate exposure levels for the farm worker or average consumer.

4.4 Other Human and Social Impacts

In addition to the direct life-cycle impacts from the packaging process and packaging's impact on spoilage and shelf-life of tomatoes, packaging may have social impacts or be dependent on social norms that indirectly affect the full life cycle of the tomato.

Packaging options may affect the frequency of shopping trips and/or the consumer's use of secondary or tertiary packaging to transport tomatoes from the stores to the home. Consumer transport requirements may be reduced if a given type of packaging significantly increases the shelf-life of tomatoes. For instance, if one form of packaging doubles shelf-life, then a consumer could buy twice the quantity at one time and eliminate every other trip to the store. This change in local transport at the consumption stage is likely to be small compared to the life cycle impacts from the tomato growing, packaging, and distribution phases, and is not considered in the quantitative analysis.

Various types of packaging may also induce consumers to use multiple packaging. This study examines the packaging used to make tomatoes ready to sell at the grocery store. However, consumers may be more likely to place certain types of packaged tomatoes in a secondary package such as plastic produce bags. The consumption of these additional packaging items is not considered in this analysis[2], as it is expected to vary widely by store, community, and larger region, and no data clearly indicate the frequency and extent of consumer use of this additional packaging.

Just as packaging types may impact consumer behavior, consumer satisfaction and demand rather than environmental benefits may drive a retail outlet's choice of packaging. For instance, according to Pactiv representative, Kevin Grogan, grapes sold in markets historically were not

[2] The polyethylene bags used to take home loose tomatoes was considered in the "loose" tomato scenario, however the possibility that a consumer would put a Polystyrene tray of tomatoes into a second bag was not considered.

bunched together in plastic bags. However, consumers began pulling grapes off, squishing them on the floor, and then suing grocery stores after pretending to slip on the grapes. After a number of copycat lawsuits in the 1990s, suppliers began bagging grapes to avoid these legal battles (Grogan, 2010).

Further, consumer preferences may depend on various non-environmental cultural indicators such as hygiene or visual appeal. The former sustainability manager for Albertson's Grocery store chain, Cynthia Forsch, suggested that in some areas such as NY and Florida, people consider loose fruit as "dirty" and would therefore not buy it. Instead, people opt for tomatoes placed in Expanded PS trays which are then shrink-wrapped. In these regions, the perception of hygiene is more important than spoilage or shelf-life, although we did find evidence that packaging—specifically PET clamshell packaging rather than PS trays—may also reduce tomato spoilage rates (Forsch, 2010). Reggie Brown, manager of the Florida Tomato Committee also noted that the way in which produce is merchandised to the consumer can play a more important role in packaging decisions than concerns about preservation (Brown, 2010). Companies may also choose certain types of packaging to boost their advertising efforts. Plastic clamshells, for instance, provide a convenient opportunity for marketing directly on the packaging.

This study does not evaluate the extent to which these social considerations impact the overall lifecycle of tomatoes. However, previous LCA literature has highlighted the potentially significant environmental impact at the consumption phase from individual behavior (Jungbluth et al., 2000).

The point of tomato spoilage after the growing phase is a contentious economic issue within the life cycle of the tomato that could influence future choices of packaging and the overall life cycle impacts. Specifically, Reggie Brown of the Florida Tomato Committee indicated that the amount of tomato spoilage in the transport phase is likely very low, since there is an economic incentive to provide packaging that protects the product (Brown, 2010). In contrast, retail store representatives indicated that there is no financial mechanism to control in-transit spoilage. Retailers can claim damage only on boxes worth at least $25, which is higher than the value of tomato or other produce boxes. As a result, retailers essentially pay for any transit damages themselves (Forsch, 2010). It is unclear who is actually responsible for any spoilage of tomatoes in transit, or exactly how significant this shrink may be. These uncertainties are not considered in the quantitative analysis.

