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Environmental Analysis of Food-Energy-Water Systems: Focus on High-value Crops and Logistics in the United States

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Environmental Analysis of Food-Energy-Water Systems: Focus on High-value Crops and Logistics in the United States

by

Eric Matte Bell

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requirements for the degree of
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of the
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Committee in charge:

Professor Arpad Horvath, Chair
Professor Scott Moura
Professor David Anthoff

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Abstract

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Professor Arpad Horvath, Chair

Agriculture is one of the most influential ways that humans interact with the environment. Our food system demands approximately 30% of global energy consumption, 70% of freshwater withdrawals, and 90% of consumptive water use. Roughly half of the Earth's habitable land area is already being used in the service of agriculture. One quarter of global greenhouse gas emissions can be attributed to food production, primarily as a consequence of land use change, livestock farming, and fertilizer use. This is to say nothing of the multitude of other impacts such as conventional air and water pollution, habitat destruction, and species extinction. Several prominent trends including population growth, the expansion of the global middle class, and urbanization threaten to further strain our already deteriorating natural systems. Estimates suggest that food production must increase 70% by 2050 in order to meet demand. Attaining this target in a sustainable manner requires the acceptance of a holistic integrated engineering approach to food, energy, and water systems. It is only through such an approach that we can arrive at optimal solutions that minimize waste streams and natural resource depletion while maximizing food output. At the core of this dissertation are three interrelated research projects addressing the production and supply of fresh produce in the United States. First, we perform an environmental assessment of four high-value crops in Ventura County, California: strawberries, lemons, celery, and avocados. We calculate life-cycle energy and greenhouse gas emissions footprints and assess the impact of switching from conventional irrigation to recycled or desalinated water. Next, we expand upon the Ventura County model to include the post-harvest processing, packaging, and transportation stages. Using oranges as a case study, we estimate the carbon footprint per kilogram of fruit delivered to wholesale market in New York City, Los Angeles, Chicago, and Atlanta, and assess the relative importance of transportation mode, transportation distance, and seasonality. Finally, we apply this cradle-to-market model at a national level to assess the environmental impact of fresh tomatoes delivered to ten of the largest cities in the United States. Using linear optimization, we compute the optimal tomato distribution scheme that minimizes greenhouse gas emissions while satisfying tomato demand. This dissertation contributes to the current body of knowledge by presenting life-cycle footprints for six high-value agricultural commodities using uniquely specific regional and temporal data. We develop a holistic cradle-to-market life cycle model that integrates growing practices, water use, and embedded energy. We then apply this

model in combination with linear optimization in order to mitigate the environmental impact of a popular agricultural commodity at the national level. This research underscores the importance of crop-specific and regionally-specific data collection and carbon footprinting. The adoption of a universal framework for agricultural data reporting would greatly expand the applications and accuracy of agricultural environmental assessments. Such a framework would lay the groundwork for optimal decision-making at the nexus of food, energy, and water. It would also allow for efficiency benchmarking in agricultural production and supply, and perhaps the incorporation of a performance-based ecolabel for resource-efficient crops.

To my parents, Judy and Glenn,

and

to my partner and best friend, Melissa, and our weird menagerie (Maggie, Scout, Calbert)

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List of Abbreviations

AMS	Agricultural Marketing Service
AWPF	advanced water purification facility
CH_4	methane
CHP	combined heat and power
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
DOT	U.S. Department of Transportation
eGRID	Emissions & Generation Resource Integrated Database
EIO-LCA	economic input-output life cycle assessment
EPA	U.S. Environmental Protection Agency
FEWS	food-energy-water systems
GHG	greenhouse gas
GIS	geographic information system
GWP	global warming potential
HDPE	high-density polyethylene
LCA	life cycle assessment
LDPE	low-density polyethylene
MGD	million gallons per day
N_2O	nitrous oxide
NASS	National Agricultural Statistics Service
PET	polyethylene terephthalate
SAGE	University of Wisconsin Center for Sustainability and the Global Environment
UNESCO	United Nations Educational, Scientific, and Cultural Organization

USDA	United States Department of Agriculture
USGS	United States Geologic Survey
WW	wastewater
WWTP	wastewater treatment plant

Glossary

Adapted environment – Includes such strategies as mulching, row covers, high tunnel, and shade cloth [Jensen and Malter, 1995]

Advanced wastewater treatment – Any wastewater treatment process above and beyond the typical primary and secondary wastewater treatment stages; commonly involves reverse osmosis and an oxidation treatment process

Anaerobic digestion – The process by which microorganisms decompose organic material (e.g., sewage, manure, crop residues) in the absence of oxygen, resulting in the production of biogas

Applied water – The total amount of water that is diverted form any source to meet the demands of water users without adjusting for water that is depleted, returned to the developed supply or considered irrecoverable (also referred to as "water withdrawals") [Brown et al., 2013]

Aquifer – Underground geologic formations composed of porous rock capable of storing water

Biogas – A mixture of gases, primarily methane (CH_4), produced by the bacterial decomposition of organic material

Blue water – The volume of surface and groundwater consumed (evaporated) as a result of the production of a good [Mekonnen and Hoekstra, 2011]

Cogeneration – The process of simultaneously producing electricity and useful heat using a thermoelectric generator (also known as combined heat and power)

Combined heat and power – see "Cogeneration"

Consumptive water use – The amount of applied water used and no longer available as a source of supply [Brown et al., 2013]

Controlled environment – Grown in a fully-enclosed permanent aluminum or fixed steel structure clad in glass, impermeable plastic, or polycarbonate using automated irrigation and climate control, including heating and ventilation capabilities, in an artificial medium using hydroponic methods [Suspension of Antidumping Investigation: Fresh Tomatoes from Mexico, 2013]

Cow water – Water removed from milk during the evaporation process in a dairy processing plant

Direct potable reuse – The incorporation of recycled water into a municipal water supply, either directly into the distribution system or upstream of the water treatment plant

Eutrophication – The addition of nutrients (mainly nitrogen and phosphorus) into water bodies, which may lead to excessive biomass growth and a subsequent depletion of dissolved oxygen

Food loss – The decrease in edible food mass throughout the part of the supply chain that specifically leads to edible food for human consumption; can take place at production, post-harvest, and processing stages in the food supply chain [Gustavsson, 2011]

Food waste – The decrease in edible food mass occurring at the end of the food chain (i.e., retail and final consumption) [Gustavsson, 2011]

Green manure – Plant residues that have been left on the field to decompose to serve as a soil amendment

Green water – The rainwater consumed (evaporated) as a result of the production of a good [Mekonnen and Hoekstra, 2011]

Greenhouse – A framed or inflated structure, covered by a transparent or translucent material that permits the optimum light transmission for plant production and protects against adverse climatic conditions. May include mechanical equipment for heating and cooling [Jensen and Malter, 1995]

Grey water – The volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards [Mekonnen and Hoekstra, 2011]

Groundwater – Water below the land surface in a region in which all interstices in, between, and below natural geologic materials are filled with water, with the uppermost surface being the water table [Regulations Related to Recycled Water, 2014]

High tunnel – A greenhouse-like unit but without mechanical ventilation or a permanent heating system [Jensen and Malter, 1995]

Indirect potable reuse – The reintroduction of recycled water into the natural water cycle upstream of the water treatment plant (e.g., reservoir, stream feeding a reservoir, aquifer)

Life cycle assessment – A framework for assessing the environmental impact of products and systems throughout their life stages (e.g., materials extraction, production, use, end-of-life) from cradle to grave [Matthews et al., 2015]

Metropolitan statistical area – A county (or counties) associated with at least one urbanized area of at least 50,000 population, plus adjacent counties having a high degree of social and economic integration [U.S. Census Bureau, 2016]

Mulching – The practice of covering the soil around plants with an organic or synthetic material to make conditions more favorable for plant growth, development, and crop production [Jensen and Malter, 1995]

Periurban – Of or relating to the interface between rural and urban zones

Primary wastewater treatment – Typically the first process in municipal wastewater treatment; removes large particles through mechanical processes (e.g., settling)

Reverse Osmosis – A water purification process that uses applied hydrostatic pressure to force water through a semipermeable membrane to remove contaminants

Row cover – A piece of clear plastic stretched over low hoops and secured along the sides of the plant row by burying the edges and ends with soil [Jensen and Malter, 1995]

Ruminants – Mammals such as cattle, goats, and sheep that utilize microbial fermentation to extract nutrients from plant material, resulting in methane as a byproduct

Secondary wastewater treatment – A wastewater treatment process that typically involves physical separation to remove settleable solids combined with a biological process of digestion with bacteria to remove organic compounds

Ultraviolet oxidation – An advanced wastewater treatment process using ultraviolet light to kill bacteria and other microorganisms

Water withdrawals – see “Applied water”

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Chapter 1.

Introduction

Our current agricultural system places high demands on our energy, water, and land resources, and releases large quantities of greenhouse gases to the atmosphere. Given the current global trends toward population growth, the expansion of the middle class, and urbanization, it is essential that we engineer ways to increase the resource efficiency of our food production and supply. One way to achieve this is by adopting a holistic engineering approach towards food-energy-water systems and capitalize on synergies to make use of existing waste streams. This dissertation presents three interrelated projects studying the environmental impacts of high-value produce in the United States. Life cycle assessment is used to assess integrated food-energy-water systems for optimal decision-making.

1.1 Motivation

Agriculture is one of the most influential ways that humans interact with the environment. The production of food necessary to support human life places substantial demands on natural resources in the form of energy use, water use, land use, and greenhouse gas (GHG) emissions. Agriculture imposes many other demands on the environment as well, including conventional air pollution, water pollution and eutrophication, habitat destruction, and species extinction.

Population growth and the emergence of the global middle class are driving a growing demand for food. The United Nations estimates that the global population may grow to 9 billion by 2050 [United Nations, 2011] and the global middle class is expected to increase to 5 billion—up from 3 billion today—by 2030 [Kharas, 2017]. As a result of these factors, food production is projected to increase 70% by 2050 [United Nations, 2011]. Further complicating matters is the rise of urbanization, dislocating people from their food sources, and contributing to dietary changes. The percentage of the world's population living in urban areas is expected to increase to 66% by 2050—up from 54% today [United Nations, 2015].

Assuming that these projections hold, it is critical to develop solutions that allow us to increase food production without overburdening our natural systems. This can be accomplished by adopting a holistic engineering approach to our food, energy, and water systems (FEWS), thereby increasing the resource efficiency of food production and supply.

Figure 1 presents a conceptual representation of the food-energy-water nexus. While historically, engineering design has approached these three systems separately, there is a growing realization that they are both interdependent and interconnected. By adapting a holistic “systems-level” view, engineers can produce optimal design solutions to meet the needs of the citizenry while minimizing strain on our natural systems.

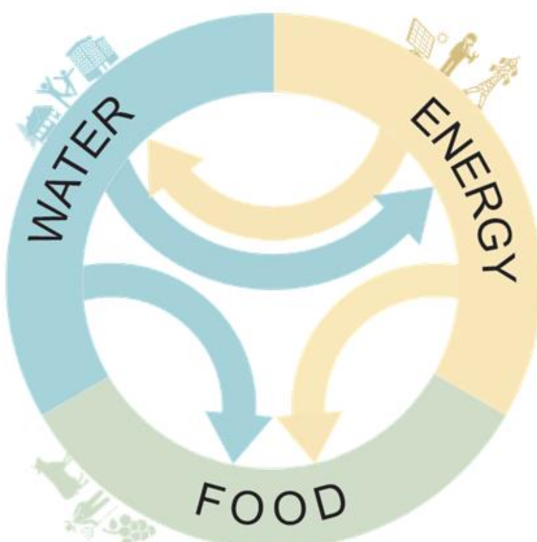

Figure 1. The food-energy-water nexus
Food, energy, and water are interconnected and interdependent. Producing energy requires water for extraction and processing of raw materials and as a coolant for thermoelectric generation. At the same time, energy is needed for the extraction, conveyance, treatment, distribution, and heating of water. Both energy and water are critical for the food sector; water is used for irrigation and food processing, while energy is needed for on-farm equipment, food processing, and transportation. [Graphic modified from NSF INFEWS proposal]

If we choose to view food, energy, and water as a single, interconnected system, we can capitalize on system synergies that may not have been otherwise evident. A product from one sector that may have traditionally been viewed as a waste product, can be reintroduced to another sector in a useful form. Figure 2 highlights one example of this concept. Wastewater (WW) is generally treated to an acceptable level before being discharged back into the environment in a river, lake, or ocean. Rather than disposing of this product as a waste, we could (a) distribute it to farms to be used for irrigation or (b) decompose it in an anaerobic digester to produce energy in the form of biogas. We could even send it straight back to the water sector in the form of direct potable reuse or inject it to recharge groundwater aquifers for indirect potable reuse. Table 1 lists some possible system synergies.

This research aims to quantify the embedded energy and water requirements of the food sector, to estimate other environmental impacts including GHG emissions, and to identify and capitalize on system synergies at the food-energy-water nexus.

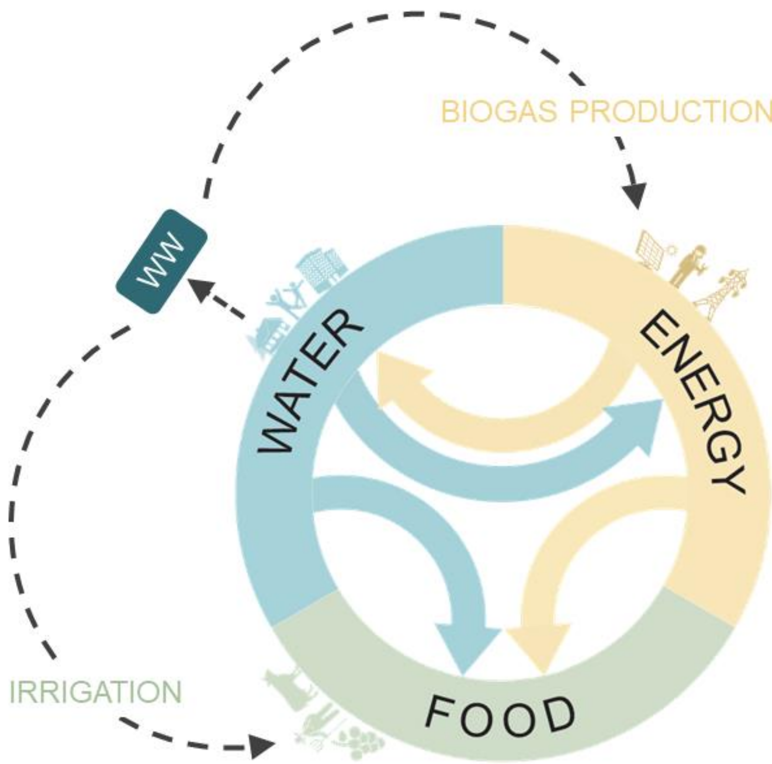

Figure 2. An example of a food-energy-water system synergy
Rather than dispose of wastewater, we can reintroduce it to the food sector in the form of water for irrigation. Alternatively, we could reintroduce in into the energy sector by decomposing it in an anaerobic digester to produce biogas. [Graphic modified from NSF INFEWS proposal]

Table 1. Examples of FEWS synergies

Category	Example(s)
F → F	Use manure or decomposed crop residues (i.e., “green manure”) to fertilize crops. Reclaim water from evaporated milk (i.e., “cow water”) for use in dairy processing plants. Use crop residues as feed for livestock.
F → E	Burn crop residues to generate electricity. Generate biogas from food waste using anaerobic digestion.
F → W	Currently no documented examples.

Table 1. Examples of FEWS synergies

Category	Example(s)
E → F	Use waste heat from thermoelectric generation to heat greenhouses. Send carbon dioxide from fossil fuel combustion to greenhouses to fertilize crops.
E → E	Capture and use waste heat from thermoelectric generation (i.e., “cogeneration”).
E → W	Currently no documented examples.
W → F	Use municipal wastewater to irrigate crops.
W → E	Generate biogas from wastewater using anaerobic digestion.
W → W	Direct or indirect potable water reuse.

1.2 Research Objectives and Contributions

This research focuses on fresh produce commodities (i.e., fresh fruits and vegetables) in the United States with a particular emphasis on California. Since fresh fruits and vegetables are high-value crops, there is a greater likelihood that the incorporation of emerging technologies and growing practices would be economically viable. The environmental impact of fresh produce is more highly dependent on transportation and logistics relative to other food commodities such as meat and staple crops. This is due primarily to two factors: transportation represents a higher proportion of the total environmental impact for fresh produce, and food losses for fresh produce are higher relative to other food categories. In addition, the environmental impact of fresh produce commodities can vary significantly with geography and growing practices. Greenhouse production, for example, typically yields significantly higher energy usage but may reduce transportation distances to the consumer.

California is the single largest agricultural producer in the United States, accounting for approximately one-tenth of the nation’s total agricultural output, by value [Cooley et al., 2015]. It is also the nation’s sole producer of many specialty crops, including artichokes, figs, kiwis, almonds, and walnuts [Cooley et al., 2015]. At the same time, it is highly susceptible to extreme hydrologic events including multiyear droughts.

In this research, we:

- Apply life cycle assessment (LCA) to assess integrated FEWS for optimal decision-making;
- Capitalize on waste streams by closing the loops in the food-energy-water nexus;
- Use highly-localized data to assess environmental impacts at the regional and farm-level scale; and
- Assess the entire fresh produce supply chain from cradle-to-market.

This research contributes to the current body of knowledge by:

- Advancing urban water and food sector integration and reinvention by quantifying the impacts of switching to future sources of irrigation water;

- Creating life-cycle footprints for high-value crops that are regionally and seasonally specific using granular data;

- Developing a model that integrates growing practices, water use, and embedded energy. Expanding this model beyond the farm gate to the wholesale market; and

- Applying optimization to minimize the life cycle environmental impact of fresh produce at the national scale.

This dissertation is divided into three interrelated projects that explore the following objectives:

- Chapter 2: Determine whether incorporating alternative water technologies into the periurban growing region of the Oxnard Plain can help alleviate regional water stress without substantially increasing the cost and environmental impact of high-value fresh produce. Determine the extent to which the results can be generalized to other similar growing areas.

- Chapter 3: Estimate the environmental impact of high-value fresh produce delivered to market as a function of production origin, transportation mode, and seasonality. Determine the relative importance of these three factors.

- Chapter 4: Assess the total carbon footprint of tomatoes delivered to market in major U.S. metropolitan statistical areas and determine the extent to which the current supply portfolio is optimal.

1.3 Background on Agriculture and the Environment

Agriculture enacts a high cost on our natural systems. On a global scale, agriculture is responsible for at least one quarter of GHG emissions, one third of energy use, two thirds of freshwater withdrawals, 90% of consumptive freshwater use, and half of the Earth's habitable land area. Sustaining one human life for a duration of one year emits, on average, 1.5 tons of CO_2e, and requires 13 GJ, 400,000 liters of water, and two thirds of a hectare of land. Assuming that current population projections hold true, it is essential to increase the resource efficiency of food production and supply, and minimize food losses throughout the system.

1.3.1 Greenhouse gas emissions

The most recent assessment report from the Intergovernmental Panel on Climate Change (IPCC) estimates global emissions from agriculture, forestry, and land use change to be approximately 10 Gt of carbon dioxide equivalent (CO_2e) per year for the period of 2000 to 2009, or roughly one quarter of all global emissions [IPCC, 2014]. The largest emissions contributors are carbon dioxide (CO_2) from land use change, methane (CH_4) from ruminant livestock, and nitrous oxide (N_2O) from synthetic fertilizers and manures. These three sources collectively account for approximately 7-8 $GtCO_2e$ per year. Considered across the entire global population, agriculture, forestry, and land use change are responsible for roughly 1.5 tons of CO_2e per person per year, or 4 $kgCO_2e$ per person per day. It is important to recognize that these numbers do not include emissions from food processing, packaging, transportation, and storage.

Weber and Matthews, 2008, used the Economic Input-Output Life Cycle Assessment (EIO-LCA) method to estimate total U.S. household emissions associated with food consumption. Their methods produced an estimate of 8.4 $kgCO_2e$ per person per day. This estimate includes emissions from transportation and the wholesaler/retailer. They further concluded that transportation of food accounts for 28% of the carbon footprint of fruits and vegetable and 11% of the overall U.S. food system.

Jones and Kammen, 2011, independently performed a similar analysis using EIO-LCA and found GHG emissions from food consumption in the U.S. to be 8.3 $kgCO_2e$ per person per day, or roughly 16% of U.S. household emissions.[1]

Heller et al., 2013, identified 32 studies that use LCA to evaluate the environmental impact of diets or meals. They reported the per-capita GHG emissions associated with food consumption for European countries as follows: France – 4.1 $kgCO_2e$ per person per day, Denmark – 5.6, Spain – 5.8, Germany – 6.0 (men) / 4.2 (women), EU 27 – 7.1, UK – 7.3.

Cradle-to-farm gate food LCAs are numerous in the literature. Clune et al., 2017, performed an extensive literature review of 369 published studies covering 168 varieties of fresh food. They determined that the existing literature is dominated by Europe; out of over 1000 utilized carbon footprints, 68% were specific to the European markets. Only 14% were specific to the United States. Field-grown vegetables and field-grown fruit were found to have average carbon footprints of 0.37 and 0.42 $kgCO_2e$ per kg, respectively—the lowest of all food categories. Beef, by contrast was found to have an average carbon footprint of 27 kgCO2e per kg of bone-free mass, a difference of two orders of magnitude.