An additional and potentially significant life cycle impact not considered in the quantitative assessment is human excrement. Munoz et al. (2010) examined the impact of human excrement in a typical Spanish diet, which includes tomatoes. Results of this full life-cycle study indicate that, although food production is the major source of emissions, human excretion along with further wastewater treatment is not a negligible process in eutrophication or global warming potential (GWP) impact categories. In fact, human excretion contributes 17% of the overall emissions in these sectors. Since the environmental impacts from human excretion of consumed food is separate from food packaging decisions, these impacts were not included in this study, although it is important to note that impacts at this life-cycle can be significant.

Finally, social indicators, such as worker health, wage rates and hours, company behavior and treatment of workers, and other related concerns associated with tomato growing and packaging are not considered in the quantitative analysis. However, there is increasing discussion within the LCA community about incorporating social indicators into LCAs either quantitatively or on a qualitative basis (Andrews, et al., 2009). These issues may be relevant to this tomato analysis at the packaging stage, since worker conditions may vary by type of packaging.

4.5 Study in Context

The analysis conducted as part of this study found the GHG footprint of producing, transporting, and retailing a 4-ounce serving of a tomato to be 0.17 lb CO_2e. As mentioned in the introduction to the report, several meat and dairy studies are currently being conducted within the United States. Preliminary results from a LCA on pork products indicate that 2.2 lb of CO_2e are produced for every 4-ounce serving of pork. This study includes inputs and emissions from the following life cycle phases: nursery to finish of the pig, sow barn (including feed and manure handling), processing, packaging, retail (electricity and refrigerants), and consumer (refrigeration and cooking) (Smith, 2010). Another set of preliminary results from a recent study on the dairy industry reflects that 1.1 lb CO_2e are generated for an 8-ounce serving of milk in the U.S (University of Arkansas, 2010). While the boundaries, methods, and data of these studies differ from those utilized in this analysis, this comparison supports the assertion that animal-derived food products cause greater environmental impacts than solely plant-based food.

A study completed by the Department for Environment, Food and Rural Affairs (Defra) in the United Kingdom calculated the greenhouse gas emissions associated with a number of agricultural and horticultural commodities. In this study, a 4-ounce service of tomatoes was found to have a GHG footprint of 2.35 lb CO_2e (Williams 2006). It should be noted that these tomatoes were grown in a greenhouse for their entire life, a more energy-intensive process than field growing tomatoes. A study conducted in Sweden in 2003, reflected a twelve-fold difference in the energy inputs to field grown tomatoes versus greenhouse grown tomatoes (Carlsson-Kanyama 2003). Using this multiplier toward our results of 0.17 lb CO_2e per 4-ounce serving would suggest a 2.04 lb CO_2e per 4-ounce serving of tomatoes grown in a greenhouse in the United States.

Finally, we compared our results at the tomato growing stage against the Carbon Trust Footprinting Company's Crop Calculator (2008). As described in section 4.3, the Crop Calculator calculates the GHG footprint of agricultural crop production based on IPCC good practice guidelines for national GHG inventories (IPCC, 2006). Using the same data inputs outlined in section 2.3, the Footprint Expert Crop Calculator estimated that growing 100 pounds of fresh tomatoes would emit 7.06 kgCO_2—a 14 percent increase compared to this study's estimate of 6.20 kgCO_2per 100 pounds of fresh tomatoes. This difference is likely driven by two differences: first, the Crop Calculator does not include an input for the irrigation of crops, which are included in this analysis; second, the Crop Calculator includes N_2O emissions from synthetic fertilizer applications, which account or 25 percent of the final footprint. As explained in section 2.9, apart from the combustion of fuels in on-farm machinery, no air or water emissions from the tomato growing stage were included in the dataset.

Another interesting study that highlights sustainable materials management and identifies food production as a significant focal area was recently conducted by Green Seal as part of their development of a certification for the Restaurant Industry known as GS-46. "Eating and Drinking Places" ranked high in the Vision Report analysis for several of the final consumption impact categories including Eutrophication Potential (2nd), Terrestrial Ecotoxicity Potential (2nd), Land Use Change (2nd) and Global Warming Potential (4th). In Green Seal's study they found that food procurement was the most significant contributor to the restaurant industries' environmental profile across several impact categories. This led to the development of a standard that focused guidance on food procurement and source reduction as a hotspot area, including in-restaurant waste audits to reduce the amount of food left on a consumer's plate and thus less upstream purchase of food. This study is a good example of how life-cycle thinking can be applied to focus areas of activity toward the greatest reduction in environmental impacts (Baldwin, 2010).

5 Conclusions

This study applies the recommendations from the Vision 2020 Report (EPA, 2009) to food packaging in order to deepen our understanding of the environmental impacts of packaging related to the delivery of produce. Following on the Report's recommendation to "select a few materials/products for an integrated life-cycle approach, and launch demonstration projects", this study evaluates the environmental impacts of fresh tomatoes packaging options from a life-cycle perspective, including the stages of growing, packaging , transportation, storage, and retail.

Although this study applies LCA as a tool, it is not an ISO-compliant LCA and should not be used to support any claims or to make definitive choices with regards to packaging or product design. Instead, this study provides a framework for the evaluation of packaging from an integrated perspective that considers not just the impacts associated with the production of packaging itself, but also the effects on packaged product as well.

Consequently, the results of this study inform four broad categories of conclusions. First, that the method and framework established by this study promote a sustainable materials management perspective of the environmental impacts associated with food packaging. Second, the results enable us to identify potential areas of significant environmental impacts associated with fresh tomatoes and three packaging options. Third, this study illustrates several advantages to adopting a life-cycle perspective to evaluate sustainable materials management options. Based on these conclusions, and the data gaps and limitations that we identified in this assessment, we recommend specific areas for improving upon and extending this analysis. These four conclusions are discussed in further detail as follows:

1. **This study contributes to a shift towards sustainable materials management by:**

    a. Evaluating the environmental impacts associated with different packaging options from an integrated perspective of food production, packaging, and delivery. This involves evaluating not just the direct impacts from manufacturing different types of packaging, but also the effect of different packaging options on the final packaged product, its use, and disposal. For example, evaluating packaging's effect on spoilage rates and how spoilage influences life-cycle environmental effects from growing and delivering food.

    b. Assessing environmental impacts from a life-cycle perspective. Instead of addressing impacts from "siloed" economic sectors such as agriculture, transportation, manufacturing, and retail/buildings, this study evaluates the impacts from a cohesive product life-cycle starting at fresh tomato growing to point of sale to consumers, and including the end-of-life disposal of packaging.

c. Extending the analysis to a number of different environmental impact categories that provide information relevant to EPA efforts to reduce GHGs, reduce air pollution, conserve water, and reduce material use. If the budget and time to collect primary data were provided, this study's framework could be extended to analyze toxic chemical impacts, eutrophication and nutrient management, and land use considerations. In addition, there are currently methodological issues in assessing the full range of water and land use impacts from a LCA perspective. Practitioners are actively involved in developing approaches to evaluate these impacts more comprehensively.

d. Applying LCA tools and thinking to characterize the materials inputs and processes specific to the life-cycle of fresh tomatoes, and the environmental impacts of these activities.

e. Developing approaches for collecting and compiling LCI data from existing USDA databases. As was demonstrated in this study for certain inputs to the tomato process (e.g., fertilizers, pesticides, water use), it would be possible to synthesize existing USDA and state-level data to quantitatively evaluate environmental impacts for agricultural crops, although a thorough review and assessment of the data availability for other impacts was beyond the scope of this analysis. This provides an example of how existing information that is not yet integrated into LCI databases can be used to develop or augment LCI data. This is particularly useful in a U.S.-context, where there is currently a lack of LCI data, particularly with respect to agricultural products.