1.3.2 Energy use

A report by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) estimates that the total global food system energy consumption is roughly 95 EJ, accounting for 30% of the world's end-use energy [UNESCO, 2014]. The vast majority of this energy—roughly 70%—is used beyond the farm gate for processing, distribution, retail, and cooking. This is the equivalent of roughly 13 GJ per person per year.

A report from the United States Department of Agriculture (USDA) used EIO-LCA methodology to estimate food system energy consumption in the United States in 2002. The results indicate

[1] "Household emissions" does not include GHG emissions associated with government expenditures.

significantly higher energy usage relative to the global average; 50 GJ per person per year, or 140 MJ per person per day [Canning et al., 2010]. This represents approximately 14% of 2002 national energy consumption.

1.3.3 Water use

According to the same UNESCO report cited above, global water withdrawals for agriculture total 2700 billion m^3 per year, accounting for an estimated 70% of total global water withdrawals [UNESCO, 2014]. This equates to roughly 1100 liters (300 gallons) of water per person per day for agriculture. In the Americas, this value is only slightly higher at 1200 liters (330 gallons) per person per day. Similarly, the National Intelligence Council reports that agriculture is responsible for over two-thirds of global freshwater withdrawals and over 90% of consumptive water use [National Intelligence Council, 2012].

Mekonnen and Hoekstra, 2011, quantified the green, blue, and grey water footprints of global crop production using a high-resolution grid-based dynamic water balance model. They calculated a total global water footprint for agriculture of 7400 billion m^3, split between green (78%), blue (12%), and grey (10%) water. They found that vegetables require, on average, 300 L of water per kg produced (60% green, 13% blue, 26% grey) and fruits require 1000 L per kg (75% green, 15% blue, 10% grey). However, the water footprint varies by crop type and geographic location. The total agricultural water footprint of crops in the United States was determined to be 826 billion m^3 per year, split between green (74%), blue (12%), and grey (14%) water.

1.3.4 Land use

Although it may seem that we have plenty of land for agriculture, not all of it is suitable for growing crops. Of the roughly 500 million km^2 of the Earth's surface, only 100 million km^2 is habitable; the majority is either barren or covered by oceans and glaciers [World Wildlife Fund, 2016]. Of the 100 million km^2 of habitable land, half is already being used for agriculture—mostly for livestock. When considered across the global population, sustaining one human life for one year requires roughly two thirds of a hectare of suitable agricultural land.[2] Three quarters of this can be attributable to livestock, including feed, with all other crops accounting for the remaining quarter. Figure 3 visualizes the distribution of global land area by use. As illustrated by the figure, agricultural land expansion will likely come at the cost of additional deforestation.

[2] Alternatively, one square kilometer of suitable land can support roughly 150 people.

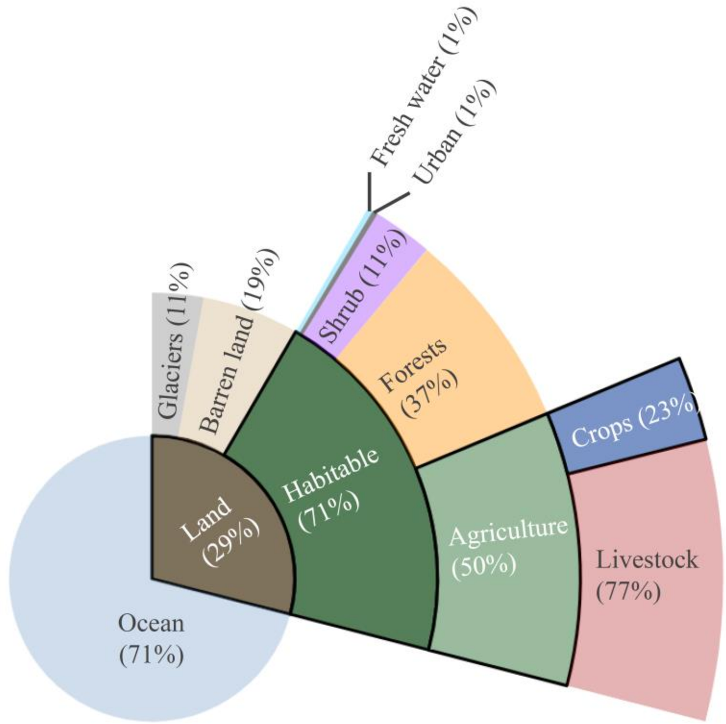

Figure 3. Distribution of global land use by area
Total land area = 510 million km^2 [Graphic by the Author, data from World Wildlife Fund, 2016]

1.3.5 Food loss

Roughly one third of all food is lost or wasted globally, equaling 1.3 billion tons of food per year [Gustavsson, 2011]. For fruits and vegetables, the percentage of lost or wasted food is even higher, at 44%. In North America, 20% of fruits and vegetables on average are lost in the agricultural production stage; 4% of the remaining supply is lost during the post-harvest handling and storage stage; a further 2% is lost in the processing and packaging stage; 12% is lost at the distribution and retail stage; and 28% is lost at the consumption stage [Gustavsson, 2011].

Food loss has been well studied in the literature. Buzby and Hyman 2012, estimated the total economic value of food loss at the retail and consumer levels alone in the United States at over $160 billion per year, or 124 kilograms per person annually. Heller & Keoleian, 2014, determined that the quantity of food lost in the average U.S. diet throughout the supply chain is equivalent to 1.5 kgCO_2e per person per day, or roughly 28% of the total dietary footprint.

1.4 Organization

The subsequent chapters of this dissertation are organized as follows:

- Chapters 2, 3, and 4 describe three interrelated projects:

  - Chapter 2 presents life-cycle energy use and GHG emissions footprints for four high-value crops in Southern California. We quantify the operational costs, crop-specific applied water demand, and on-farm labor requirements of these crops, and we assess the impact of switching from conventional irrigation (i.e., groundwater and surface water) to recycled or desalinated water as the primary irrigation source.

  - Chapter 3 expands upon the modeling framework developed in Chapter 2 to characterize the cradle-to-market carbon footprint of fresh produce. The model includes the production, post-harvest processing, packaging, and transportation stages. Using oranges as a case study, we quantify the variability in the carbon footprint of fresh fruit delivered to a wholesale market in New York City, Los Angeles, Chicago, and Atlanta.

  - Chapter 4 applies the cradle-to-market model described in Chapter 3 to the fresh tomato markets of ten of the largest metropolitan statistical areas in the United States. Assuming fixed supply and demand, we apply linear optimization to compute the ideal supply portfolio for each metropolitan statistical area that will minimize the sum of environmental costs across all areas. We then assess the degree to which the optimal supply portfolio matches the existing supply portfolio and calculate the potential for environmental savings.

- Chapter 5 summarizes the key conclusions stemming from this research and provides recommendations on future areas of study.

Chapter 2.

Environmental Evaluation of High-value Agricultural Produce with Diverse Water Sources: Case Study from Southern California

The following chapter is adapted from Bell E M, Stokes-Draut J R, and Horvath A 2018 Environmental evaluation of high-value agricultural produce with diverse water sources: case study from Southern California Environmental Research Letters 13 025007, with permission from Jennifer R. Stokes-Draut and Arpad Horvath. Copyright 2018, The Authors. Published by IOP Publishing Ltd.

Meeting agricultural demand in the face of a changing climate will be one of the major challenges of the 21st century. California is the single largest agricultural producer in the United States but is prone to extreme hydrologic events, including multi-year droughts. Ventura County is one of California's most productive growing regions but faces water shortages and deteriorating water quality. The future of California's agriculture is dependent on our ability to identify and implement alternative irrigation water sources and technologies. Two such alternative water sources are recycled and desalinated water. The proximity of high-value crops in Ventura County to both dense population centers and the Pacific Ocean makes it a prime candidate for alternative water sources. This study uses highly localized spatial and temporal data to assess life-cycle energy use, life-cycle greenhouse gas emissions, operational costs, applied water demand, and on-farm labor requirements for four high-value crops. A complete switch from conventional irrigation with groundwater and surface water to recycled water would increase the life-cycle greenhouse gas emissions associated with strawberry, lemon, celery, and avocado production by approximately 14%, 7%, 59%, and 9%, respectively. Switching from groundwater and surface water to desalinated water would increase life-cycle greenhouse gas emissions by 33%, 210%, 140%, and 270%, respectively. The use of recycled or desalinated water for irrigation is most financially tenable for strawberries due to their relatively high value and close proximity to water treatment facilities. However, changing strawberry packaging has a greater potential impact on life-cycle energy use and greenhouse gas emissions than switching the water source. While this analysis does not consider the impact of water quality on crop yields, previous studies suggest that switching to recycled water could result in significant yield increases due to its lower salinity.

2.1 Introduction

Recent estimates indicate that approximately four billion people now live under conditions of severe water scarcity at least one month out of the year [Mekonnen and Hoekstra, 2016]. Water shortages are projected to increase in the decades to come as a result of both demand-side drivers (e.g., population growth, urbanization, economic development) and reductions in supply due to climate change [OECD, 2012]. As the primary consumer of fresh water, agriculture has a central role to play in mitigating future water stress. Agriculture accounts for more than two-thirds of global freshwater withdrawals and over 90% of consumptive water use [National Intelligence Council, 2012]. Water needs will increase as demand for food is expected to increase 50% by 2030 [World Economic Forum, 2011]. To satisfy agriculture's thirst for water, regions including Australia, the European Union, Israel, and parts of the United States have turned to recycled municipal wastewater [Anderson, 2003; Bixio et al., 2006; Tal 2006; Parsons et al., 2010]. In drought-prone regions, recycled water can be a reliable, cost-effective alternative to conventional irrigation sources. This is particularly pertinent for California, one of the world's most productive agricultural regions with a long history of water challenges.

California is the single largest agricultural producer in the United States, accounting for over $50 billion in output, or approximately one tenth of the nation's total [Cooley et al., 2015]. Globally, California ranks among the top ten countries for agricultural value and is the U.S.'s single largest agricultural exporter [Barker et al., 2009; Ross, 2015]. It is also the nation's sole producer and foreign exporter of many individual commodities, including almonds, walnuts, pistachios, and olives [Cooley et al., 2015; Ross, 2015]. At the same time, California is susceptible to extreme hydrologic events which threaten the long-term sustainability of agriculture and the more than 400,000 farm jobs that it maintains [Cooley et al., 2015]. From 2012 to 2014, California experienced the driest three-year period on record [Cooley et al., 2015]. Global climate change has increased the likelihood of atmospheric anomalies, including the persistent ridging that was characteristic of California's most recent drought [Swain et al., 2014]. Climate models predict more frequent and severe droughts, particularly in the arid southwestern United States [Wehner et al., 2011]. Agriculture is the single greatest user of water in California, comprising 80% of applied water and 82% of consumptive water use in the developed environment in 2010 [Brown et al., 2013]. If California is to maintain its current level of agricultural production, alternative sources of irrigation water such as recycled and desalinated water must be considered.

In this study, we (1) calculate life-cycle energy use and greenhouse gas (GHG) emissions; (2) quantify operational costs, crop-specific applied water demand, and on-farm labor requirements; and (3) assess the impact of switching from conventional irrigation (i.e., groundwater and surface water) to recycled or desalinated water as the primary irrigation source for four high-value crops in Southern California.

The study focuses on Ventura County, and in particular, the Oxnard Plain agricultural region. There are several reasons Ventura County was selected as a case study. First, water consumption in Southern California far exceeds local supplies, resulting in higher water scarcity and a reliance on imports relative to the northern half of the state [Hanak et al., 2011]. The Oxnard Plain is located between the Pacific Coast and the Transverse Mountain Ranges. Its relative geographic isolation contributes to the high cost, energy intensity, and unreliability of imported water from the Sacramento-San Joaquin River Delta [Klein et al., 2005]. Second, the proximity of agriculture to an urban population center, combined with the characteristics of Oxnard's current wastewater treatment system, make recycled water a viable option. Oxnard is the largest city in Ventura County, with a population of approximately 200,000 [Hoang, 2016]. Oxnard's wastewater treatment plant (WWTP) currently treats an average of 80,600 m^3 of water per day (21.3 million gallons per day [MGD]) to a secondary level and discharges the effluent to the ocean [Carollo Engineers, 2015b]. The recently constructed Advanced Water Purification Facility (AWPF) treats the secondary effluent from Oxnard's conventional wastewater treatment plant using an advanced treatment train consisting of microfiltration, reverse osmosis, and ultraviolet advanced oxidation [Lozier and Ortega, 2010]. The result is high-quality effluent that can be used for agriculture, landscape irrigation, industry, or groundwater recharge. The AWPF has a current capacity of 23,700 m^3 per day (6.25 MGD) of product water with plans to expand, eventually treating 100% of Oxnard's municipal wastewater. Third, Ventura County's proximity to the ocean both renders groundwater vulnerable to saltwater intrusion and allows for the possibility of desalination. The Oxnard Plain groundwater basin is currently experiencing significant issues with saltwater intrusion and the problem is worsening as a result of groundwater overdraft [Anselm et al., 2014]. Leveraging alternative water sources such as recycled and desalinated water for agriculture has the potential to mitigate Oxnard's saltwater intrusion problem by limiting groundwater withdrawals. Moreover, the salinity of AWPF water is lower than that of Oxnard's groundwater, potentially resulting in higher crop yields in the Oxnard Plain. Lastly, Ventura County is one of the top agricultural counties in California, ranking tenth in 2014 by crop value [Ross, 2015]. Only Ventura and Monterey Counties, among the top ten, could use desalination to support agriculture. The other eight are all located in the Central Valley—California's primary agricultural region. A table of California's top ten growing counties and an accompanying map are included in Appendix A.

This study focuses on four of Ventura County's top agricultural products: strawberries, lemons, celery, and avocados. Together, they account for more than half of Ventura County's gross agricultural value [Gonzales, 2015]. By our estimates, they also account for more than half of the applied irrigation water in the County, excluding residential irrigation. Refer to Appendix A for calculation. Table 2 summarizes Ventura County's top ten agricultural products by gross value, as well as their statewide and national significance. The selection represents a variety of food types, growing practices, and irrigation water quality standards. Under California Title 22 Regulations, recycled wastewater used for irrigation of "[o]rchards where the recycled water does not come into contact with the edible portion of the crop" (e.g., lemons, avocados) must be at least undisinfected secondary recycled water [Regulations Related to Recycled Water, 2014]. Recycled wastewater used for irrigation of food crops "where the recycled water comes into contact with the edible portion of the crop" (e.g., strawberries, celery) must be at least disinfected tertiary water

[Regulations Related to Recycled Water, 2014]. Current WWTP discharge in Oxnard meets the former standard; effluent from the AWPF facility meets the latter.

Table 2. Summary of Ventura County's top crops in 2014

No.	Crop	Gross Value for Ventura County [Gonzales, 2015]	Ventura County's Share of California Production [Ross, 2015]	California's Share of U.S. Production [Ross, 2015]
1	Strawberries	$628,000,000	27%	91%
2	Lemons	$269,000,000	37%	91%
3	Raspberries	$241,000,000	52%	65%
4	Nursery Stock	$180,000,000	6%	–
5	Celery	$152,000,000	36%	95%
6	Avocados	$128,000,000	31%	83%
7	Tomatoes	$72,200,000	4%	91%
8	Bell Peppers	$67,300,000	22%	60%
9	Cut Flowers	$47,600,000	6%	–
10	Kale	$35,900,000	–	–

Notes: A dash indicates that data were unavailable. Share of California production based on gross value. "Gross value" refers to payments to the grower, plus any selling commissions and assessments. Share of U.S. production based on mass produced.

Substantial literature exists on food life-cycle assessments (LCAs). Two recent publications performed literature reviews of LCA studies for various food categories, collectively assessing several hundred published studies [Heller and Keoleian, 2014; Clune et al., 2017]. However, the existing literature is mostly specific to Europe; the GHG footprints of lemons, celery, and avocados have never been determined for the United States. The GHG footprint of strawberries in the United States has been estimated by three studies, two of which are specific to California, but not to Ventura County [Gonzales et al., 2011; Venkat, 2012; Tabatabaie and Murthy 2016]. The applied water demand of all four crops has been previously estimated for California as a whole but not at the county level [Mekonnen and Hoekstra, 2011]. Since applied water demand is dependent on rainfall, it would be inaccurate to assume a single value for all of California, which has significant variability in rainfall throughout the state [The Delta Stewardship Council, 2013]. A summary of the existing literature is included in Appendix A.

Unlike previous work, this study uses highly localized spatial and temporal data to assess energy use, GHG emissions, operational costs, and applied water demand. Production practices herein are specific to Southern California and, in most cases, to Ventura County. Geographic information system (GIS) analysis is used to estimate the monthly energy demand of irrigation water on a field-by-field basis. On-farm labor demand and associated costs were also assessed to quantify the economic significance of these crops to Ventura County. Finally, this study is unique in its comparison of the relative impacts of alternative irrigation sources including recycled and desalinated water.

2.2 Methods

Cradle-to-farm gate life-cycle footprints for energy and GHG emissions were estimated for strawberries, lemons, celery, and avocados on a per-kilogram basis. Operational costs were quantified per kilogram of crop delivered to the farm gate. Demand for irrigation water was determined both on a per-kilogram basis and on a monthly basis for Ventura County. Production practices for each of the four crops are based on “cost and return studies” developed by the University of California, Davis (UC Davis) College of Agricultural and Environmental Sciences Cooperative Extension [Daugovish et al., 2011; O’Connell et al., 2015; Takele and Daugovish, 2013; Takele and Faber, 2011]. The UC Davis cost and return studies describe production practices considered typical for a particular crop and growing region. They are based on surveys and interviews with growers and are updated roughly every five years. The cost and return studies used herein for strawberries, celery, and avocados are specific to Ventura County, while the study for lemons (unavailable for Ventura County) is specific to the southern San Joaquin Valley. Agricultural inputs including biocides, direct fuel use, direct electricity use, fertilizers, materials, and applied water as well as economic costs were determined for each crop based on these studies. A complete table of inputs and returns for each crop is available in Appendix A. The results presented in this chapter represent conventional growing practices. In Ventura County, a small fraction of strawberries, lemons, celery, and avocados (5%, 3%, 8%, and 2% by land area, respectively) are produced organically. Operations that grow organically were excluded from this analysis due to their differing inputs and growing practices. In addition, collecting comparable data proved challenging due to the limited number of studies and lower-quality data currently available for organic production. A summary of the life-cycle energy and GHG emission factors used in this analysis is included in Table 3. Additional details are presented in Appendix A.

2.2.1 Biocides

Biocides considered in this analysis include fungicides, herbicides, and insecticides. Life-cycle energy and GHG emission factors for herbicides and insecticides are based on the California-modified Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (CA-GREET) model [Wang, 2015] where they were used to evaluate the impacts of biofuel production. Due to a lack of reliable data, the life-cycle energy and GHG emission factors for fungicides are modeled as the average of herbicides and insecticides. Ranges of life-cycle energy and GHG emission factors for fungicides, herbicides, and insecticides from the literature are included in Appendix A.

2.2.2 Direct Electricity

A small amount of direct electricity is consumed for strawberry and celery production as a result of the post-harvest cooling process. Since cooling is performed by a custom contractor in both cases, the quantity of electricity used for cooling is not reported in the cost and return studies. Electricity consumption from cooling therefore had to be estimated from the literature. An estimate of 59 kWh per metric ton of produce was used for both strawberries and celery [Thompson, 2010]. In addition, all four crops use electricity for irrigation in the form of electric pumps. In the presentation of results, the energy, GHG emissions, and costs associated with electricity for irrigation are included in the "Applied Water" category, rather than "Direct Electricity" category. This was done to better draw direct comparisons between the three water alternatives. (Refer to Section 2.2.6 for additional details.) Emission factors and primary energy demand for electricity were estimated by applying the power mix of Oxnard's electricity provider, Southern California Edison, to fuel-specific life-cycle factors taken from the literature [California Energy Commission, 2017; Gursel, 2014]. The results presented herein reflect the current state of electricity generation in Ventura County; changes in future electricity generation were considered as a parameter in the uncertainty analysis discussed in Section 2.3.

2.2.3 Direct Fossil Fuel

The direct fossil fuel demand associated with the production of these four crops primarily consists of diesel fuel for tractors as well as gasoline for trucks and all-terrain vehicles. In addition, lemon production requires a relatively small amount of propane for the operation of wind machines (used to prevent frost). The production of avocados requires a relatively small amount of jet fuel for application of insecticides by helicopter. In addition, a small fraction of irrigation pumps relies on diesel fuel rather than electricity. Impacts associated with machinery were not considered in this analysis, but a previous study of strawberry production in California found they were relatively insignificant due to the long life and limited operation hours of the machinery [Tabatabaie and Murthy, 2016]. The energy, GHG emissions, and costs associated with diesel fuel for irrigation are included in the "Applied Water" category, rather than the "Direct Fuel" category. Refer to Section 2.2.6 for additional details. Energy and emission factors for all fossil fuels include both combustion and production and are based on data from the CA-GREET model.