2. **This study finds that the following are significant impacts associated with the production and packaging of tomatoes:**

    a. The contribution of transportation to global warming, acidification, respiratory effects, and smog impacts are sizable, and may dominate the impacts from other life-cycle stages at longer distances. A sensitivity analysis confirmed that the magnitude of transportation's environmental impacts across these categories varies greatly, depending on total transportation distance.

    b. The impacts associated with producing and transporting packaging for tomatoes are surprisingly large relative to the impacts associated with growing tomatoes, especially considering the relatively small amount of material required to package tomatoes. This result is assumed to be different if the tomatoes were greenhouse grown instead of field grown. We have also identified a number of data gaps in this analysis, primarily at the growing stage, which would need to be addressed in order to verify this finding.

c. The changes in impacts across the packaging options considered in this study were relatively modest. Of the three options, the impacts from producing PET clamshell packaging were greater than PS trays and loose tomatoes in terms of global warming, acidification, respiratory effects, and smog impacts.

d. Producing, packaging, and distributing tomatoes require large inputs of water, particularly at the growing and packaging stages. Growing, packaging, and transporting one pound of tomatoes to the supermarket requires between 700 to 850 pounds (80-100 gallons) of water. The largest sources of water consumption were irrigation at the growing stage, and the use of water in generating electricity used in the production of corrugated containers and other packaging materials.

e. There is evidence that packaging can influence the quantity of tomatoes discarded as waste due to spoilage before sale to the consumer. We located a number of estimates suggesting that plastic MAP packaging can increase the shelf life of tomatoes, potentially reducing the amount of fresh produces that spoils in the retail store. It was less clear whether the type of packaging influences the quantity of tomatoes damaged in transport, as we received conflicting accounts from industry experts.

f. A sensitivity analysis of the effect of packaging on the life-cycle GHG emissions of tomatoes demonstrated that different packaging options could increase or reduce life-cycle GHG emissions, depending on the emissions associated with producing the packaging, and the effect that packaging has on reducing spoilage before the tomatoes are sold to consumers.

g. Other considerations that are relevant to packaging decision-making include: product marketing and merchandising, hygienic or visual appeal of the product, the influence of packaging and shelf life extension on consumers' trips to the store, and in inducing consumers to use additional packaging.

h. The impacts associated with cool storage of the tomatoes after harvest and at retail are minor compared to the other life-cycle stages.

3. **By applying tools of LCA to evaluate the impacts of packaging options for tomatoes, this study has illustrated the following advantages to a life-cycle approach:**

a. Evaluating as full a range of environmental impacts as possible allows the assessment to inform multiple EPA programs and priorities. For example, the results of this demonstration project are relevant to EPA's work in areas such as Design for the Environment (DfE, http://www.epa.gov/dfe/), Green Chemistry (http://www.epa.gov/gcc/), Resource Conservation (http://www.epa.gov/epawaste/conserve/rrr/index.htm), Lean Manufacturing (http://www.epa.gov/lean/), EPA's Sustainable Products Network (SPN), as well as EPA partnerships through groups such as the Sustainable Packaging Coalition (SPC).

b. The life-cycle perspective enables policy makers to assess trade-offs in environmental impacts along the life-cycle. This helps ensure that environmental impacts are assessed holistically and reduces the risk of missing important impacts or inadvertently shifting impacts from one stage or sector to another. For example, in evaluating the effect of packaging on spoilage rates we were able to identify which packaging scenario reduced overall environmental impacts relative to loose fresh tomatoes in cardboard containers.

c. Finally, LCA can identify hot spots and areas for further investigation. For example, we found that transportation contributed significantly to life-cycle impacts across several categories. In a sensitivity analysis, we were able to show the extent to which these impacts could be mitigated by reducing transportation distance.

4. This study established a framework that can be improved and extended:

a. The data gaps and limitations included in this study can be improved upon by:

i. Gathering further data on other impact categories, including eutrophication, carcinogenics, non-carcinogenics, ozone depletion, ecotoxicity, land use, and social LCA considerations. Quantifying these environmental impacts may require developing models to accurately assess the inputs and outputs from the system; for example, modeling the flow of nutrient inputs to tomatoes at the growing stage to evaluate eutrophication or N_2O emissions from the application of fertilizers.

ii. Supporting efforts to improve LCA methodologies or other life-cycle tools that evaluate hard-to-quantify aspects of water and land use environmental impacts, and social impacts.

b. The framework and results from this study can also be extended to evaluate:

i. Other packaging options, such as processed tomato packaging in steel cans, glass jars, or aseptic containers. We have included additional data on processed tomatoes (as opposed to fresh tomatoes) in Appendix A to serve as a starting point for evaluating these options in further work.

ii. Identifying additional data sources and using information from literature, industry experts, or other resources to include greenhouse tomatoes, or tomatoes grown in other parts of the United States (e.g., Florida, another major producer in the United States).

iii. Extending the analysis to include other vegetables. For example, assessing carrots (a relatively hardy vegetable with a longer shelf life than tomatoes) or spinach (a vegetable with a short shelf life and number of fresh and processed packaging options, similar o tomatoes) alongside the tomato analysis. We have included information from the literature survey we conducted on these three vegetable types in Appendix A.

iv. Evaluating other packaging-product systems outside of produce from an integrated life-cycle perspective.

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Appendix A: Additional Analyses

Due to time, data, and budget constraints, this project was only able to address one vegetable type (i.e., tomatoes), and focused only on fresh tomatoes and their associated packaging options. There are two directions that could be explored in further work that would leverage and extend the existing work completed to date. One direction would be to analyze processed tomatoes and the associated packaging, like diced tomatoes in steel cans, aseptic (pouch or carton) containers, and glass jars. The second direction would be to analyze other types of vegetables and their associated packaging; for example, examining vegetables with a longer shelf-life, such as carrots, as a counter-point to tomatoes.

The next two sections provide an outline of work developed in these two directions and list data sources identified during the initial research of this project. This information is provided to support further exploration on the relationship of vegetables and packaging in sustainable materials management.

Processed Tomatoes

While primary and secondary data on the packaging types associated with diced tomatoes (processed) was available, the life cycle data for the actual processing of the tomatoes was not readily available. Information on processing descriptions, possible life-cycle data sources, and packaging data were identified and included below. Also, cursory research on the issue of Bisphenol-A (BPA) in can linings was conducted and articles purchased to support this section.

Processed Tomato Descriptions

After tomatoes reach a processing plant, they are typically canned whole, diced, or pureed, or they are frozen. Tomatoes that will be canned are first graded on color, firmness, defects, and size. They are then washed thoroughly in order to remove contaminants. Most often tomatoes are soaked for several minutes in large tanks with paddles or aeration that agitates the tomatoes and loosens any dirt. A final rinse removes remaining debris.

Next the tomatoes are machine sorted, typically using a photoelectric sorter that removes green tomatoes before peeling, and pink tomatoes after peeling. In the past, tomatoes were cored by machine after being sorted. However, since tomato varieties are now bred with very small cores, this step is no longer needed. Instead, after sorting, the tomatoes are peeled using a steam or lye process. In California, most peeling is done by steam: fruit are placed on a moving belt and passed through a steam box under high temperatures. Waste peels that are produced can be used as fertilizer or animal feed or processed into other products. Tomatoes in the Midwest are typically peeled by passing them under jets of hot lye (sodium hydroxide) or through a lye tank. The lye effectively breaks down the skin cells by dissolving the cuticular wax and hydrolyzing the pectin, at which point the skins fall off. Potassium hydroxide is sometimes used instead of lye. Steam peeling results in a higher tomato yield, but removes much less of the peel than lye. After each of these processes, the tomatoes pass through a series of rubber disks or a rotating drum under high-pressure water sprays to remove any adhering peel.