2.2.4 Fertilizer

Fertilizers are categorized by mass of nitrogen, phosphorus, and potassium. Life-cycle energy and GHG emission factors are based on the CA-GREET model. Per the IPCC Guidelines for National Greenhouse Gas Inventories, direct emissions of nitrous oxide from nitrogen fertilizers was estimated to be 1% of nitrogen applied [Klein et al., 2006].

2.2.5 Materials

Materials for strawberry production include high-density polyethylene (HDPE) for drip tape, low-density polyethylene (LDPE) for plastic mulch film, and polyethylene terephthalate (PET) for plastic clamshells. Due to a lack of reliable data, nursery plants and saplings were excluded from this analysis.

Table 3. Life-cycle energy and GHG emission factors for agricultural inputs

		Energy		Emissions		
Category	Input	Value	Unit	Value	Unit	Source
Biocides	Fungicide	310	MJ/kg	23	$kgCO_2e/kg$	proxy[a]
	Herbicide	280	MJ/kg	21	$kgCO_2e/kg$	i
	Insecticide	340	MJ/kg	25	$kgCO_2e/kg$	i
Electricity	Grid electricity	8.6	MJ/kWh	0.27	$kgCO_2e/kWh$	ii,iii
Fossil Fuel	Diesel	44	MJ/L	3.3	$kgCO_2e/L$	i
	Gasoline	41	MJ/L	2.5	$kgCO_2e/L$	i
	Jet fuel[b]	45	MJ/L	3.4	$kgCO_2e/L$	i
	Propane[c]	26	MJ/L	1.8	$kgCO_2e/L$	i
Fertilizer	Nitrogen	64	MJ/kg	9.4	$kgCO_2e/kg$	i
	Phosphorus	26	MJ/kg	1.8	$kgCO_2e/kg$	i
	Potassium	9.3	MJ/kg	0.69	$kgCO_2e/kg$	i
Materials	High-density polyethylene (HDPE)	74	MJ/kg	2.5	$kgCO_2e/kg$	iv
	Low-density polyethylene (LDPE)	82	MJ/kg	3.0	$kgCO_2e/kg$	iv
	Polyethylene terephthalate (PET) clamshells	3.9	MJ/unit	0.16	$kgCO_2e/unit$	v

Notes: [a] Due to a lack of reliable data, fungicides are estimated as the average of herbicides and insecticides. Additional information regarding uncertainty is available in Appendix A. [b] Jet fuel used for application of insecticides by helicopter in avocado production. [c] Propane used for operation of wind machines for frost protection in lemon production.
References: (i) Wang, 2015; (ii) California Energy Commission, 2017; (iii) Gursel, 2014; (iv) Harding et al., 2007; (v) Madival et al., 2009

2.2.6 Applied Water

The cost and return studies [Daugovish et al., 2011; O'Connell et al., 2015; Takele and Daugovish, 2013; Takele and Faber, 2011] report the quantity of irrigation water applied on a monthly basis per unit area of cropland. Figure 4 illustrates the estimated monthly irrigation demand in Ventura County for each of the four crops considered in this analysis. The figure was developed by scaling up the irrigation demand data from the cost and return studies in proportion to the total crop acreage in the County. Applied water data from the cost and return studies describe a typical production season but may vary from year-to-year based on rainfall.

Since this study focuses on freshwater stress in Ventura County, the results presented herein reflect applied irrigation water; any upstream water use (i.e., water embedded in the material and energy inputs) have been excluded from the analysis.

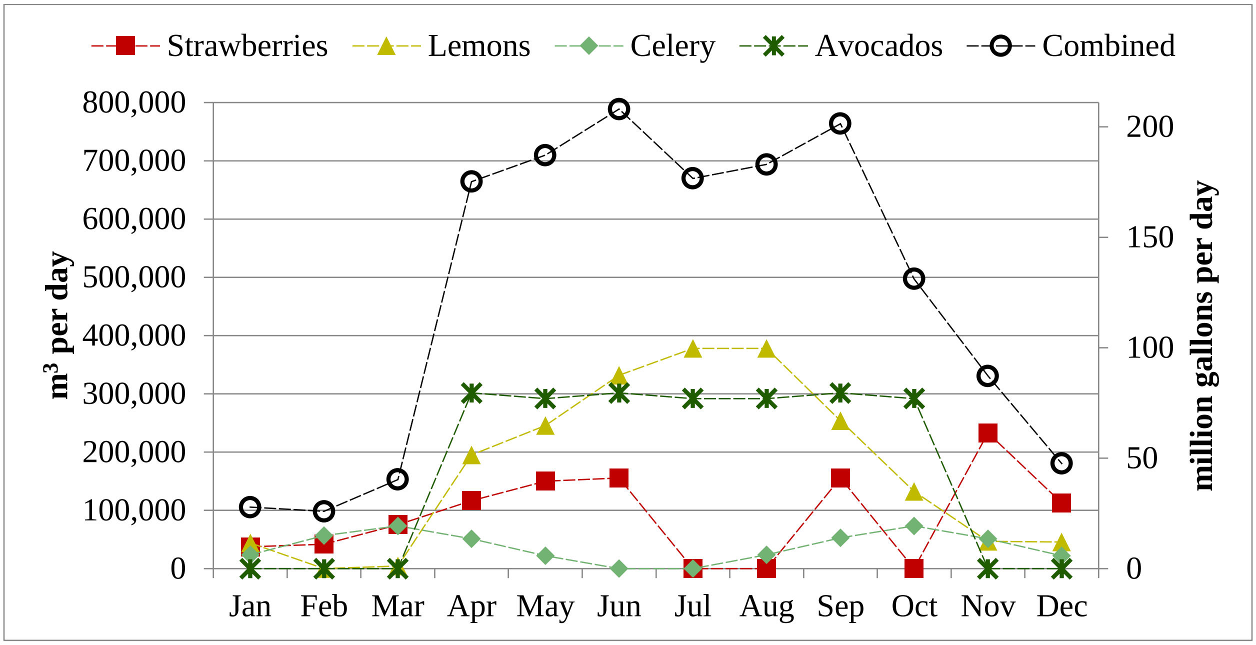

Figure 4. Monthly average applied water in Ventura County
[Modified from UC Davis cost and return studies]

This study estimates the changes in energy, GHG emissions, and costs associated with three alternative irrigation water sources: conventional irrigation (i.e., groundwater and surface water), recycled water, and desalinated water. The environmental impact of applied irrigation water was estimated for each crop on a field-by-field basis using GIS-based analysis. GIS shapefiles depicting urban areas, crops, wastewater treatment plants, and water purveyors were provided by the Ventura County Resource Management Agency [Moreno, 2016]. GIS shapefiles depicting groundwater basins were provided by the Ventura County Watershed Protection District [Dorrington, 2016]. The location of groundwater wells was obtained from the United States Geological Survey (USGS) National Water Information System [USGS, 2015].

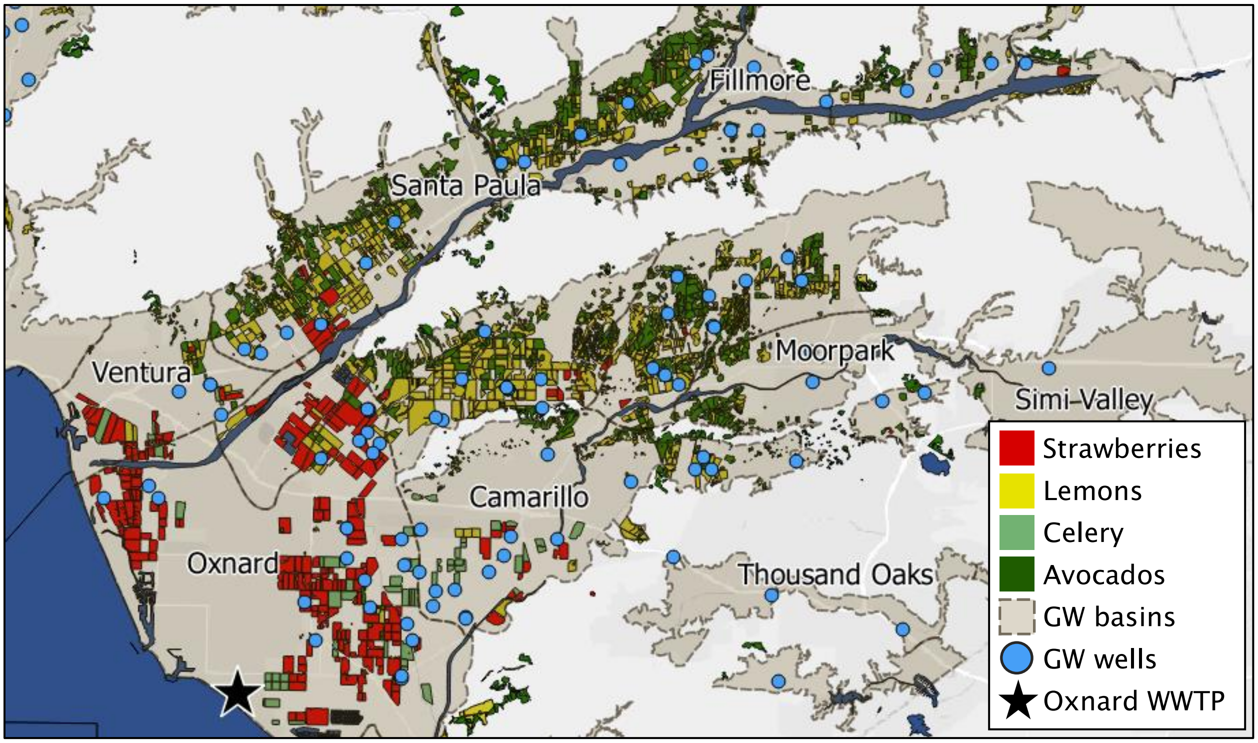

Figure 5. Geographic layout of farms and water sources in Ventura County
[Ventura County Resource Management Agency / Ventura County Watershed Protection District / USGS]

2.2.6.1 Conventional Irrigation

In Ventura County, approximately three-quarters of irrigation water is sourced from local groundwater and one-quarter from local surface water [USGS, 2010]. For each individual field, (1) we determined whether the field currently draws from groundwater or surface water based on the water purveyor, (2) if groundwater is used, we identified the groundwater depth of the closest well located within the same groundwater basin as the field, and (3) we quantified additional crop-specific on-farm water-related energy use. If the specific proportion of groundwater and surface water was unknown, the countywide average was applied. Groundwater depths were obtained from local groundwater reports [Clifford et al., 2014; Clifford et al., 2015]. In most cases, groundwater depths for each well were measured seasonally. Linear interpolation was used to estimate the depths of each well on a monthly basis. Figure 6 shows the average groundwater depth in Ventura County—based on over 150 well locations throughout the county—and the combined monthly water demand of all strawberry, lemon, celery, and avocado farms (i.e., the combined value from Figure 4). The average groundwater depth in the county dropped by nearly four meters between July 2013 and July 2014. Furthermore, the data illustrate that the rate of groundwater depletion is greatest when the irrigation demand of these four crops is high. Since there are other large water users in the county that are not seasonally-dependent (e.g., residential, industrial) as well as other crops, this correlation highlights the significance of the four crops considered in our analysis.

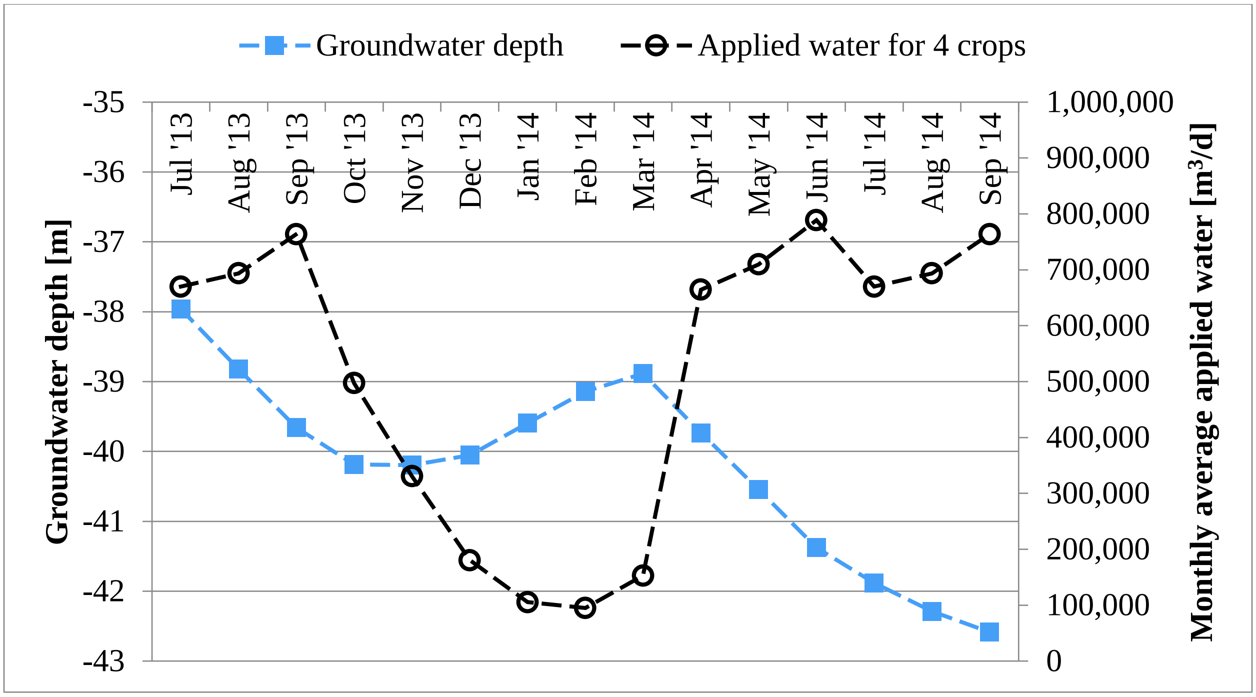

Figure 6. Average groundwater depth and estimated applied water for four crops in Ventura County

Notes: Seasonal groundwater depths for over 150 well locations were obtained from two regional groundwater reports [Clifford et al., 2014; Clifford et al., 2015]. Linear interpolation was used to estimate monthly groundwater depths given seasonal measurements. The data presented in the figure represent the average of all wells within Ventura County for which measurements exist. Applied water for the four crops was determined by scaling the "per-acre" monthly applied water demand for each crop by the total county-wide acreage. Monthly applied water demand water was determined from the cost and return studies [Daugovish et al., 2011; O'Connell et al., 2015; Takele and Daugovish, 2013; Takele and Faber, 2011]. County-wide acreage for each crop was determined from GIS crop shapefiles [Moreno, 2016].

The overall extraction energy (E_e) for irrigation water per unit area of land over the course of one year can be described by the following equation:

$$E_e = \frac{f_{GW}\rho g}{\eta}\sum_{m=1}^{12}[(d_m + DD + CL)V_m] + f_{SW}E_{SW}\sum_{m=1}^{12}V_m$$

Where: f_{GW} = *fraction of irrigation water from groundwater*
ρ = *density of water*
g = *gravitational constant*
η = *overall pumping plant efficiency*
d_m = *groundwater depth in month "m"*
DD = *drawdown*
CL = *column loss*
V_m = *total volume of water applied in month "m" per unit area of land*

f_{SW} = *fraction of irrigation water from surface water*
E_{SW} = *surface water extraction energy per unit volume (assumed to be negligible)*

The drawdown and column loss were assumed to be 11 m (35 ft) and 2.4 m (8 ft), respectively, based on the average values for the County's evapotranspiration zone [Burt et al., 2003]. In addition to extraction energy, additional on-farm energy was estimated from the literature based on the typical operating pressure of the crop-specific irrigation system [Phocaides, 2000].

2.2.6.2 Future Water Sources for Irrigation

Life-cycle energy, GHG emissions, and costs were recalculated after replacing conventional irrigation with alternative irrigation water sources (i.e., recycled water and desalinated water). Importing additional water for irrigation was not considered, as this option will likely not be available to growers due to California water policy [Brown et al., 2013].

For lemons and avocados, it was assumed that the two crops are irrigated together with the 80,600 m^3 per day (21.3 MGD) of secondary effluent available from Oxnard's WWTP. The model assumes that the lowest-elevation fields are supplied with water first, and irrigation continues until all of the available water has been used. Maps of the "irrigation sheds" for each pair of crops are available in Appendix A, which illustrate the extent of the acreage which could be irrigated using this water before supplies are depleted. The results presented herein are based on the average daily irrigation demand for the crops averaged over the year. In practice, the total acreage that could be supplied with recycled water will fluctuate somewhat from month-to-month based on temporal irrigation demands. Our analysis represents an average month. We assume that when recycled water is insufficient, supplementary water can be obtained through conventional means to make up the difference. Though not completely offsetting conventional water use for all farms, the recycled water would significantly reduce pressure on the existing supplies. The results for lemons and avocados take into account the energy, GHG emissions, and costs associated with distributing the secondary effluent from Oxnard's WWTP to the nearest fields and the construction of the distribution system.

For strawberries and celery, it was assumed that the two crops are irrigated together with the 61,500 m^3 per day (16.2 MGD) of advanced-treated effluent that would be available if the City of Oxnard were to follow through with the planned AWPF expansion. A recovery rate of 76% is assumed, based on the existing AWPF [Carollo Engineers, 2015b]. The results for strawberries and celery take into account the energy, GHG emissions, and costs associated with the construction of an expanded AWPF, the additional treatment required to bring the secondary effluent up to an advanced level, the distribution of the water to the fields, and the construction of the distribution system.

The desalination scenario takes into account the energy, GHG emissions, and costs associated with the construction of a seawater reverse osmosis desalination plant, the treatment of the water, the distribution of the water to the fields, and the construction of the distribution system. All scenarios assume the same on-farm irrigation energy use within each crop type, although on-farm irrigation energy use varies slightly from crop to crop (Table 5). In order to draw a fair comparison between the three scenarios, the same irrigation sheds were assumed for each scenario, and the same distribution systems were assumed for the recycled and desalinated scenario. The AWPF is located adjacent to Oxnard's WWTP, and this analysis assumes that the hypothetical desalination plant could be constructed in approximately the same location as well.

Table 4 and Table 5 summarize the data used for each scenario. Distribution energy was calculated for each individual field based on the piping distance, elevation gain, volumetric flow rate of water, and other relevant factors. Additional information and schematics for each scenario are included in Appendix A. Distribution energy for lemons and avocados is higher relative to strawberries and celery because the lemon and avocado orchards are located farther from the treatment facilities.

Table 4. Life-cycle energy intensity for alternative water supply scenarios [MJ/m^3 of applied water]

	Conventional	Recycled Secondary (lemons, avocados)	Recycled Advanced (strawberries, celery)	Desalinated
Extraction	0.53 to 13	–	–	–
Treatment	–	–	13 [i]	33 [ii]
Distribution	–	0.36 to 5.4	0.18 to 0.72	0.18 to 5.4

Notes: A dash indicates zero or negligible energy required.
References: (i) Holloway et al., 2016; (ii) Stokes and Horvath, 2009

Table 5. On-farm life-cycle energy intensity for irrigation by crop [MJ/m^3 of applied water]

Strawberries	Lemons	Celery	Avocados
1.4	1.3	1.4	1.6

Note: The data above were estimated based on the type of irrigation system (drip, sprinkler, or microsprinkler), the typical operating pressure of the system, and the regionally-specific electricity mix [Phocaides, 2000].

2.3 Results

Figure 7 and Figure 8 show the results for life-cycle energy use and operational costs per kilogram of produce, respectively. The life-cycle energy values per kilogram of produce were determined to be 12 ± 1, 2.9 ± 0.4, 1.7 ± 0.2, and 6.7 ± 2.1 MJ/kg for strawberries, lemons, celery, and avocados, respectively. The uncertainty ranges represent one standard deviation and were determined via Monte Carlo simulation. Appendix A shows the life-cycle GHG emissions for the four crops, including their uncertainty ranges. Additional information regarding the uncertainty assessment is available in Appendix A.

To express the energy results in terms of food energy, the energy to produce a strawberry is approximately 9 times greater than the caloric energy of the strawberry itself. For lemons, celery, and avocados, these factors are roughly 2, 2, and 1, respectively. The life-cycle GHG emissions per kilogram of strawberries, lemons, celery, and avocados were determined to be 0.63 ± 0.05, 0.19 ± 0.02, 0.10 ± 0.01, and 0.45 ± 0.13 kgCO_2e, respectively. For strawberries, the greatest contributor to energy and GHG emissions is materials, primarily the PET clamshells used for packaging. According to shipping reports from the U.S. Department of Agriculture, greater than 99% of strawberries shipped in the United States are packaged in 1-lb clamshells [USDA, 2017c]. While local farms may employ more sustainable packaging options, it appears that there are few other options currently available for long distance shipping. For lemons and celery, direct fuel use accounts for roughly half of the total energy and GHG emissions. For avocados, there is no single greatest contributor; biocides, direct fuel, applied water, and fertilizers contribute in roughly equal proportions to the energy use and GHG emissions. This analysis is not meant to advocate for a dietary substitution or cross-crop comparison, but rather to illustrate the substantial production differences between four high-value crops. The results obtained are generally comparable to previous LCA studies. A detailed discussion is included in Appendix A.