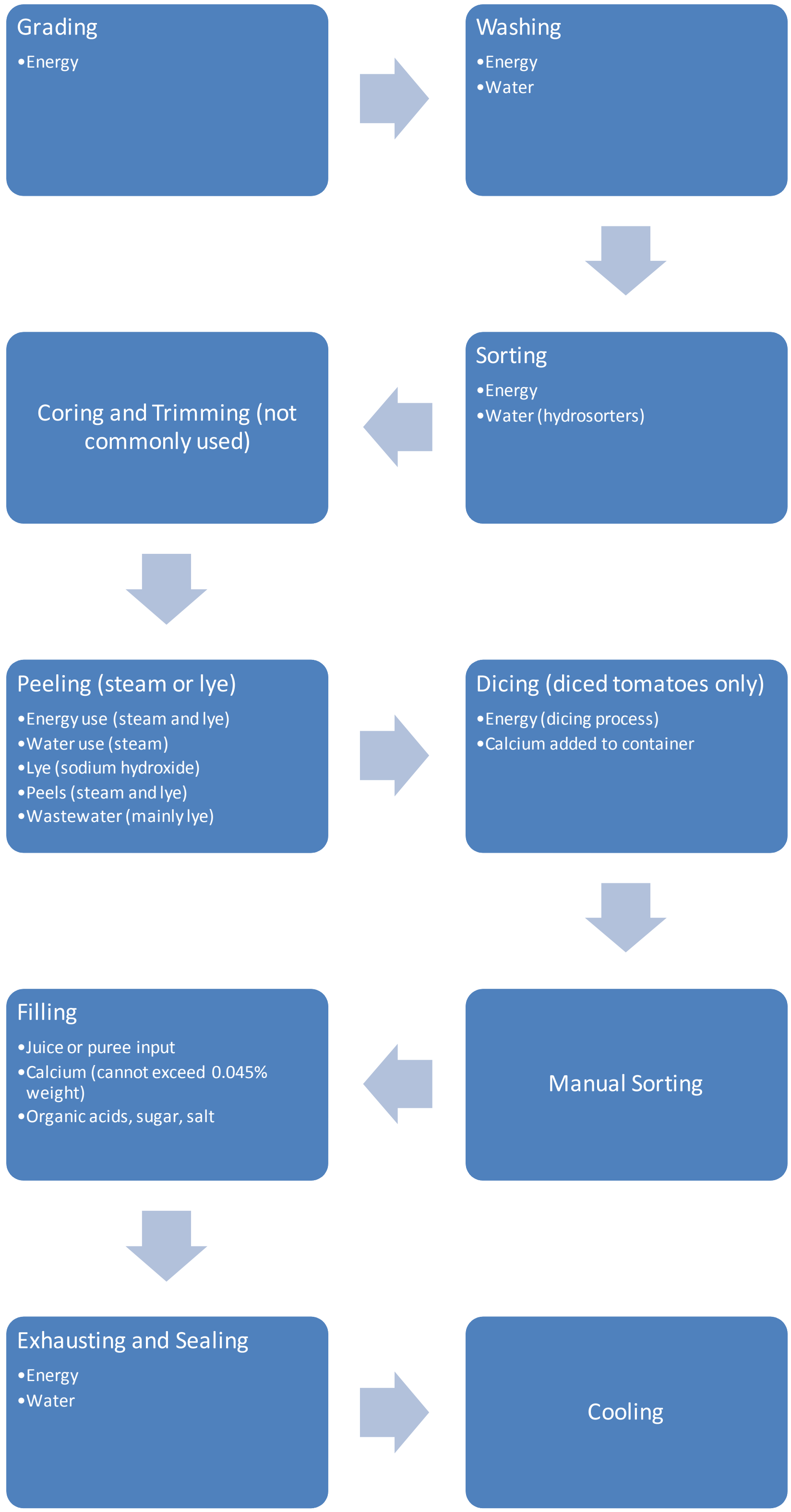
Before filling into cans, tomatoes are manually sorted to remove any rotten parts, and diced and inspected for green or blemished dices if appropriate. They are then heated and packed in enameled cans and lids. FDA standards of identity require that some form of tomato juice or puree be used as the packing medium in the container. In addition, a small quantity of calcium (not to exceed 0.045% by weight), organic acids (such as citric acid), sugar, and/or salt may be added. As the can is sealed, steam is injected into the top. Once sealed, the cans are cooled by chlorinated water or air to 100 degrees Fahrenheit before being shipped to stores. Canned tomatoes typically have a shelf-life of 18-24 months.

The LCI data collected for processed tomatoes are provided in Exhibit A-1. Exhibit A-2 provides a process flow chart for the steps involved in tomato processes.

Exhibit A-1: Annual inputs for processed tomatoes grown in California

INPUT	ANNUAL INPUT	DATA	SOURCE
Acres Planted	acres	283,000	USDA 2010
Acres Harvested	acres	282,000	USDA 2010
Yield	short tons	36	USDA 2010
Production	short tons	10,104,000	USDA 2010
FERTILIZERS- data for entire CA acres planted			
Nitrogen	1,000 lbs	52014.6	USDA 2007
Phosphate	1,000 lbs	20407.1	USDA 2007
Potash	1,000 lbs	9445.2	USDA 2007
Sulfur	1,000 lbs	1807.7	USDA 2007
PESTICIDES- data for entire CA acres planted			
Herbicide	1,000 lbs	362.1	USDA 2007
Insecticide	1,000 lbs	426.3	USDA 2007
Fungicide	1,000 lbs	6669.2	USDA 2007
Other	1,000 lbs	1453.6	USDA 2007
IRRIGATION WATER			
Irrigation Water Use	m3 per acre	3675.78	California Department of Water Resources 2001

Exhibit A-2: Process diagram for processing processed tomatoes after growing



BPA Migration

Bisphenol A (BPA) is a widely-used compound used in the manufacture of polycarbonate plastics and epoxy resins. Studies have shown that BPA, a systemic toxicant and endocrine disruptor, has reproductive and developmental health implications (EPA 2010). Since the public is exposed to BPA through consumer food product packaging, and especially given its presence in children's formula bottles and canned foods, the potential health and environmental impacts of BPA have become a serious concern.

BPA is present in the tomato life cycle through the lining of steel cans used to package processed tomatoes. Processed food from cans is a source of BPA exposure, as the substance can leach from the lining into the ingested food product (FDA 2010). Studies have investigated whether BPA migration is caused by storage conditions such as shelf time, heat, or can damage. Goodson et al. (2004) and Cao et al. (2009) both concluded that storage conditions do not change BPA levels significantly, indicating that most migration (80-100% of BPA from coating) occurs during the canning processing stage under high heat sterilization. Few alternative can lining materials are available for processed tomatoes due to their high acidity which breaks down vegetable-based resins.

Given the health and environmental concerns on the effects BPA exposure, federal and state governments have begun investigate the issue. The U.S. Environmental Protection Agency (EPA) has identified BPA on the Concern List under the Toxic Substances Control Act (TSCA). While the EPA has taken steps to address then environmental concerns of BPA, the Food and Drug Administration (FDA) has addressed human health effects through re-assessing established safety levels, pursuing further research in scientific findings and supporting efforts to replace or minimize BPA levels in food can linings (FDA 2010). State governments have also taken action on their own to impose legislation regulating BPA in consumer products. Connecticut, Minnesota, Wisconsin, Washington, Chicago, and Suffolk County, N.Y., have all banned the sale of polycarbonate baby bottles, food containers, and cups that contain BPA in an effort to reduce infant exposure levels (EPA 2010).

Other Vegetables

The original proposal indicated that one or more vegetables could be studied for this demonstration project. The team identified three possible vegetables during the preliminary literature search and based on a multiplicity of packaging types: tomatoes, spinach, and carrots. Because of the lack of life cycle inventory (LCI) data on agricultural processes, entire data sets had to be developed for this project. This limited the amount of resources available for data development of other vegetables. The following section outlines information found on spinach and carrots in the preliminary literature search which could be used toward further analysis.

Initially, we contacted industry experts and conducted a preliminary review of available literature to identify the three candidate vegetables for this analysis: tomatoes, carrots, and spinach. These vegetables were selected because each: (i) provides a number of packaging options that allow for a wide range of potential packaging alternatives to be assessed in the comparative assessment; (ii) has a "no packaging" option (i.e., sold as fresh produce); and (iii) a preliminary assessment indicated that it was likely that sufficient LCI data could be compiled to conduct an analysis of food packaging impacts, although data gaps were identified for the vegetable options.