There are several sources of uncertainty in this analysis. For each of the four crops, a fraction of the on-farm operations was performed by a third-party contractor. The energy and environmental impacts associated with this work was estimated using proxy cost and return studies. In addition, a small fraction of agricultural inputs (e.g., saplings, nursery plants) were excluded from the energy and GHG footprints due to lack of reliable data. A detailed discussion of the sources of uncertainty can be found in Appendix A.

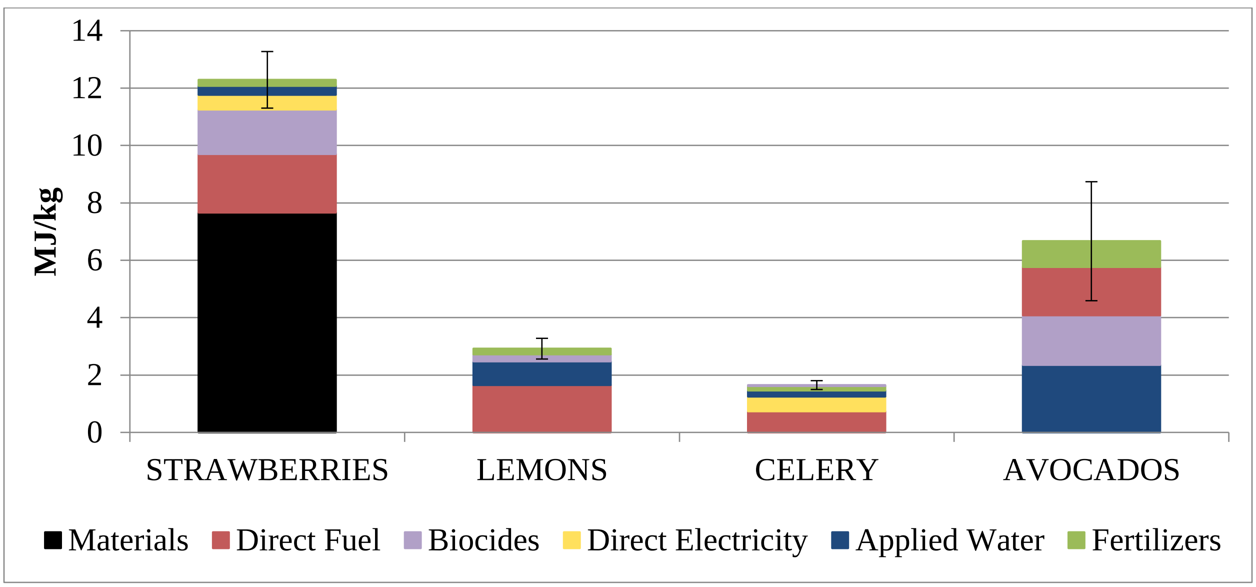

Figure 7. Baseline cradle-to-farm gate life-cycle energy use for four crops
Notes: The “Direct Electricity” and “Direct Fuel” categories exclude electricity and fuel used for irrigation water, which are included in the “Applied Water” category. Uncertainty bars represent one standard deviation as determined using a Monte Carlo simulation. The intent of this figure is to establish baseline energy values for each crop, rather than advocate for dietary substitution or provide a cross-crop comparison.

Labor is the single greatest contributor to operational costs, accounting for between 40% and 80% of the total. Excluding labor costs, material costs are the major contributor for strawberries and celery. Direct fuel and applied water are the most significant non-labor expenses for lemons and avocados, respectively. Growers typically pay between \$0.09 and \$0.26 per cubic meter for irrigation water, including pumping costs, but it is not uncommon for prices to increase significantly in drought years [Daugovish et al., 2011; O'Connell et al., 2015; Takele and Daugovish, 2013; Takele and Faber, 2011].

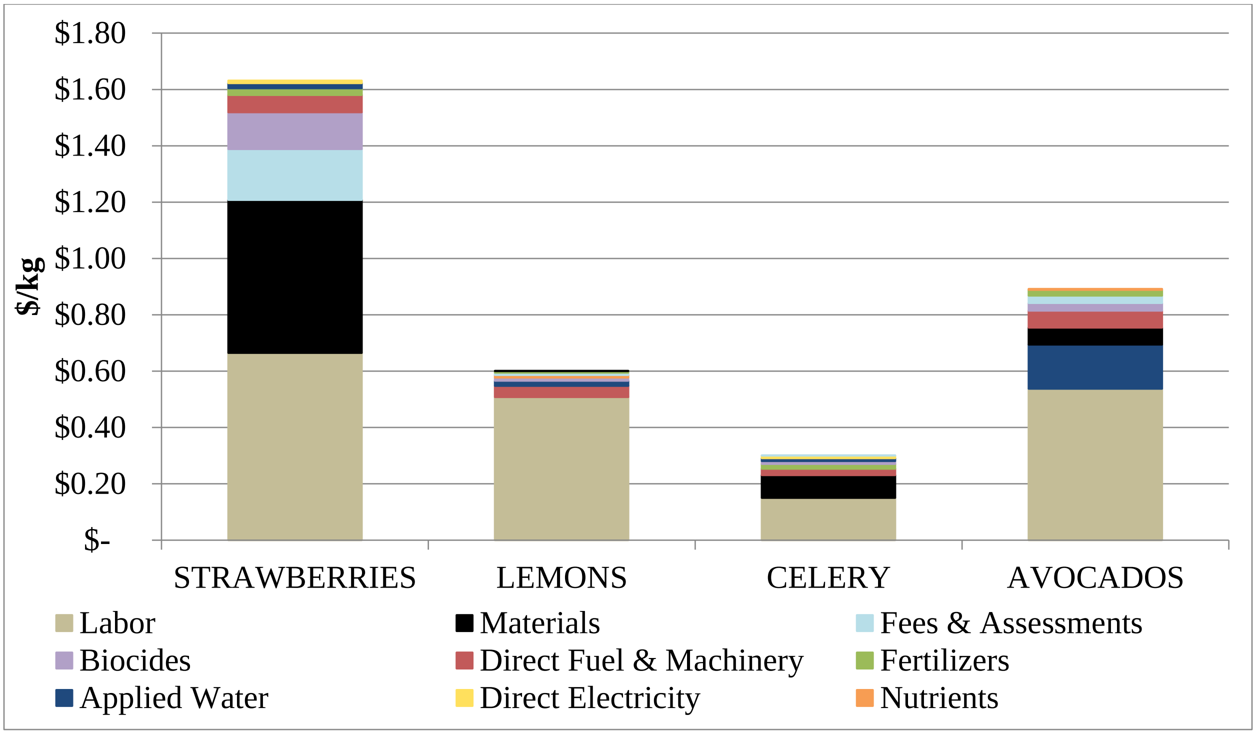

Figure 8. Baseline operational costs for four crops

Notes: "Operational Costs" refers to cultural costs, harvest costs, and assessments. It does not include interest on operating capital or overhead costs (e.g., land rent, property taxes, insurance). "Cultural costs" refer to all cultivation costs before, during, and after planting of the crops, but before harvest. The "Direct Electricity" and "Direct Fuel" categories exclude costs associated with electricity and fuel used for irrigation water, which are included in the "Applied Water" category.

The results for applied irrigation water and labor are shown in Figure 9 and Figure 10, respectively. From the perspective of water productivity, strawberries provide the highest returns, both in terms of value and mass (\$20 per m^3 of water applied, 0.1 m^3 of water per kg produced). Strawberries also require the most labor to produce. Avocados require six times the amount of water to produce the same mass as strawberries and result in one-fifth of the value. It is worth noting, however, that avocados have nearly five times the caloric content per unit mass relative to strawberries. Assessing quantity of water applied per calorie produced results in a much closer comparison; strawberries require 0.3 m^3 of water applied for every one million calories produced, compared with 0.4 m^3 for avocados. Given these results, it is feasible that crop switching may emerge as a strategy to promote economic growth in the face of limited freshwater resources; however, there are many other considerations at play (e.g., availability of suitable land), therefore assessing the impacts of crop switching was beyond the scope of this project.

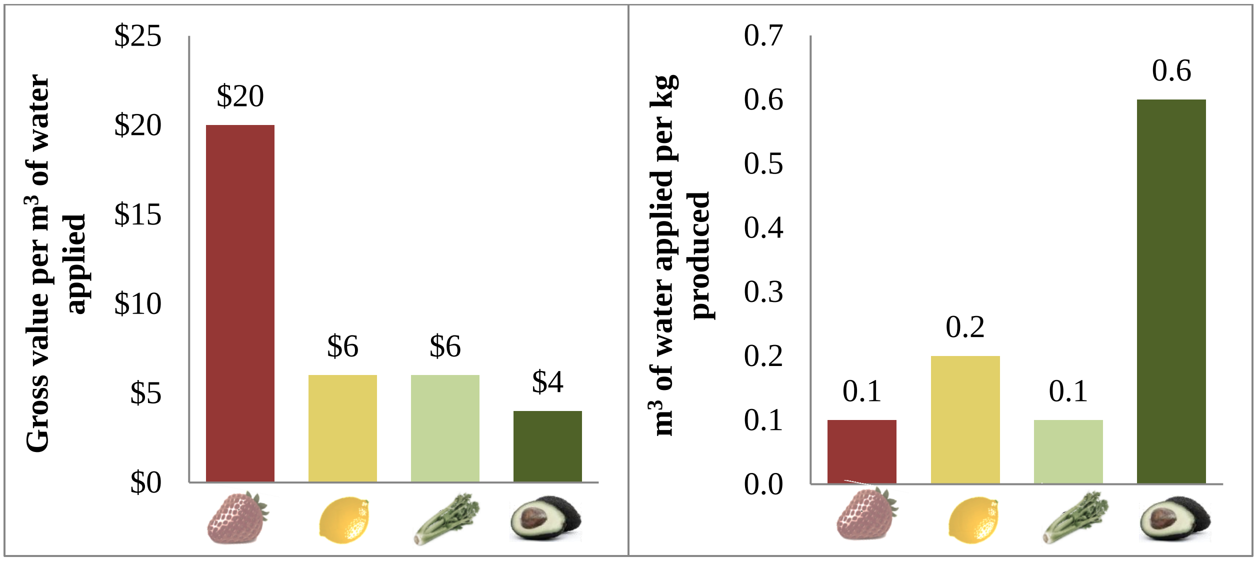

Figure 9. Applied water for four crops.
Note: “Gross value” refers to payments to the grower, plus any selling commissions and assessments

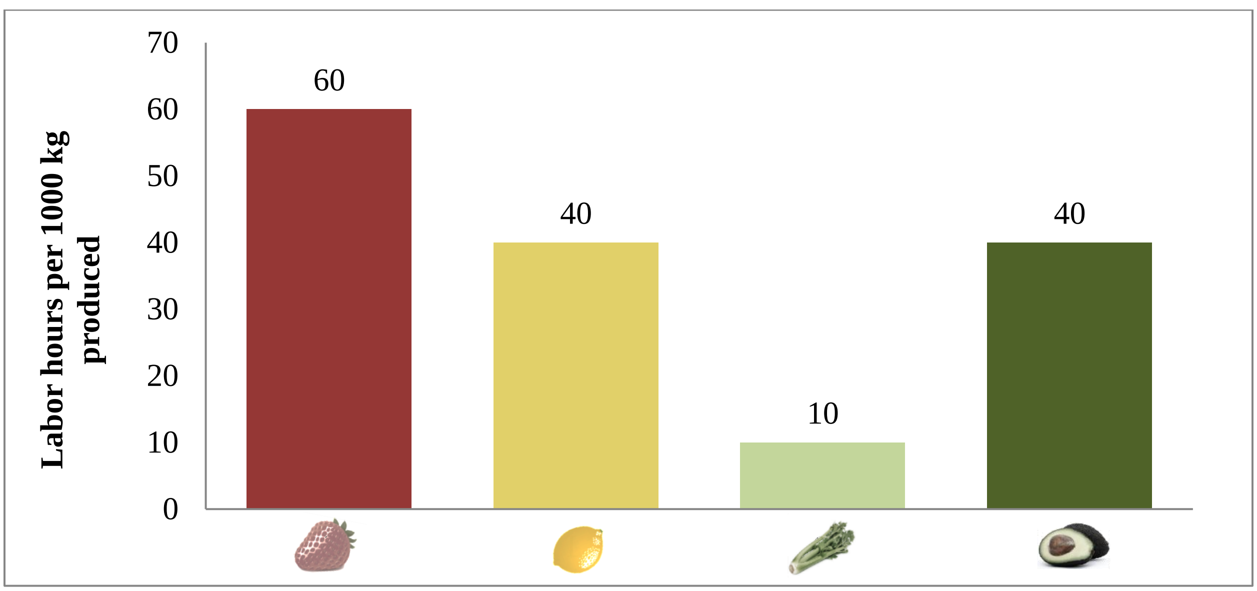

Figure 10. Direct (i.e., on-farm) labor required to produce four crops

Results for the scenarios using alternative irrigation water sources are presented in Figure 11, Figure 12, and Figure 13. These results illustrate a sharp contrast between recycled and desalinated water and emphasize the importance of a crop-by-crop analysis. Large-scale use of desalinated water for irrigation results in significant increases in energy use, GHG emissions, and costs—with the possible exception of strawberries. For lemons, celery, and avocados, switching to desalinated water would at least double life-cycle energy use and GHG emissions, and would increase operational costs by at least half. Although strawberries fare somewhat better due to their high value, a switch to desalinated water would still increase energy consumption by 28%, GHG emissions by 33%, and operational costs by 15%. Recycled water proves to be a better option in all four cases, but results vary greatly from crop-to-crop. A switch to recycled water appears to be most practicable for strawberries, a high-value crop with relatively low irrigation demand. The purchase price of secondary recycled water was assumed to be $0.77 per cubic meter [Cooley and Phurisamban, 2016]. This estimate assumes that the secondary effluent itself is free; the only costs are associated with distribution. The purchase price of advanced recycled water was assumed to be $1.15 per cubic meter, per the City of Oxnard's current rate for recycled water for irrigation [Carollo Engineers, 2015a]. Finally, the purchase price of desalinated water was assumed to be $2.31 per cubic meter [Cooley and Phurisamban, 2016]. This estimate assumes $1.54 per cubic meter for treatment and $0.77 per cubic meter for distribution [Cooley and Phurisamban, 2016].

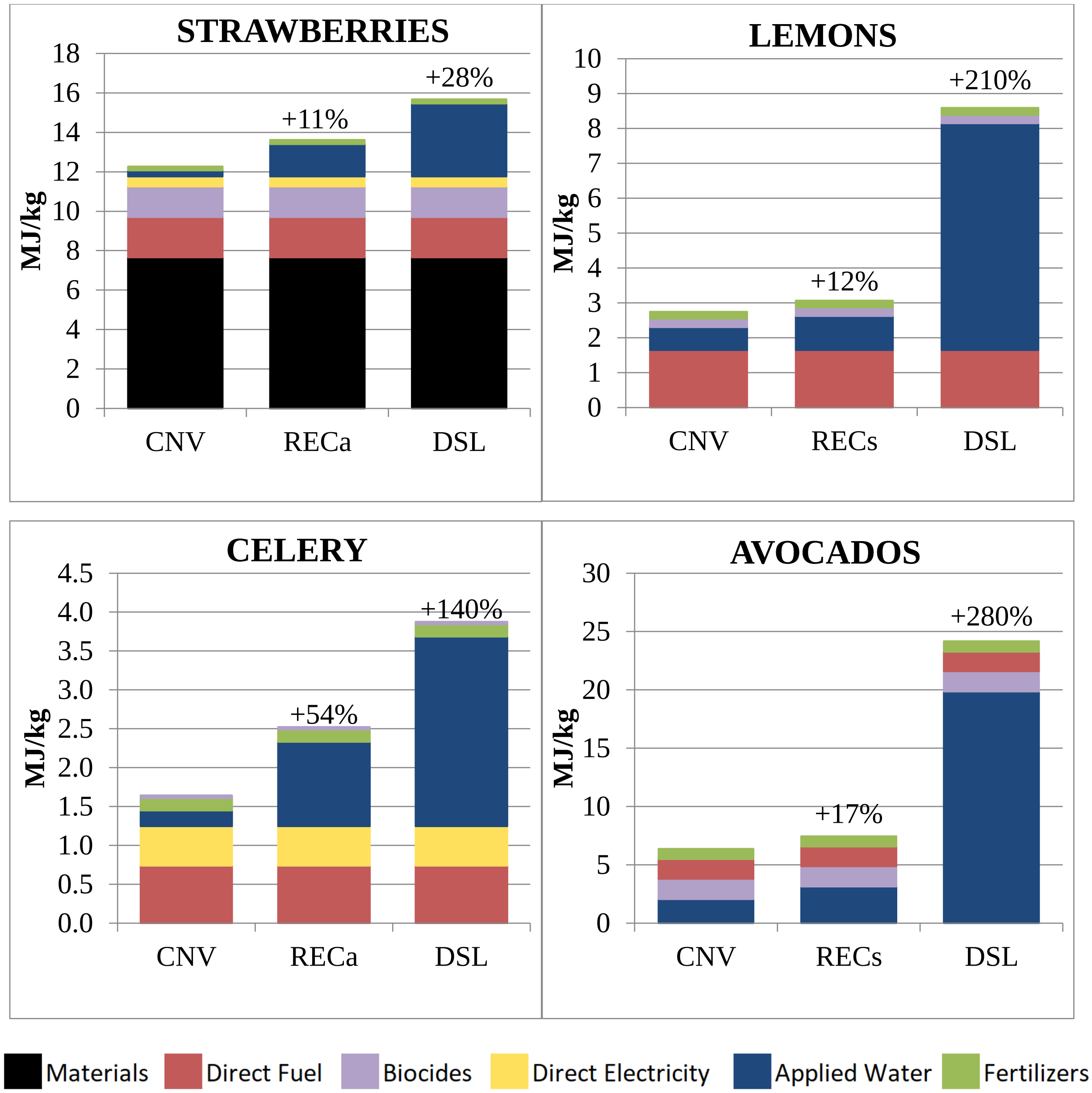

Figure 11. Life-cycle energy for conventional irrigation (CNV), recycled secondary water (RECs), recycled advanced water (RECa), and desalinated water (DSL)

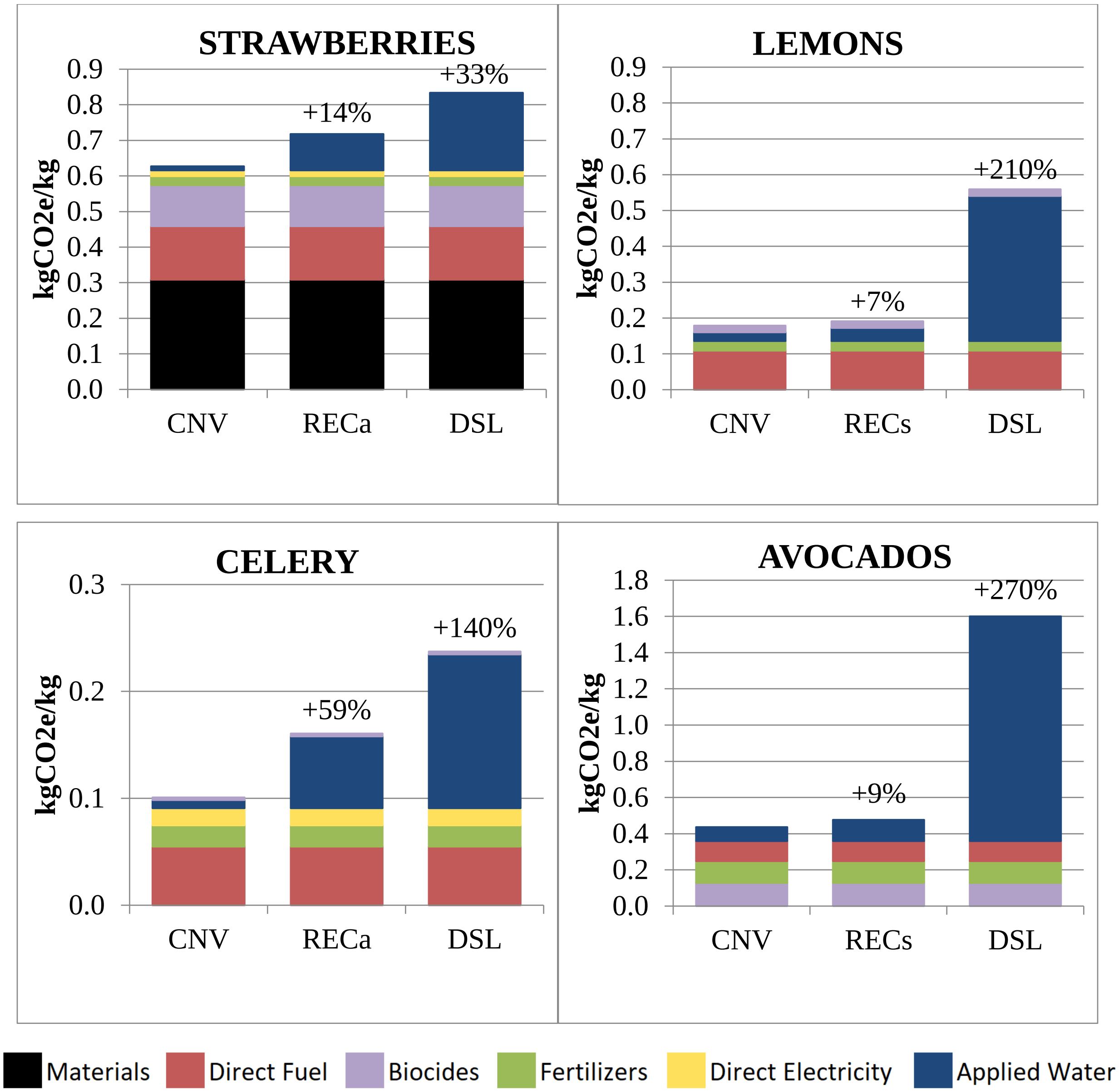

Figure 12. Life-cycle GHG emissions for conventional irrigation (CNV), recycled secondary water (RECs), recycled advanced water (RECa), and desalinated water (DSL)

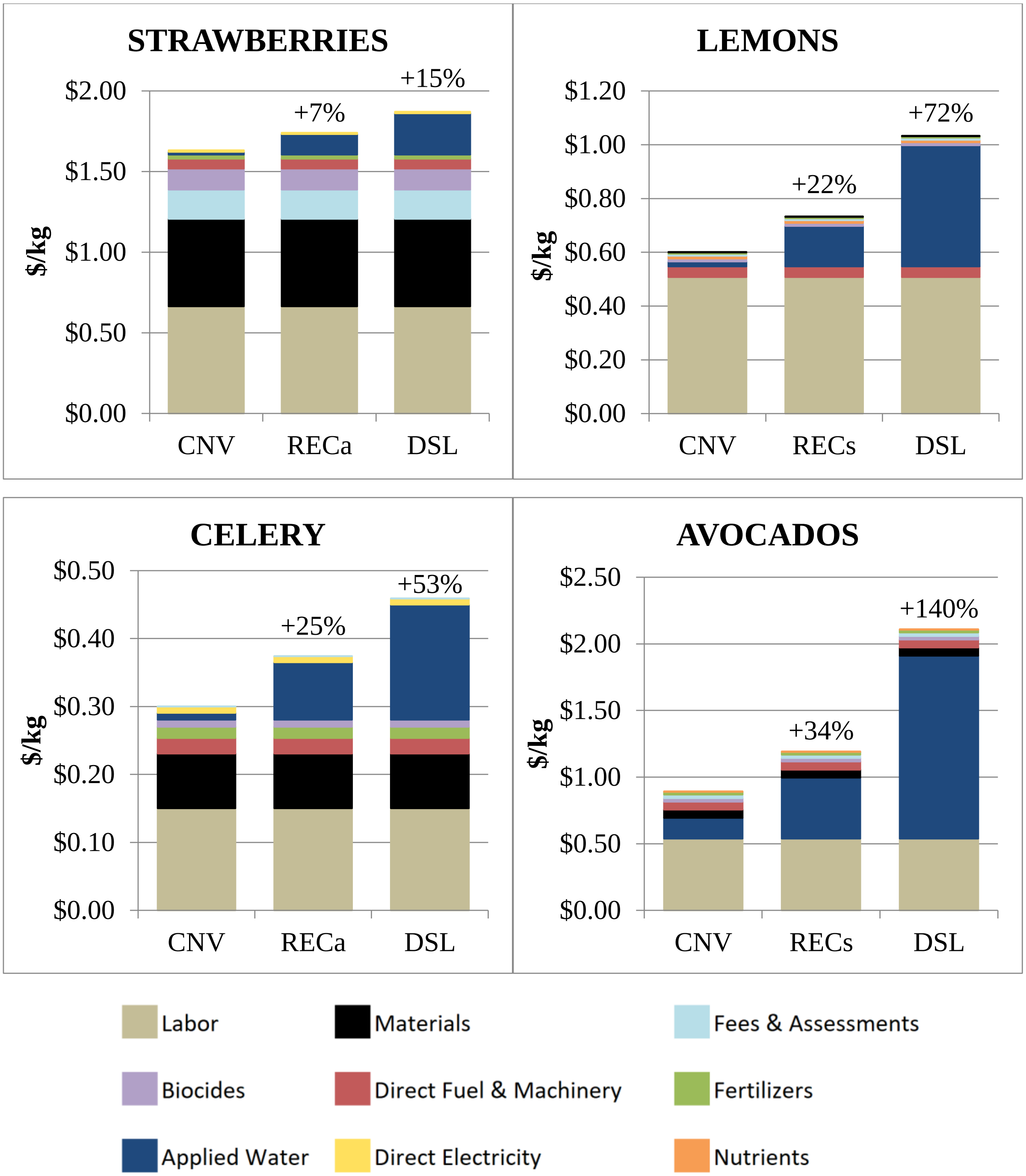

Figure 13. Operational costs for conventional irrigation (CNV), recycled secondary water (RECs), recycled advanced water (RECa), and desalinated water (DSL)

2.4 Discussion

Maintaining agricultural production—and subsequently, employment—in drought-prone areas such as Ventura County will require that growers have access to diverse and reliable sources of water. While this analysis considered extreme scenarios involving the complete substitution of irrigation water sources, a hybrid approach may prove more practical. Growers may wish to blend multiple irrigation water sources for reasons of economy, reliability, or water quality. This analysis stopped short of addressing the specific water quality needs of each crop, but blending may prove necessary to meet these needs.

While the technologies for water recycling and desalination are proven and mature, a significant barrier exists in the adoption of alternative water sources by growers. Our analysis indicates that switching to an alternative water source would result in at least a factor of 3 increase—and more likely, an order of magnitude increase—in the average cost of irrigation water. Furthermore, there is likely a reluctance on the part of growers to disrupt the status quo and place their trust in an unfamiliar system. At the same time, some growers may be willing to pay a premium for the consistency and reliability in both quality and quantity that alternative water sources can provide. Regardless of the challenges, diverse water sources must be deployed if Ventura County is to maintain agricultural production; the current situation, whereby groundwater overdraft is accelerating saltwater intrusion, is unsustainable.

While the analysis only considered four of Ventura County's top crops, a more comprehensive assessment would likely reduce the energy and GHG emissions associated with alternative water sources by decreasing distribution distances and elevations. Strawberries and celery resulted in less distribution energy in our analysis compared with lemons and avocados because they are primarily grown in the Oxnard Plain and are therefore relatively close to the treatment facilities. Expanding the analysis to include raspberries and other row crops would result in smaller irrigation sheds, reducing both pumping energy and the extent of the piping network.

In addition, while this study is specific to a particular growing region and selection of crops, the results have significant implications for other coastal growing regions throughout the United States and abroad. In particular, the use of recycled water for crop irrigation has been successfully implemented in Florida (citrus) and Monterey County, California, (artichokes, lettuce, strawberries, celery, and others) as a means of slowing coastal saltwater intrusion [Parsons et al., 2010]. In the absence of technological intervention, saltwater intrusion throughout much of coastal North America will worsen as a result of increased groundwater use [Barlow and Reichard, 2010]. More importantly, recycled water has the potential to address groundwater overdraft issues nationwide, regardless of whether saltwater intrusion is of concern.

There are a few additional benefits associated with switching to alternative water sources. Well water in the Oxnard area was found to have an average salinity more than seven times higher than water from Oxnard's AWPF [Sheikh, 2014]. Salinity is known to impede the growth of plants [Shannon, 1997]. A recent study of agriculture in Ventura County suggests that switching to AWPF water could increase yields of strawberries, lemons, celery, and avocados by 62%, 47%, 22%, and 60%, respectively, as a result of decreased salinity [Sheikh, 2014]. If such yields could be realized in practice, this would greatly impact the results presented herein, likely rendering recycled water competitive with conventional irrigation with regards to energy, GHG emissions, and cost. In addition, a switch to lower-salinity water could reduce the overall quantity of water required for irrigation by reducing the leaching requirement needed to prevent salt buildup in the root zone. Quantifying these effects was beyond the scope of this project. Furthermore, while this project stopped short of addressing nutrient management, the application of recycled water with nutrient retention has the potential to offset certain chemical fertilizer requirements, leading to benefits in cost and environmental impacts.

2.5 Conclusion

This analysis used highly localized data to assess the energy and GHG footprints of four high-value crops in one of the most significant agricultural regions in the United States and the world, and estimated the impacts of using alternative water sources for irrigation. Converting from conventional groundwater and surface water irrigation to future water sources such as recycled and desalinated water requires a careful analysis of energy, environmental, and cost impacts. Our model indicates that the lower treatment energy associated with recycled water makes it a more tenable option relative to desalination across all four crops considered, but the results vary greatly from crop to crop. High-value crops that are located in close proximity to water treatment facilities are the most likely candidates for recycled water. For certain crops, however, packaging is potentially a significant contributor to the overall environmental impact, and in the case of strawberries, was found to be more significant than the water source or any other production input.

Future work is needed to address some of the study's limitations, such as the focus on a single growing region, selection of crops, and termination of the analysis at the farm gate. Furthermore, there is currently only a small number of real-life alternative water systems with agricultural applications from which to draw data. A more comprehensive nationwide and worldwide model must be developed in tandem with regionally-specific life-cycle crop footprints and local water data. The development of such a model is crucial for the assessment and planning of future of agricultural systems both in California and throughout the world.

Chapter 3.

Modeling the Carbon Footprint of Fresh Produce: Effects of Transportation, Localness, and Seasonality on U.S. Orange Markets

The following chapter is adapted from Bell E M and Horvath A 2018 Modeling the carbon footprint of fresh produce: effects of transportation, localness, and seasonality on U.S. orange markets Environmental Research Letters (under review), with permission from Arpad Horvath.

Agriculture is one of the most significant ways that we interact with the environment. Food production is expected to increase 70% by 2050 as a result of population growth and the emergence of the global middle class. Meeting the expected demand in a sustainable manner will require an integrated systems-level approach to food, energy, and water. In this paper, we present a general model for estimating the cradle-to-market life-cycle greenhouse gas emissions impact of fresh produce commodities, including the production, post-harvest processing, packaging, and transportation stages. Using oranges as a case study, we estimate the carbon footprint per kilogram of fruit delivered to wholesale market in New York City, and assess the relative importance of transportation mode, transportation distance (i.e., localness), and seasonality. We find that the cradle-to-market carbon footprint of oranges delivered to New York City varies by a factor of three, depending on the production origin (0.28 $kgCO_2e/kg$ for California vs. 0.83 $kgCO_2e/kg$ for Mexico). Transportation mode was found to have a significant impact on the results; transportation-related greenhouse gas emissions associated with oranges trucked from Mexico to New York City were found to be six times higher than those transported by containership from Chile, in spite of traveling less than half the distance. This result can be attributed to the roughly order-of-magnitude differences in freight emission factors for truck, rail, and containership. Seasonality was found to have an impact on the results: “out-of-season” oranges in New York City have an average carbon footprint roughly 30% higher than “in-season” oranges. This study highlights the value of regionally-specific carbon footprints for fresh produce and the need for a consistent and standardized data reporting framework for agricultural systems.

3.1 Introduction

Agriculture imposes significant demands on the world's natural resources while releasing large quantities of pollutants. It is estimated that our global food system accounts for roughly one third of energy consumption and 70% of all water withdrawals worldwide [UNESCO, 2014]. Moreover, agriculture—as defined by both crop and livestock production—currently occupies 50 million square kilometers of land, roughly half of the Earth's habitable land area [World Wildlife Fund, 2016]. In the process, it is responsible for at least one quarter of global greenhouse gas (GHG) emissions [IPCC, 2014]. This is to say nothing of the host of other resource and environmental impacts including conventional air pollution, eutrophication, groundwater contamination, habitat destruction, and species extinction. In short, agriculture is one of the most impactful ways that we interact with our environment. Ensuring the sustainable growth of agriculture is critical to our continued welfare.

Several prominent global trends present challenges to the long-term sustainability of our food system. It is estimated that the world's population may grow to over 9 billion by 2050 [United Nations, 2011]. In addition, the global middle class is expected to increase to over 5 billion by 2030—up from 3 billion today—shifting current consumption practices, and the subsequent demand for certain goods and services [Kharas, 2017]. As a result of these trends, food production must increase by an estimated 70% by 2050 to meet demand [United Nations, 2011]. Further complicating matters, the percentage of the world's population living in urban areas is expected to increase to 66% by 2050—up from 54% today—leading to lifestyle changes and greater transportation distances between production and consumption hubs [United Nations, 2015].

In this paper, we develop a modeling framework to characterize the environmental impact of fresh produce (i.e., fresh fruits and vegetables) supply, applicable in the United States but also in other places in the world where supply chains are similar. The model calculates "cradle-to-market" life-cycle carbon footprints (in kilograms of carbon dioxide equivalent [CO_2e] emitted per kilogram of produce delivered to market), including production, post-harvest processing, packaging, and transportation. Using oranges as a case study, we illustrate the variability in the carbon footprint of fresh fruit delivered to a wholesale market in New York City, Los Angeles, Chicago, and Atlanta, broken down by transportation mode, production region, and season. We discuss how the model can be used to optimize the food supply system in the United States by minimizing the seasonally-varying GHG emissions per unit of food delivered to market.

Literature review has yielded nine cradle-to-farm gate life-cycle assessment (LCA) studies of producing oranges, in various geographic regions.[3] The studies yielded average emissions of 0.17 $kgCO_2e$ per kilogram of oranges produced with a minimum of 0.07, a maximum of 0.31, and a standard deviation of 0.10 $kgCO_2e$. These values reflect production only; post-harvest processing, packaging, and transportation were not accounted for. A summary of the literature is provided in Appendix B. The results presented herein are unique in their application of a modeling framework

[3] Audsley et al., 2009; Beccali et al., 2009; Dwivedi et al., 2012; Gonzalez et al., 2011; Jungbluth et al., 2013; Knudsen et al., 2011; Pergola et al., 2013; Ribal et al., 2017; Yan et al., 2016

to regionally-specific carbon footprints and temporal variations in an average city-wide carbon footprint.

This study focuses specifically on the demand for fresh produce in the United States. The U.S. food system as a whole is responsible for the emissions of approximately 2.6 metric tons of carbon dioxide equivalent per person per year [Weber and Matthews, 2008]. By our calculations, this accounts for roughly 10% of overall U.S. GHG emissions [Weber and Matthews, 2008; US EPA, 2016]. Fresh produce, in turn, accounts for roughly one-tenth of GHG emissions within the food system, or approximately 1% of overall U.S. GHG emissions [Weber and Matthews, 2008].

Fresh produce makes for an interesting case study for a number of reasons. First, the environmental impact of fresh fruits and vegetables can vary significantly with geography. One study found the carbon footprint of strawberries produced in North Carolina to be three times higher than those produced in California [Tabatabaie and Murthy, 2016]. A principal reason for this discrepancy is California's optimal growing climate, which delivers higher yields relative to other production regions. By varying the supply portfolio of a particular crop to favor higher-yield production regions, a wholesaler could mitigate the environmental impact of a particular commodity over the course of a year. In addition, the carbon footprint of fresh produce can be influenced by variable production practices such as the source of irrigation water [Bell et al., 2018]. Second, transportation is of relative importance for fruits and vegetables. Although transportation accounts for only 11% of the carbon footprint of all U.S. food on average, it makes up 28% of the carbon footprint of fruits and vegetables [Weber and Matthews, 2008]. This allows for the possibility of mitigating the environmental impact of certain fresh produce commodities by redesigning supply networks or integrating emerging transportation technologies. Third, fruits and vegetables are highly perishable, resulting in higher rates of food loss[4] (roughly 30% in North America) relative to other food groups such as meat (~10%) and grains (~10%) [Gustavsson et al., 2011]. The relatively short shelf life of fresh produce also eliminates the possibility of long-term storage. Last, unlike staple crops such as corn and wheat, fruits and vegetables are high-value specialty commodities. This increases the likelihood that the integration of an emerging technology into the supply chain would be economically viable. In addition, demand for such specialty crops will only increase with the growth of the global middle class. Knowledge of this imminent growth allows us the opportunity to prepare early for the expansion of the fresh produce market in a manner that is deliberate and sustainable.

[4] While the exact definition of 'food loss' is not universal, it refers herein to the decrease in the edible food mass throughout the production, post-harvest, processing, and transportation-to-market stages of the food supply chain. Food loss does not include losses at the retailer or consumer stages, which are generally categorized as 'food waste.' Considered collectively, over 50% of fruits and vegetables are lost or wasted in North America [Gustavsson et al., 2011].

3.2 Methods

The environmental impact (EI) of a given agricultural commodity delivered to a given U.S. city—measured in kilograms of CO_2e per kilogram of produce—can be expressed for each production region (i) by Equation 1:

$$EI_i = PD_i + \frac{PS_i}{(1 - l_{PS})} + \frac{PK}{(1 - l_{PK})} + \frac{TR_{AVGi}}{(1 - l_{TR})} \quad < Eq. 1 >$$

Where:

PD = GHG emissions associated with the production stage (i.e., cultivation and harvest)
PS = GHG emissions associated with the post-harvest processing stage
PK = GHG emissions associated with packaging
TR_{AVG} = GHG emissions associated with the transportation of the commodity from the production region to a wholesale market in a given U.S. city
l_{PS}, l_{PK}, l_{TR} = food loss during the processing, packaging, and transportation stages, respectively

Figure 14 further breaks down the individual processes included in the model. A detailed explanation of each stage follows.

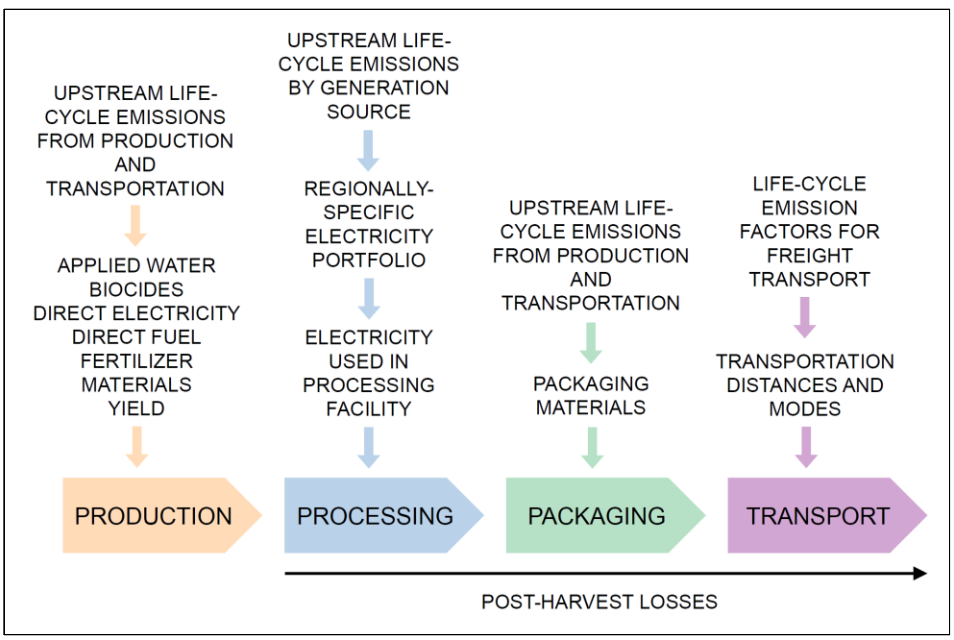

Figure 14: Process flow diagram for agricultural production and supply model

3.2.1 Production

GHG emissions associated with the production of fresh produce include all on-farm inputs (applied water, biocides, direct electricity use, direct fuel use, fertilizer, and materials) as well as the upstream GHG emissions associated with the production and supply of these inputs. Carbon footprints associated with the production stage were taken from the available literature (as described below and shown in Appendix B). Since the environmental impact of a particular crop can vary geographically, there would ideally be one characteristic life-cycle carbon footprint available for each geographic production region. Unfortunately, this is not currently the case. One recent publication conducted a literature review of over 350 LCA studies of various food crops and growing regions, encompassing over 1,700 carbon footprints [Clune et al., 2017]. In spite of this comprehensive effort, the resulting database is far from complete. The majority of the studies are specific to Europe; many crops have not been assessed at all in the United States, let alone at the state or county levels. In addition, a cross-comparison between life-cycle studies from different authors is not prudent due to differing boundary definitions and assumptions.

In light of these findings, the model used herein estimates the production-related GHG emissions for each production region by modulating the GHG emissions impact per unit area of farmland by the regionally-specific annual yield, per Equation 2:

$$PD_i = \frac{PD^*}{Y_i} \quad < Eq. 2 >$$

Where:

PD_i = GHG emissions associated with crop production, by production region, per unit mass produced [kgCO_2e/kg]

PD^* = GHG emissions impact per unit area of farmland [kgCO_2e/ha]

Y_i = average annual net harvested yield,[5] by production region [kg/ha]

This method assumes that the regional carbon footprint of a particular crop is roughly inversely proportional to the regionally-specific crop yield. While this approach is not ideal, other studies have found correlations between the carbon footprint of specialty crops and output yield [Yan et al., 2016; Tabatabaie and Murthy, 2016]. Climate was identified as one of the most significant factors in these yield variations. Production regions whose climates are ideally suited to a particular crop will have higher crop outputs per unit hectare and therefore lower GHG emissions per unit output.