Next, we conducted a detailed literature survey using several bibliographic databases, including: AGRICOLA, CAB Abstracts, Biosis Previews, CA SEARCH – Chemical Abstracts, Food Science and Technology Abstracts, and EMBASE (a comprehensive biomedical database). Each database was searched using three different search categories:

1. [vegetable name] and packaging and shelf life impact keywords
2. [vegetable name] and packaging and LCA environmental impact keywords
3. [vegetable name] and LCA environmental impact keywords

Where [vegetable name] was replaced with each of the three candidate vegetables: tomatoes, carrots, and spinach. This detailed survey produced a number of academic articles on packaging and vegetable shelf life, LCAs of vegetables and packaging, and research on BPA. Titles of the most-relevant articles located are summarized in Exhibit A-3.

Exhibit A-3: Summary of the titles of the most-relevant articles located in the detailed literature survey, sorted by search term topic and vegetable

Search Term Topic	Spinach	Tomatoes	Carrots
Packaging effects on food quality, shelf life	• Microbial and quality changes in minimally processed baby spinach leaves stored under super atmospheric oxygen and modified atmosphere conditions • Retention of folate, carotenoids, and other quality characteristics in commercially packaged fresh spinach • Shelf life of fresh-cut spinach as affected by chemical treatment and type of packaging film • The antioxidant activity and	• Quality changes in fresh cut tomato as affected by modified atmosphere packaging • Maintaining quality of fresh-cut tomato slices through modified atmosphere packaging and low temperature storage • Storage studies of tomato and bell pepper using eco-friendly films • Effect of packaging methods on the shelf life of tomato (Lycopersicon esculentum Mill.). • Handbook of vegetable	• Improving the health-promoting properties of fruit and vegetable products • Effect of modified atmosphere packaging on the quality and shelf life of minimally processed carrots. • Post harvest technology of vegetables

	composition of fresh, frozen, jarred and canned vegetables	preservation and processing	
LCAs of environmental impacts associated with food production	• A new method for assessing the sustainability of land-use systems (II): Evaluating impact indicators.	• An improved water footprint methodology linking global consumption to local water resources: a case of Spanish tomatoes • Identification of the main factors affecting the environmental impact of passive greenhouses. • Including environmental aspects in production development: a case study of tomato ketchup • Environmental impact of greenhouse tomato production strategies using life cycle assessment approach	• Life-cycle assessment of carrot puree • Environmental life-cycle assessment of agricultural food production.
BPA	—	—	• Migration of bisphenol A from can coatings--effects of damage, storage conditions and heating

The detailed literature survey provided a number of useful insights and findings on the available literature:

1. In general, the detailed literature survey uncovered many articles on the effects of packaging on food quality. In particular, articles focused on plastic films and Modified Atmosphere Packaging (MAP), but we located less information on canning and frozen foods.

2. There were a few (predominantly older) studies on canning and freezing spinach.

3. Most importantly, only a few articles summarized the life-cycle environmental impacts associated with packaging or vegetable production. No comprehensive source of U.S.-specific LCI data was located for production of any of the three vegetable options. Out of the three vegetables, we found that a majority of LCA studies have been conducted on tomatoes.

The detailed literature review and project scoping uncovered an encouraging amount of data; however, there were a number of important data gaps that we identified. Extending the analysis conducted for tomatoes in this study to other vegetables such as carrots or spinach will need to address these data gaps:

- U.S.-specific LCI data availability on food production. Although we uncovered useful U.S.-specific LCI data sources, and contacted several U.S.-based LCI practitioners, we did not locate a comprehensive data source for information on the targeted list of vegetables. We anticipate that it will be necessary to develop information on the environment impacts of each vegetable based on a number of secondary data sources, followed by review with LCA practitioners and industry experts.

- Environmental impact data availability. Based on our detailed review of literature, we anticipate that impact assessment data for environmental toxicity, human toxicity, and eutrophication impacts will be harder to locate or develop than for land use (i.e., surface area used), water use (i.e., blue water consumption), energy use, and GHG emission impact categories. For impact categories where there is less data available, it may be possible to use the more aggregate environmental impact data from the Vision 2020 report (EPA, 2009) to discuss potential impacts based on specific insights gained from the comparative assessment of the packaging scenarios and their effect on food production processes.

Appendix A References

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