The GHG emissions impact per unit area of farmland used in this model (PD^*) was determined from the literature. Domestic yields were determined at the state level from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) Quick Stats Database based on a five-year average from 2012 to 2016 [USDA, 2017b]. International yields were determined at the national level from geographic information system (GIS) land use data sets

[5] "Net harvested yield" refers to "[t]he portion of total crop production removed from the field, expressed as a quantity per unit of area, and derived by deducting harvesting and other losses from the biological yield." [0]

developed by the University of Wisconsin Center for Sustainability and the Global Environment (SAGE) and McGill University's Department of Earth System Science Program [Monfreda et al., 2008; EarthStat, 2018]. International yields are based on a five-year average from 1997 to 2003.

3.2.2 Processing

The post-harvest processing stage may include electricity from post-harvest cooling and from packaging facilities (e.g., cleaning, grading, sorting). Electricity consumption per unit mass of food was determined from the literature. Since post-harvest processing occurs at or near the point of harvest, regionally-specific electricity mix portfolios were used to estimate the GHG emissions from electricity consumption per unit mass of food processed. Domestic electricity portfolios were determined at the state level from the U.S. Environmental Protection Agency's (EPA's) Emissions & Generation Resource Integrated Database (eGRID) [US EPA, 2017]. International electricity mixes were determined at the national level from The World Bank Group [The World Bank Group, 2018]. Life cycle GHG emission factors by electricity generation type were determined from the literature [Gursel, 2018].

3.2.3 Packaging

This model assumes that the GHG emissions impact of packaging is independent of the production region. It further assumes that packaging is uniform, as determined by the most common packaging configuration. Data on the carbon footprint of packaging materials were taken from the literature.

3.2.4 Transportation

The GHG emissions associated with transporting fresh produce from farm to market are a function of the transportation mode (truck, rail, containership); the transportation distances between the origin (i.e, production-weighted centroid for each region) and destination (i.e., wholesale market); and freight emission factors. The freight emission factors applied in this model are 86 gCO_2e/tkm for truck, 13 gCO_2e/tkm for rail, and 4.6 gCO_2e/tkm for containership [Taptich et al., 2015]. All transportation modes, except for truck, are technically multimodal (i.e., maritime and rail transportation also use trucks for first- and last-mile deliveries); the "mode," therefore, references the primary mode of transportation. The average transportation emissions for each production region, weighted by transportation mode, can be described by Equation 3:

$$TR_{AVGi} = \sum_{n=1}^{N} \left[SM_{ij} .* TR_{ij} \right] \forall\, m \quad < Eq. 3 >$$

Where:

SM_{ij} = matrix describing the proportional food supply by production region (i) and transportation mode (j)

TR_{ij} = matrix describing transportation emissions by production region (i) and transportation mode (j)

m = matrix row

n = matrix column
N = total number of columns in matrix

The supply-by-mode (SM_{ij}) matrix is based on movement reports from the USDA Agricultural Marketing Service (AMS) [USDA, 2017c]. The reports describe the quantity, transportation mode, origin, and packaging of common crops shipped within the United States. The results presented herein are based on a five-year average from 2012 to 2016.

The transportation (TR_{ij}) matrix is based on the transportation distances between origin and destination and the mode-specific freight emission factors. Precise production origins were determined by calculating the production-weighted centroid of each production region, based on the SAGE/McGill GIS land use data sets [Monfreda et al., 2008; EarthStat, 2018]. Destinations were defined as the largest wholesale produce market in the chosen U.S. city. Trucking transportation distances were determined via Google Maps. Rail transportation distances were determined from GIS datasets of intermodal rail hubs and U.S. Department of Transportation (DOT) railroad lines [Oak Ridge National Laboratory, 1998; US DOT, 2017]. First, Google Maps was used to determine the shortest trucking route from the production origin to the closest intermodal rail hub. Next, a shortest-path algorithm was used to compute the shortest distance between the origin hub and the destination hub along the DOT railroad network. The destination hub was defined as the closest intermodal hub to the destination wholesale market. Lastly, Google Maps was again used to determine the shortest truck route from the destination hub to the wholesale market. Containership transportation distances were determined based on tables of nautical shipping distances between major ports [National Geospatial-Intelligence Agency, 2001]. First, Google Maps was used to determine the shortest trucking route from the production origin to the closest major port. Next, the nautical shipping distance between the origin port and the destination port was determined. The destination port was determined from the USDA AMS movement reports [USDA, 2017c]. Lastly, Google Maps was again used to determine the shortest trucking route between the destination port and the wholesale market.

3.2.5 Food Loss

Food loss was determined from USDA's Loss-Adjusted Food Availability Dataset [USDA, 2017a], which reports the total percentage of specific fruits and vegetables in the U.S. that are lost between the post-harvest and the delivery-to-market stages. Due to a lack of more detailed information, the model used herein assumes that losses are distributed equally across the processing, packaging, and transportation stages. Since the yield data used in this analysis represents the net harvested yield, food loss at the production stage is already accounted for.

3.2.6 Weekly Weighted-average Environmental Impact

By determining the proportion of demand met by each of the production regions in each week during the year, it is possible to calculate a weighted-average carbon footprint for a given crop and illustrate how this carbon footprint varies seasonally. The weighted-average carbon footprint of a given agricultural commodity delivered to a given U.S. city in a particular week (k) can be described by Equation 4:

$$EI_{AVGk} = SW_{ki} * EI_i \quad < Eq. 4 >$$

Where:

SW_{ki} = matrix describing the proportional supply by week (k) and production region (i)
EI_i = vector describing the environmental impact of an agricultural commodity delivered to a given U.S. city by production region (i), as determined from Equation 1

The supply-by-week (SW_{ki}) matrix is based on movement and terminal market reports from the USDA AMS, aggregated at the weekly level [USDA, 2017c; USDA 2017d]. The results presented herein are based on a five-year average from 2012 to 2016. Movement reports were used to determine the proportion of the United States' total demand met by each production region in each week during the year. Since the movement reports only include data on the origin—but not the destination—of agricultural shipments, city-level supply matrices had to be estimated by adjusting national-level movement data based on city-level terminal market reports. The terminal market reports declare the prices and origins of shipments received by all major U.S. cities on a weekly basis. National-level data had to be adjusted by eliminating any production regions which did not contribute to the given U.S. city's supply in a given week. Additional information regarding this approach is available in Appendix B.

3.2.7 Case Study: Oranges Supplied to New York City

The New York City orange market was selected as a case study for several reasons. First, oranges are one of the most popular fresh produce items in the United States. Roughly 5 kg of fresh oranges are consumed per capita in the U.S. annually,[6] ranking fourth on the list of most popular fresh fruits—behind bananas, melons, and apples [USDA, 2017a]. New York City is the largest U.S. city, the Hunt's Point Cooperative Market (the major distribution hub for the New York City metro area) is the largest facility of its kind in the world, and New York City is not located near any major orange production regions which may dominate the analysis. Results for the Los Angeles (#2 city), Chicago (#3 city), and Atlanta (close to the Florida growing region) orange markets are included Appendix B. Second, the seasonal variability in orange supply makes for an interesting case study. Fresh oranges consumed in New York City are supplied by either California or Florida for the majority of the year, but during a particular period from mid-July to mid-October, fresh oranges are not available from either of these two regions, and demand for fresh oranges are met with imports from Chile, South America, and Australia (Figure 15). A small quantity of oranges is also supplied by Texas and Mexico. Lastly, the relative uniformity of fresh orange packaging simplifies the analysis of this fruit.

As illustrated by Figure 15, seven regions supply oranges to New York City. The annual average orange yields for these seven regions range from 12,000 kg/ha (Mexico, Peru) to 29,000 kg/ha (California). A GHG emissions impact of 5,570 $kgCO_2e/ha$ with a standard deviation of 3,050 $kgCO_2e/ha$ was assumed per the literature [Ribal et al., 2017] and adjusted to account for variations

[6] This does not include the additional 20 kg of oranges consumed per capita annually in the form of juice (roughly 12 liters per person per year) [USDA, 2017a].

in yield. A Monte Carlo assessment was conducted to assess—among other factors—the uncertainty in GHG emissions per hectare and crop yield.

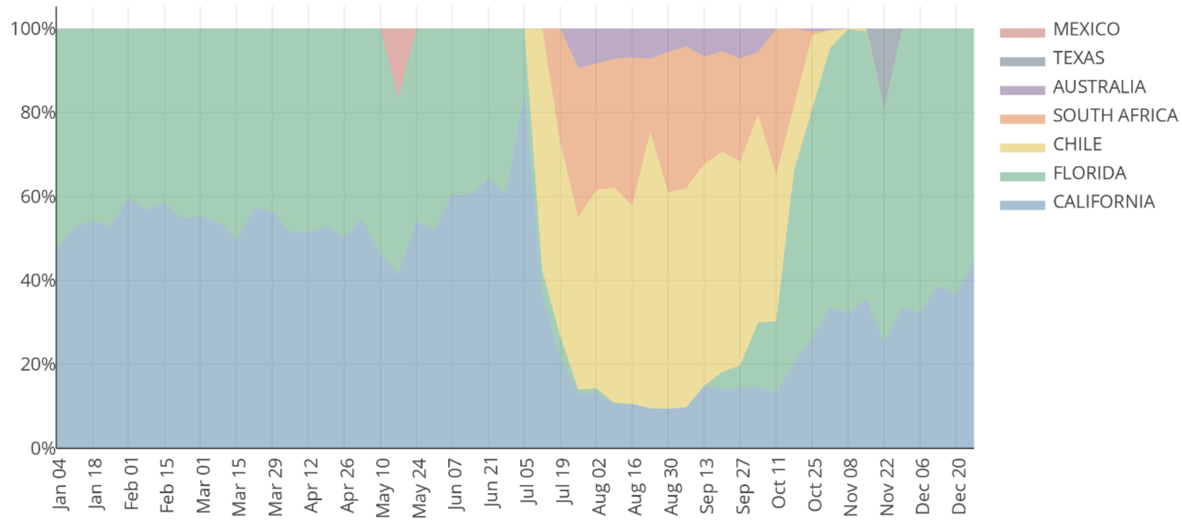

Figure 15: New York City fresh orange supply by proportion (2012-2016 average)
Generated from USDA AMS movement and terminal market reports [USDA, 2017c; USDA, 2017d]

Post-harvest processing was assumed to include washing, waxing, drying, sorting, grading, packing, and short-term cold storage for a total of 39 kWh/ton of oranges processed [USAID, 2009]. Life-cycle GHG emissions for post-harvest processing ranged from 10 gCO_2e/kg of oranges processed (Peru) to 33 gCO_2e/kg of oranges processed (South Africa).

All oranges were assumed to be packaged in cardboard cartons holding 4/5 of a bushel (roughly 18 kg) of oranges. The life-cycle carbon footprint of cardboard was found to be 1.0 $kgCO_2e$/kg of cardboard [PE-Americas and Five Winds International, 2010]. The resulting life-cycle GHG emissions impact of packaging was, therefore, estimated to be 9 gCO_2e/kg of oranges packaged. This value was assumed to be independent of the production region.

Throughout the course of the year, New York City receives oranges by truck (Florida, Mexico, Texas), rail (California, Florida [negligible quantity]), and containership (Australia, Chile, South Africa). As mentioned above, Hunt's Point was chosen as the shipping destination. Figure 16 illustrates the origin and destination nodes as well as the transportation routes for each production region.

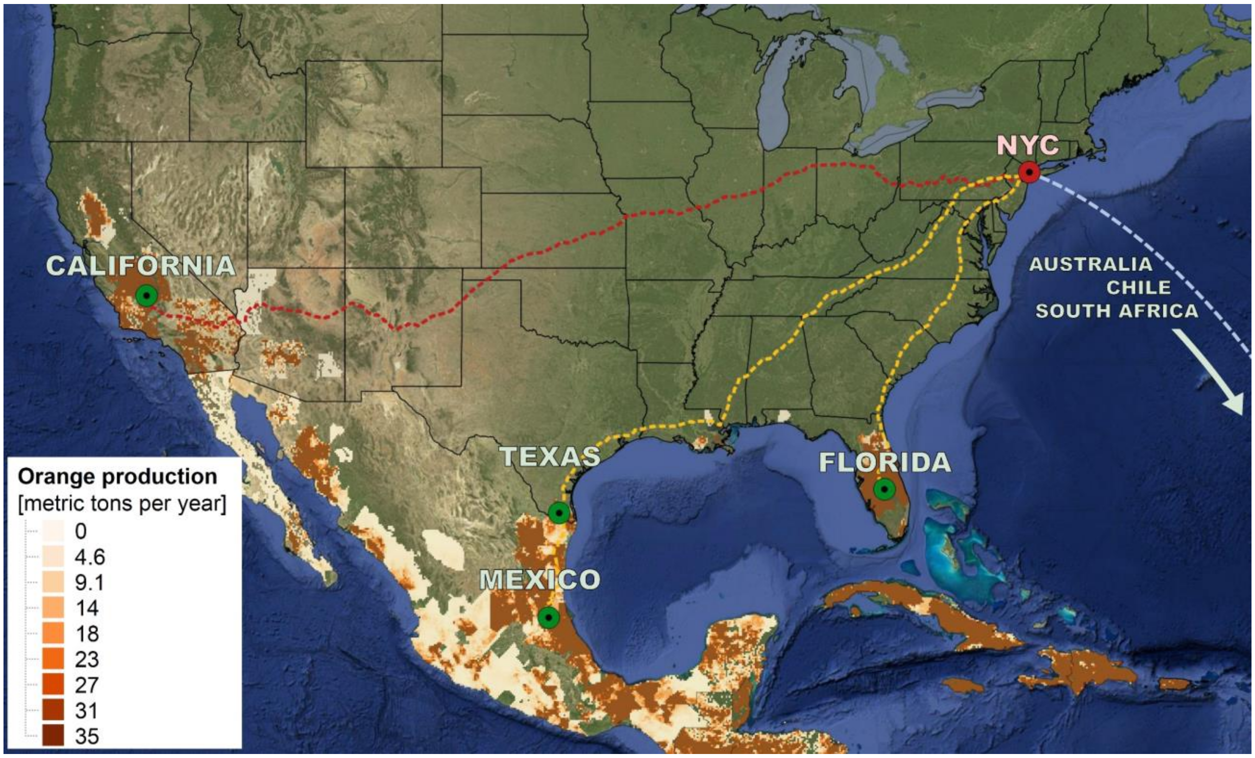

Figure 16: Production regions and transportation routes for New York City's fresh orange market
Notes: The green circles indicate production origins, as defined by the production-weighted centroid of each production region. The red circle indicates the wholesale market destination (in this case Hunts Point Cooperative Market in New York City). The yellow, red, and blue dashed lines indicate shortest-path transportation routes for truck, rail, and containership, respectively. Orange production data are based on the SAGE/McGill GIS land use data sets [Monfreda et al., 2008; EarthStat, 2018].

3.3 Results

3.3.1 Results for New York City

Figure 17 illustrates the life-cycle GHG emissions associated with transporting fresh oranges from each of the seven production regions to New York City. When comparing across transportation modes, there is roughly an order of magnitude difference between freight transported by truck, rail, and containership (86, 13, and 4.6 gCO_2e/tkm, respectively). This fact yields some interesting results. The production regions that are geographically closer to the destination market do not necessarily have the lowest transportation-related GHG emissions. In fact, freight shipped from greater distances is more likely to travel by means of a high-efficiency, low-cost transportation mode (containership or train). As indicated by the results, Chile is the production region with the lowest transportation-related GHG emissions,[7] in spite of the fact that Chilean orange production is over 8,000 kilometers away by containership from New York City. Since Chilean orange

[7] Excluding Florida oranges supplied by rail, which account for only 0.1% of all Florida oranges transported in the United States.

production is proximate to the Pacific coast, “truck-miles” are minimized in the supply chain in favor of the higher-efficiency “boat-miles.” Mexican oranges, by contrast, are supplied exclusively by truck, resulting in over six times the transportation-related GHG emissions relative to Chilean oranges, in spite of traveling less than half of the distance. The error bars represent one standard deviation and were calculated via Monte Carlo simulation, based on uncertainty regarding the freight emission factors. Additional information regarding uncertainty is provided in Appendix B.

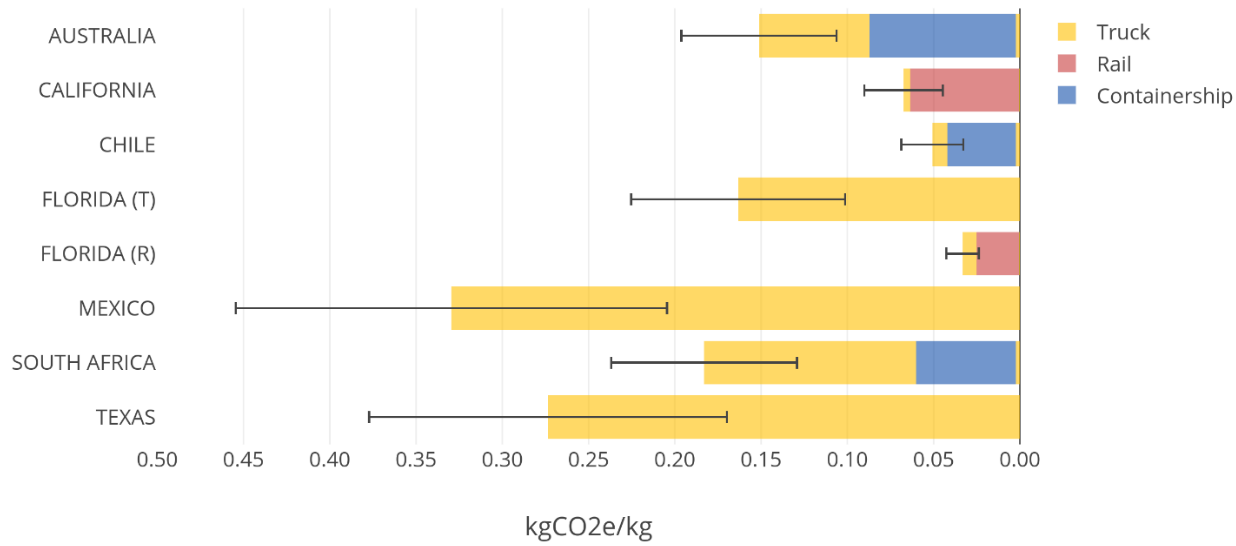

Figure 17: Life-cycle GHG emissions associated with transportation of fresh oranges to New York City by transportation mode

Notes: 99.9% of Florida oranges shipped in the United States are transported by truck (T). The remaining 0.1% are transported by rail (R). Error bars represent one standard deviation.

Figure 18 summarizes the total life-cycle carbon footprint of New York City oranges by production region and life-cycle stage. The carbon footprint is dominated by the production and transportation stages; processing and packaging together account for only 3-9% of the total. Transportation impacts range from 11% (Chile) to 48% (Texas) of the total. Overall, oranges from California have the lowest carbon footprint (0.3 $kgCO_2e/kg$), a result of relatively high yields and efficient transportation. Chile ranks fifth (0.5 $kgCO_2e/kg$) in spite of having the lowest transportation emissions, a consequence of relatively low yields.

The error bars represent one standard deviation and were calculated via Monte Carlo simulation. The primary source of uncertainty in this analysis is crop yields, which are unpredictable and can vary significantly from year-to-year due to annual weather conditions. As a result, regions where the carbon footprint is dominated by the production stage (e.g., Chile) exhibit the largest uncertainty. Other sources of uncertainty include variations in the carbon impact per unit hectare and uncertainty in the freight emission factors. Additional details are provided in Appendix B.

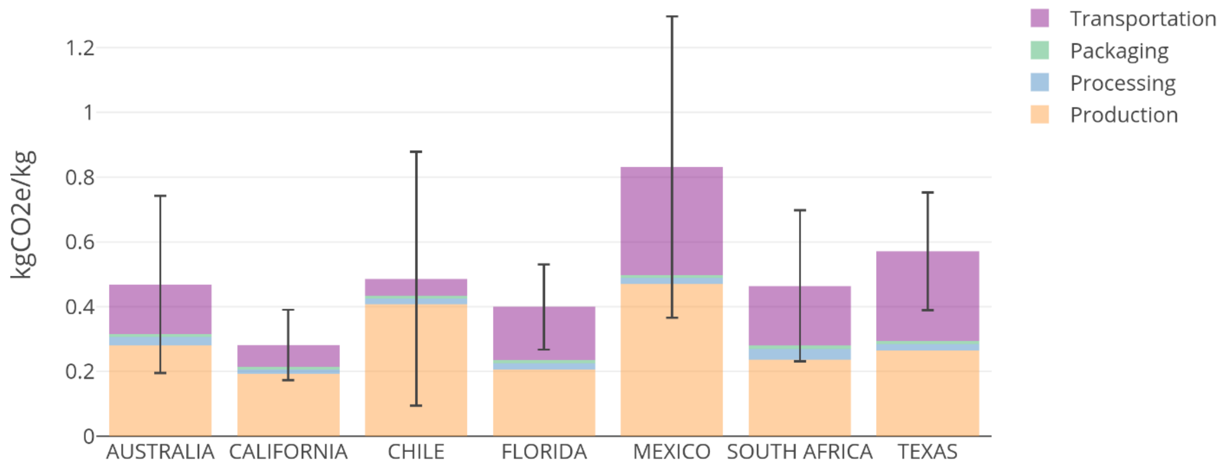

Figure 18: Carbon footprint of fresh oranges supplied to New York City by production region
Note: Error bars represent one standard deviation.

Figure 19 is the result of applying the data from Figure 18 to a matrix of values representing the proportion of New York City's orange supply met by each production region in each week of the year. The weighted-average carbon footprint of New York City oranges is roughly constant throughout much of the year; however, during the period from mid-July through mid-October, oranges are not in season in either California or Florida, the two most efficient production regions. During this 14-week period, the carbon footprint of oranges is roughly 30% higher than the average of the rest of the year. As indicated by the uncertainty band, however, this difference could be as high as 2-3 times, or perhaps zero. The two spikes that occur in May and November are the result of brief periods of time when some oranges are sourced from Mexico and Texas, respectively.

There is some uncertainty in the proportion of New York City's weekly orange supply satisfied by each production region (Figure 15). Since shipping data were not available for specific crops at the city level, the proportion of New York City oranges sourced from each production region had to be estimated from a combination of national-level data and terminal market cost reports. This uncertainty was accounted for in the results by varying the proportion of orange supply satisfied by each production region. Additional details are provided in Appendix B.

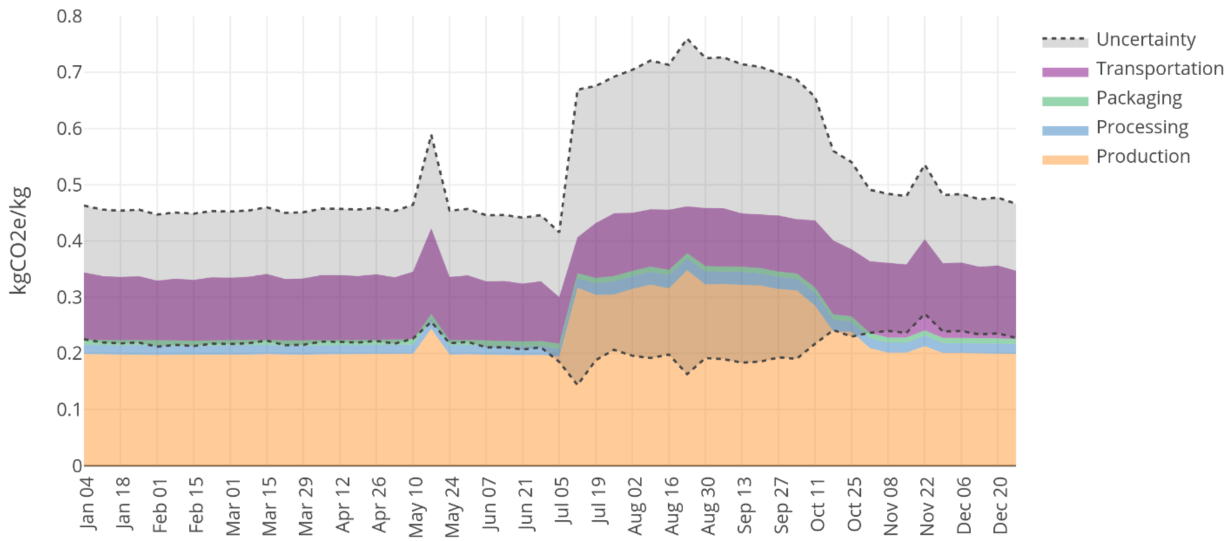

Figure 19: Seasonal variation in the average carbon footprint of oranges supplied to New York City

Note: The uncertainty range represents one standard deviation.

3.3.2 Results for Los Angeles, Chicago, and Atlanta

The results for three other major orange markets are included in Appendix B. While the specific details of each city vary, the overall trends and key conclusions are consistent. All cities source their oranges domestically, with the exception of a few months in late summer and early fall when demand for oranges is primarily met by imports. All four cities demonstrate a similar distribution of impacts across the four life-cycle stages, with the production stage being the most prominent. All four cities exhibit a modest increase in the carbon footprint of oranges during the “out-of-season” period.

3.4 Discussion

The results highlight the significance of transportation mode. There is roughly an order of magnitude difference in the GHG emissions intensity of freight transport by truck, rail, and containership. As a result, mode switching may prove an effective strategy for mitigating the environmental impact of fresh produce. For example, the GHG emissions associated with transporting fresh oranges by rail from Florida to New York City are roughly five times lower per kilogram of oranges than by truck. There may be practical limitations to increasing the proportion of Florida oranges supplied by rail, however, including railroad network constraints and the additional time required for loading and unloading.

From a global-warming perspective, “local” produce is not necessarily more environmentally friendly. Produce shipped from greater distances is more likely to benefit from the economies of scale associated with long-distance transportation modes (containerships or trains). The results of this paper indicate that oranges supplied to New York City from California have a lower cradle-to-market carbon footprint than Florida, Texas, or Mexico, despite being farther away. This conclusion can be attributed to the fact that California oranges are primarily shipped by rail, whereas Florida, Texas, and Mexico rely on trucking. If New York City were to increase the proportion of oranges sourced from California, it could reduce the overall environmental impact of the city's orange supply. However, this proposition must be approached with caution. Increasing the flow of oranges from California to New York City may come at the cost of decreasing the flow to other vital markets (e.g., Los Angeles and other big urban areas), resulting in a net environmental loss.

The results show a moderate seasonal variation in the carbon footprint of oranges supplied to New York City. Specifically, "out-of-season" oranges were found to have a carbon footprint roughly 30% higher than "in-season" oranges. A similar trend is exhibited by the Los Angeles, Chicago, and Atlanta orange markets. This fact can be attributed primarily to variations in yield rather than transportation distances. One possible mitigation strategy is to reduce demand for oranges in the off-season (i.e., encourage consumers to substitute for a lower-carbon footprint fruit in their diet from mid-July through mid-October). At the same time, a 30% increase in the carbon footprint of oranges, while not trivial, is also not an order-of-magnitude-scale problem. Other common fresh produce items including apples and bananas do not display the seasonal variability in supply that is characteristic of oranges (based on a similar analysis conducted by the authors) and are therefore likely to exhibit a relatively constant carbon footprint throughout the seasons.

While this model can be applied to most fresh produce commodities, its main limitation lies in the fact that the framework only holds for perishable crops. While some short-term storage is accounted for in the post-harvest processing stage, the model assumes that commodities cannot be stored long term. As a result, the accuracy of this model likely diminishes for crops with longer shelf lives (e.g., nuts, frozen produce).

There are several sources of uncertainty in this model, which were addressed with a Monte Carlo uncertainty assessment and incorporated into the presentation of the results in Figure 17, Figure 18, and Figure 19. Most significant are crop yields, which can vary from year-to-year due to annual conditions. This variation is the result of natural phenomena and cannot be significantly helped. In addition, there is uncertainty regarding production practices—which can vary both between regions and even from orchard to orchard within a region—as well as limited shipping data. While our analysis addresses these uncertainties by varying inputs and assumptions, they highlight the need for regionally-specific carbon footprinting and a consistent and reliable worldwide system of reporting agricultural production methods and data.

3.5 Conclusion

The presented model used to estimate the life-cycle GHG emissions footprints of oranges supplied to New York City and other major U.S. cities could assess other relevant metrics (e.g., economic costs, energy consumption, water use) and fresh produce commodities in other locations. The adoption of a universal framework for agricultural data collection and reporting would greatly strengthen the accuracy of the results presented herein, as well as the number of applications of the model. Such a framework would allow for the development of regionally- and temporally-specific carbon footprinting of agricultural commodities, and lay the groundwork for optimal decision-making at the nexus of food, energy, and water. Moreover, it would allow for efficiency benchmarking in agricultural production and supply, and perhaps the incorporation of a performance-based ecolabel for resource-efficient crops.

Chapter 4.

Optimal Allocation of Tomato Supply to Minimize Carbon Footprint in Major U.S. Metropolitan Markets

The United States food system requires energy, water, and land in significant proportions. At the same time, it releases large quantities of climate-damaging greenhouse gases and contributes to other environmental concerns, including eutrophication and habitat destruction. Meeting future demand for fresh food will require the adoption of holistic, systems-level thinking to maximize food production and supply while limiting the consequences to our natural resources. In this analysis, we apply a comprehensive cradle-to-market life-cycle environmental model to assess the carbon footprint of fresh tomatoes supplied to ten of the largest metropolitan statistical areas in the United States. A linear optimization algorithm is applied to determine the optimal tomato distribution scheme that will minimize tomato-related greenhouse gas emissions across all ten areas. Results indicate that the current tomato distribution scheme is suboptimal; re-allocating the fresh tomato supply across these ten areas has the potential to decrease overall tomato-related greenhouse gas emissions by 7%—from 298,000 MTCO2e to 278,000 MTCO2e—and transportation-related emissions by 20%. The substantial variability of the optimized scenario raises concerns about its practical implementation. Ultimately, however, production practices and geography are more significant with respect to environmental impact than the supply allocation or the seasonality. Our analysis found a roughly six-fold difference between Philadelphia tomatoes sourced from open-field Virginia production (0.38 $kgCO_2e/kg$) compared with controlled-environment Mexican production (2.2 $kgCO_2e/kg$).

4.1 Introduction

The United States food system places high demands on our nation's natural resources. As a whole, our food system is responsible for the emissions of approximately 2.6 $MTCO_2e$ per person per year, or 8.4 $kgCO_2e$ per person per day [Weber and Matthews, 2008]. By our calculations, this accounts for roughly 10% of overall U.S. greenhouse gas (GHG) emissions [Weber and Matthews, 2008; US EPA, 2016]. It also demands 140 MJ of energy per person per day—four times the global average—and 1200 liters (330 gallons) of water per person per day [Canning et al., 2010; UNESCO, 2014]. These values account for approximately 14% of national energy consumption and half of our national water withdrawals.

As the global population continues to grow and the global middle class expands, demand for food—and in particular, high-value specialty products—will increase. The United Nations estimates that global food production must increase 70% by 2050 in order to satisfy demand [United Nations, 2011]. If this expansion in production is to occur in a sustainable manner, care must be taken to minimize the environmental impact of our agricultural systems at a national or global level.

In this study, we build upon the model presented in Chapter 3 to estimate the cradle-to-market life-cycle GHG emissions associated with fresh tomatoes supplied to ten of the largest metropolitan statistical areas in the U.S.—representing roughly one quarter of the U.S. population—based on six unique geographic production regions and four tomato growing methods. We characterize the carbon footprint of fresh tomatoes for each of these metropolitan statistical areas during each week of the year. Next, we implement a linear optimization algorithm with 5720 decision variables to compute the optimal tomato distribution scheme for the ten metropolitan statistical areas that minimizes the total environmental impact across all ten areas. Last, we comment on whether the presence of an omnipresent national-level agricultural "social planner" could potentially mitigate food-related GHG emissions, or whether the current scheme—whereby each city acts in its own particular self-interest—is preferable.

Tomatoes were chosen as the focus of this study for a number of reasons. First, tomatoes are one of the most popular specialty commodities in the United States. Roughly 9 kilograms (20 pounds) of fresh tomatoes and 23 kilograms (50 pounds) of processed tomatoes are consumed annually per person in the United States. [USDA 2017a]. Second, tomatoes are grown using a variety of production methods, including indoor. In 2012, greenhouse tomatoes were a $400 billion industry with over 1000 acres of greenhouse tomatoes in production [USDA, 2017b]. Tomatoes account for more than half of all greenhouse production by area and nearly two-thirds of all greenhouse production by economic value [USDA, 2017b]. Although indoor tomato production often requires more energy relative to conventional production, transportation distances to the consumer are typically shorter. Finally, tomato production in the United States is diffuse; in 2017, ten states reported over 1000 acres harvested [USDA, 2017b].

Life cycle assessments of tomatoes are numerous in the literature. Table 6 presents 36 cradle-to-farm gate life-cycle carbon footprints collected from 18 published journal articles. The values represent a variety of growing practices and geographic regions. The data presented in Table 6 reflect only the tomato production stage; processing, transportation, storage, and other stages beyond the farm gate are not included. In some cases, estimates were made in order to subtract transportation-related GHG emissions from the original value presented in the journal article. If the methodology of a journal article was insufficiently transparent to isolate the cradle-to-farm gate portion of the life-cycle carbon footprint, that article was excluded from Table 6.

Table 6. Summary of cradle-to-farm gate life-cycle carbon footprints from the literature

Source	Value [kgCO_2e/kg]	Geographic scope	Description / Notes
Goldstein et al., 2016	0.08	Northeast U.S.	Field-based, urban agriculture
Andersson et al., 1998	0.15	Mediterranean	Open field, used for production of ketchup
Martinez-Blanco et al., 2011	0.15-0.18	Mediterranean	Unheated greenhouse, plastic, minimal climate controls, some electricity use (range based on variability in fertilizer use)
Roos and Karlsson, 2013	0.15	Spain	Unheated greenhouse, soil medium, no water recycling
Martinez-Blanco et al., 2011	0.16-0.29	Mediterranean	Open field (range based on variability in fertilizer use)
Jones et al., 2012	0.19-0.27	Florida, U.S.	Open field (range based on variability in irrigation systems)
Roy et al., 2008	0.19	Japan	Plastic cover
Roos and Karlsson, 2013	0.21	Sweden	Hydroponic unheated greenhouse, uses recycling of drainage water
Maraseni et al., 2010	0.22	Australia	Open field
Payen et al., 2015	0.22	Morocco	Unheated plastic greenhouse, soil substrate
Sanye-Mengual, 2015	0.22	Mediterranean	Rooftop greenhouse, uses residual heat and CO_2 from building, rainwater collection
Torrellas et al., 2012	0.25	Spain	Multi-tunnel greenhouse, unheated, natural ventilation
Goldstein et al., 2016	0.26	Northeast U.S.	Unconditioned green roof
Gonzalez et al., 2011	0.28	United States	Open field
Roos and Karlsson, 2013	0.28	Sweden	Hydroponic climate-controlled greenhouse, mainly non-fossil energy, recirculation of drainage water
Page et al., 2012	0.3	Australia	Open field
Webb et al., 2013	0.30	Spain	Open field
Gonzalez et al., 2011	0.37	Spain	Open field
Del Borghi et al., 2014	0.40-0.59	Italy	Open field, used for production pureed, chopped, and peeled tomatoes (range based on different tomato products)

Table 6. Summary of cradle-to-farm gate life-cycle carbon footprints from the literature

Source	Value [kgCO_2e/kg]	Geographic scope	Description / Notes
Page et al., 2012	0.43	Australia	Unheated greenhouse, open hydroponic system (i.e., no water recycling)
Boulard et al., 2011	0.51	France	Unheated greenhouse (20-y GWP)
Roy et al., 2008	0.77	Japan	Greenhouse, heated
Cellura et al., 2012	0.82-1.02	Italy	Unheated greenhouse, pavilion style (range based on variability in yield)
Roos and Karlsson, 2013	0.85	Netherlands	Hydroponic climate-controlled greenhouse, uses fossil fuels with CHP system, recirculation of drainage water
Boulard et al., 2011	1.6-2.4	France	Heated greenhouse, plastic, predominantly natural gas (20-y GWP, range based on geographic variability)
Goldstein et al., 2016	1.6	Northeast U.S.	Conditioned greenhouse
Page et al., 2012	1.7	Australia	Heated greenhouse, coal heating, open hydroponic system (no water recycling)
Boulard et al., 2011	1.8-2.1	France	Heated greenhouse, glass, predominantly natural gas (20-y GWP, range based on geographic variability)
Page et al., 2012	1.9	Australia	Conditioned greenhouse, coal and natural gas heating, closed hydroponic system (i.e., water is recycled)
Webb et al., 2013	2.1	United Kingdom	Heated greenhouse, primarily natural gas
Goldstein et al., 2016	2.2	Northeast U.S.	Conditioned rooftop greenhouse, rainwater capture, integrated with building energy system
Carlsson-Kanyama, 1998	2.7	Sweden	Heated greenhouse, fuel oil (20-y GWP)
Gonzalez et al., 2011	2.8	Holland	Heated greenhouse, natural gas heating
Gonzalez et al., 2011	3.7	Sweden	Heated greenhouse, electricity and propane heating
Berners-Lee et al., 2012	5.6	United Kingdom	Heated greenhouse

Although the cradle-to-farm gate carbon footprint of tomatoes has been studied extensively, a much smaller number of studies estimate the cradle-to-market or cradle-to-consumer environmental impact. Even fewer consider the impacts of seasonality and logistics. Roos and Karlsson, 2013, found that the carbon footprint of Swedish tomato consumption was strongly impacted by seasonality since out-of-season tomatoes are likely to be traveling greater distances or produced in heated greenhouses. Kulak et al., 2013, estimated the environmental impact of fresh produce sourced from an urban community farm and versus those obtained through conventional means. They used linear optimization to determine the optimal community farm design to maximize environmental savings.

This study is unique in its application of a holistic cradle-to-market environmental model to estimate the carbon footprint of tomatoes from a variety of production regions and production practices. It is also the first study of its kind to apply linear optimization to compute the optimal supply portfolio of an agricultural commodity at a national level.

4.2 Methods

The objective of this linear optimization is to develop a mathematical model to minimize the total annual environmental cost of meeting the fresh tomato demand of major U.S. metropolitan areas. The model assumes that supply and demand are both fixed; production cannot be increased beyond the current capacity of each production origin and per-capita tomato consumption cannot change from the status quo of each destination city. The problem formulation is as follows:

$$\min_{x_{ijk}} \sum_{i=1}^{11} \sum_{j=1}^{10} \sum_{k=1}^{52} c_{ij} x_{ijk}$$

Where:

i = production origin
j = destination city
k = week
c_{ij} = environmental cost of supplying one unit of tomatoes from production origin (i) to destination city (j) [kgCO2e/kg]
x_{ijk} = quantity of tomatoes supplied by production region (i) to destination city (j) in week (k) [kg]

The cost function is subject to the following three constraints:

i. $x_{ijk} \geq 0 \;\; \forall \;\; i, j, k$ supply cannot be negative

ii. $\sum_{i=1}^{11} x_{ijk} \geq d_{jk} \;\; \forall \;\; j, k$ tomato demand must be met for each city in each week

iii. $\sum_{j=1}^{10} x_{ijk} \leq s_{jk} \;\; \forall \;\; i, k$ supply cannot exceed the production capacity of the region

The United States primarily relies on 11 production pathways to supply the majority of our fresh tomatoes. California, Florida, Mexico, South Carolina, and Virginia are home to significant open field tomato production. In addition, California, Canada, Florida, and Mexico have protected production. Mexico’s protected tomato production can be further subdivided into adapted environment, greenhouse, and controlled environment. Table 7 summarizes the various classifications of protected agriculture used in this analysis.

Table 7. Classification of protected tomato production

Adapted environment (AE)	Includes such strategies as mulching, row covers, high tunnel, and shade cloth [Jensen and Malter, 1995]
Greenhouse (GH)	A framed or inflated structure, covered by a transparent or translucent material that permits the optimum light transmission for plant production and protects against adverse climatic conditions. May include mechanical equipment for heating and cooling [Jensen and Malter, 1995]
Controlled environment (CE)	Grown in a fully-enclosed permanent aluminum or fixed steel structure clad in glass, impermeable plastic, or polycarbonate using automated irrigation and climate control, including heating and ventilation capabilities, in an artificial medium using hydroponic methods [Suspension of Antidumping Investigation: Fresh Tomatoes from Mexico, 2013]

This analysis considers ten of the twelve most populous metropolitan statistical areas[8] in the United States (Table 8). USDA's Agricultural Marketing Service did not compile data for Houston and Phoenix; those two cities were, therefore, excluded from the analysis. The ten metropolitan statistical areas included in this analysis total roughly one quarter of the U.S. population.

Table 8. Summary of top metropolitan statistical areas in the United States [U.S. Census Bureau, 2016]

Rank	Metropolitan statistical area	2017 estimate	Shorthand name
1	New York-Newark-Jersey City	20,320,876	"New York City"
2	Los Angeles-Long Beach-Anaheim	13,353,907	"Los Angeles"
3	Chicago-Naperville-Elgin	9,533,040	"Chicago"
4	Dallas-Fort Worth-Arlington	7,399,662	"Dallas"
5	*Houston-The Woodlands-Sugar Land*	*6,892,427*	*"Houston"*
6	Washington-Arlington-Alexandria	6,216,589	"Washington DC"
7	Miami-Fort Lauderdale-West Palm Beach	6,158,824	"Miami"
8	Philadelphia-Camden-Wilmington	6,096,120	"Philadelphia"
9	Atlanta-Sandy Springs-Roswell	5,884,736	"Atlanta"
10	Boston-Cambridge-Newton	4,836,531	"Boston"

[8] A county (or counties) associated with at least one urbanized area of at least 50,000 population, plus adjacent counties having a high degree of social and economic integration [U.S. Census Bureau, 2016]

Table 8. Summary of top metropolitan statistical areas in the United States [U.S. Census Bureau, 2016]

Rank	Metropolitan statistical area	2017 estimate	Shorthand name
11	*Phoenix-Mesa-Scottsdale*	*4,737,270*	*"Phoenix"*
12	San Francisco-Oakland-Hayward	4,727,357	"San Francisco"

Notes: Italicised rows indicate metropolitan statistical areas that were excluded from the analysis due to lack of data. The total population for all ten areas included in the analysis comes to 85.5 million, representing roughly one quarter of the U.S. population in 2017.

Using the same methodology presented in Chapter 3, an environmental cost matrix consisting of 110 origin/destination pairs was computed (Table 9). Each value in the cost matrix (c_{ij}) represents the cradle-to-market life-cycle carbon footprint between the production origin and the destination city (i.e., the environmental cost of supplying one unit of tomatoes from the production origin to the destination city, measured in $kgCO_2e$ emitted per kg of tomatoes delivered to market).

Table 9. Environmental cost matrix for linear optimization [$kgCO_2e$ emitted per kg of tomatoes delivered to market]

		Destination cities									
		NY	LA	CH	DA	DC	MI	PH	AT	BO	SF
Production origins	California	0.76	0.37	0.64	0.57	0.74	0.77	0.75	0.68	0.78	0.34
	California_GH	2.15	1.77	2.04	1.97	2.14	2.16	2.15	2.08	2.18	1.74
	Canada_GH	1.80	1.94	1.78	1.91	1.80	1.94	1.80	1.85	1.81	1.89
	Florida	0.54	0.74	0.55	0.54	0.50	0.38	0.52	0.44	0.57	0.79
	Florida_GH	1.91	2.12	1.92	1.91	1.88	1.76	1.89	1.81	1.94	2.16
	Mexico	0.76	0.63	0.68	0.54	0.73	0.70	0.75	0.64	0.80	0.69
	Mexico_AE	0.82	0.69	0.73	0.59	0.78	0.75	0.80	0.69	0.85	0.74
	Mexico_CE	2.25	2.12	2.16	2.02	2.21	2.18	2.23	2.12	2.28	2.17
	Mexico_GH	2.10	1.97	2.01	1.87	2.06	2.03	2.08	1.97	2.13	2.02
	South Carolina	0.52	0.77	0.54	0.56	0.49	0.49	0.51	0.45	0.55	0.81
	Virginia	0.40	0.74	0.47	0.54	0.36	0.49	0.38	0.43	0.43	0.78

Key: AE = adapted environment, CE = controlled environment, GH = greenhouse

The environmental cost matrix includes GHG emissions associated with the production, post-harvest processing, packaging, and transportation stages. An example using Philadelphia is included in Figure 20. Results for the remaining nine metropolitan statistical areas are included in Appendix C.

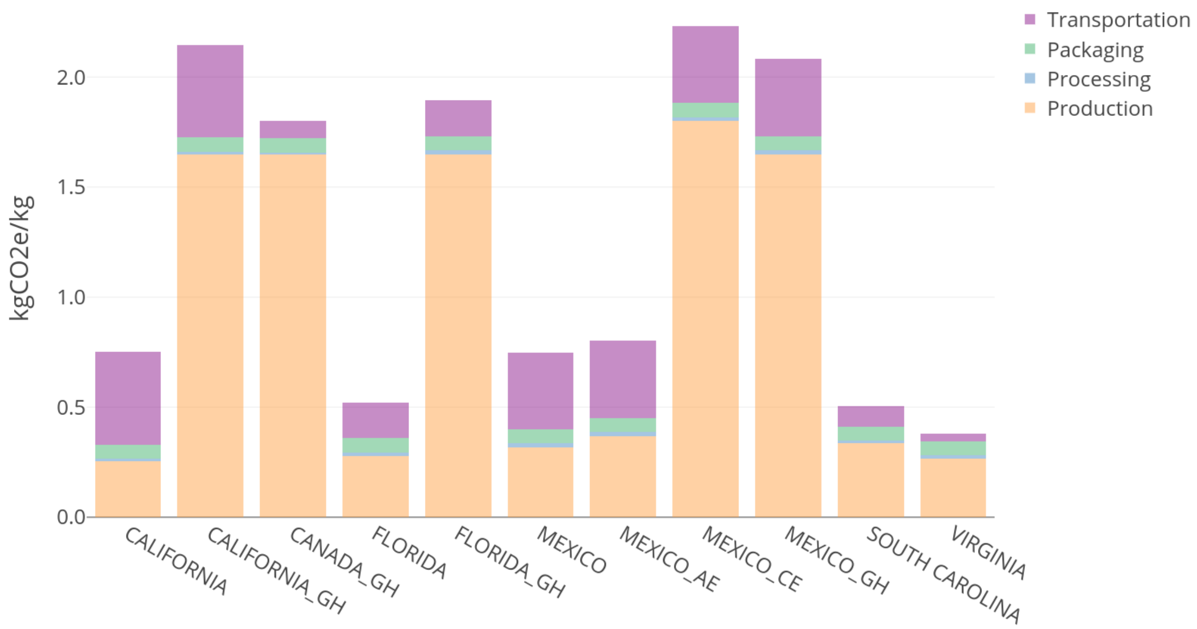

Figure 20. Cradle-to-market life-cycle GHG emissions for Philadelphia fresh tomato supply
Key: AE = adapted environment, CE = controlled environment, GH = greenhouse

The available supply for each production origin in each week was assumed to be the current tomato production, as determined from USDA Agricultural Marketing Service (AMS) specialty crop movement reports [USDA, 2017c]. These national-level data were scaled down proportionally to account for the fact that the ten metropolitan statistical areas considered only comprise one quarter of the U.S. population. This analysis does not consider the possibility of increasing regional tomato production.

The fresh tomato demand for each city in each week was calculated from the national-average per-capita fresh tomato availability, scaled up based on the population of each metropolitan statistical area [USDA, 2017a; U.S. Census Bureau, 2016].

4.3 Results

Results for Philadelphia are displayed in Figure 21 and Figure 22 for illustrative purposes. Complete results for the remaining nine cities are included in Appendix C. The top panel of Figure 21 shows Philadelphia's current (i.e., baseline) tomato supply on a weekly basis. As illustrated by the figure, Philadelphia currently receives tomato shipments from nine out of the eleven major production origins. Under an optimized scenario (bottom panel), Philadelphia's tomato supply would be restricted to fewer production regions—five in this case. In addition, the optimized scenario suggests that Philadelphia should receive a larger proportion of its tomatoes from nearby regions (e.g., South Carolina, Virginia) and a lesser proportion from distant regions (e.g., California, Mexico). These general conclusions are consistent across all ten destination cities.

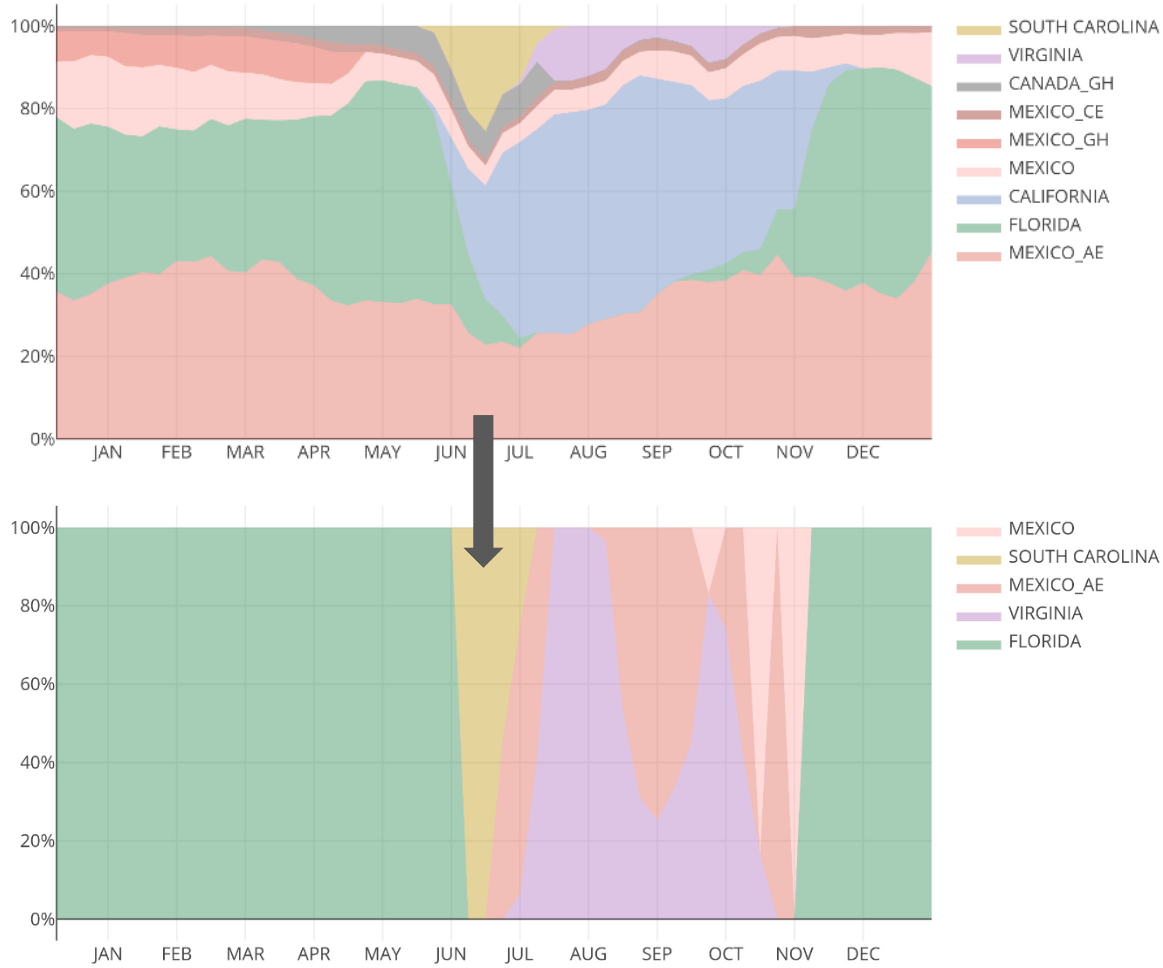

Figure 21. Tomato supply portfolio for Philadelphia market under baseline (top) and optimized scenario (bottom)

The top panel of Figure 22 illustrates the current cradle-to-market carbon footprint of Philadelphia tomatoes on a weekly basis. Considering the temporal variation in tomato supply shown in the top panel of Figure 21, the carbon footprint of Philadelphia tomatoes is surprisingly consistent, remaining around 0.75 kgCO_2e per kg throughout the year. Under the optimized scenario (bottom panel), the carbon footprint drops to roughly 0.50 kgCO_2e per kg for the majority of the year. However, the carbon footprint under the optimized scenario experiences three distinct spikes in July, September, and November. These spikes can be attributed to an increase in shipments of Mexican tomatoes during these time periods. Once again, these conclusions are consistent across all ten destination cities. In general, the carbon footprint of tomatoes is lower under the optimized scenario but is prone to significant fluctuations. This fact raises some concerns for practical implementation, as will be discussed in Section 4.4.

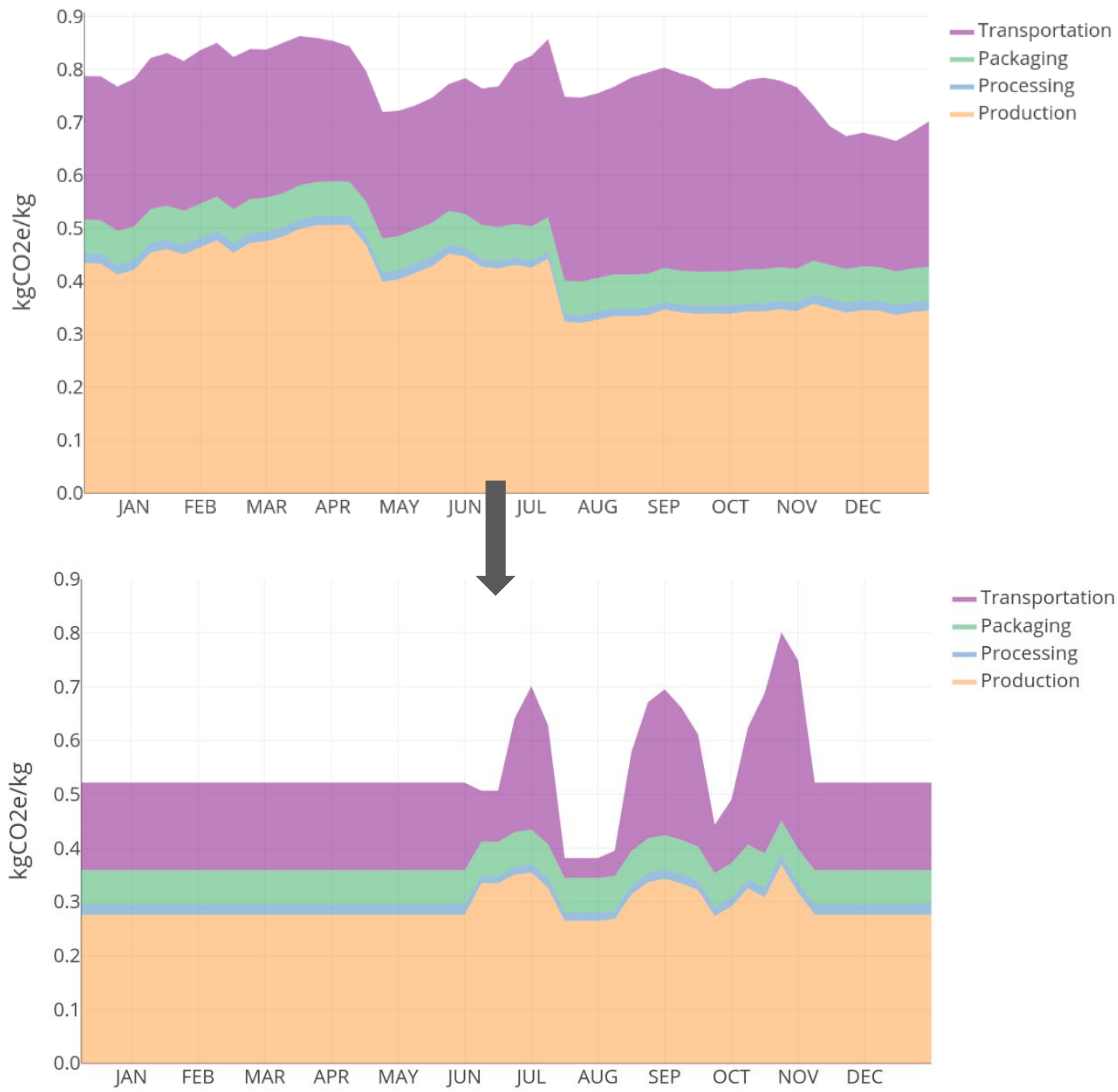

Figure 22. Environmental impact of fresh tomatoes delivered to Philadelphia market under baseline (top) and optimized scenario (bottom)

Figure 23 plots the environmental impact of fresh tomatoes delivered to market in all ten cities under the current system. The environmental impact varies relatively little throughout the year and from city to city—roughly 40% between the best city (Dallas) and worst city (Boston). The results can be roughly grouped by geography; the northeastern cities of Boston, New York City, Philadelphia, and Washington DC all share similar characteristics. The same can be said of the southeastern cities (Atlanta, Miami) and the western cities (Los Angeles, San Francisco). Chicago appears to be in a category of its own, although it shares many characteristics with the northeastern grouping. Dallas is similarly in its own category and exhibits the lowest overall carbon footprint, primarily due to its proximity to Mexico.

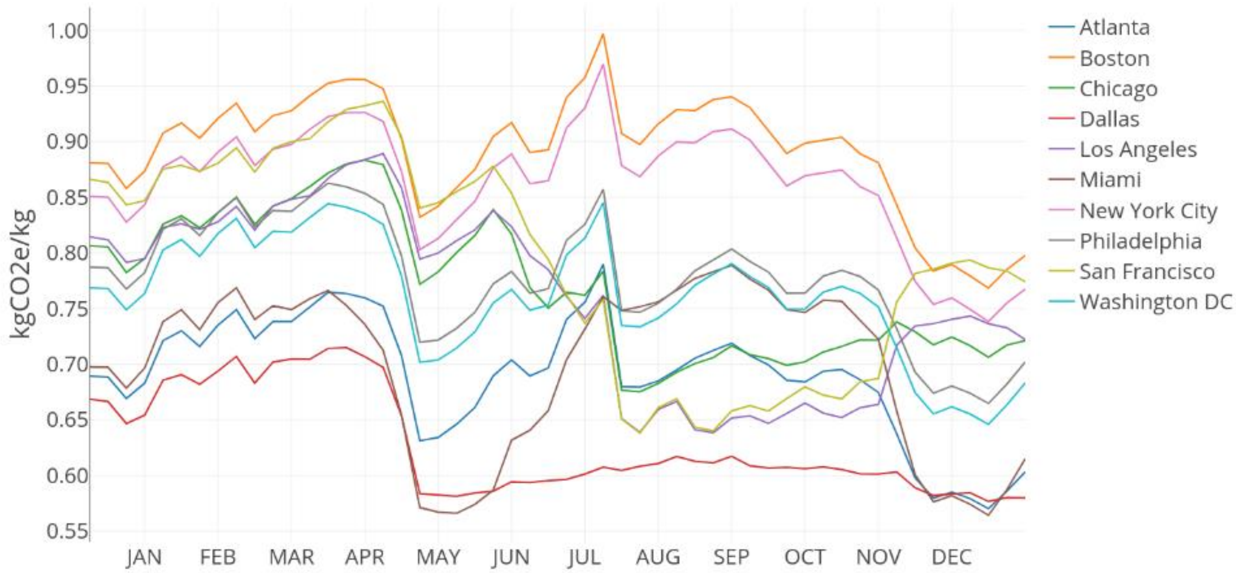

Figure 23. Environmental impact of fresh tomatoes delivered to market in ten U.S. cities (baseline)

Figure 24 plots the environmental impact of fresh tomatoes delivered to market in all ten cities under the optimized scenario. Clearly, the optimized scenario exhibits much less order and uniformity. While most cities display a lower overall environmental impact, fluctuations are frequent and significant. For example, the environmental impact of fresh tomatoes delivered to the San Francisco market remains low at less than 0.4 $kgCO_2e$ per kg for the majority of the year, but spikes to 2 $kgCO_2e$ per kg—a nearly five-fold increase—during those periods when tomatoes are supplied by Mexican greenhouses. This “spikiness” is characteristic of most of the ten destination cities.

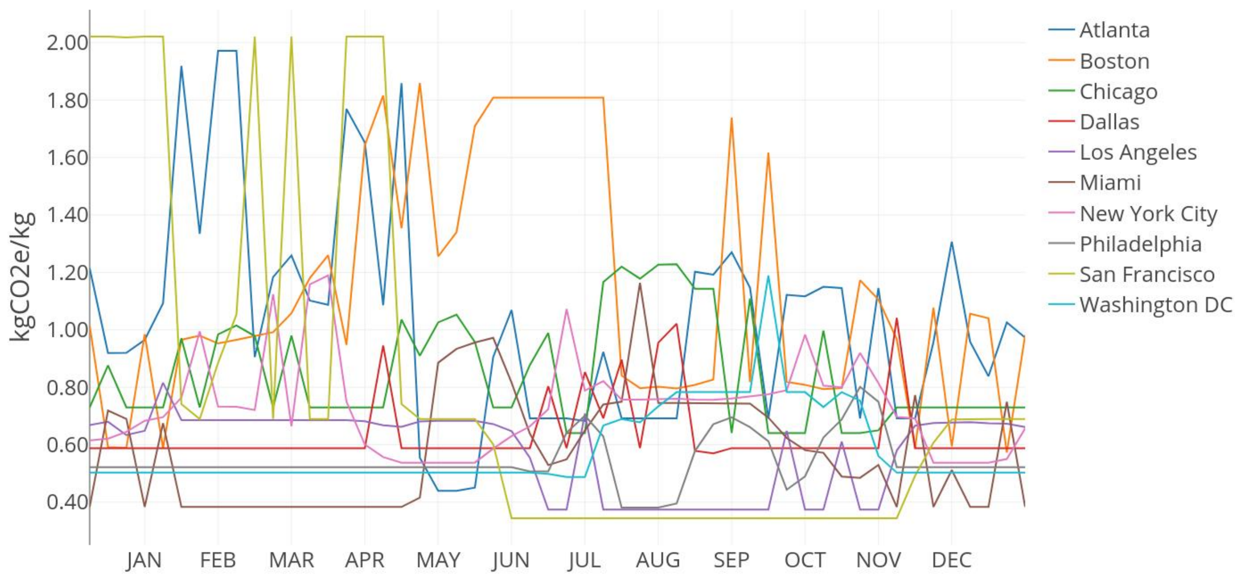

Figure 24. Environmental impact of fresh tomatoes delivered to market in ten U.S. cities (optimized scenario)

Figure 25 was created by summing the environmental impact of fresh tomatoes across all ten destination cities. Under the current (i.e., baseline) scenario, supplying these ten regions with fresh tomatoes releases roughly 298,000 metric tons of CO_2e per year. The optimization scenario saves roughly 20,000 $MTCO_2e$ per year—a 7% improvement. Since our model assumes fixed supply and demand, the only opportunity for improvement is in reducing transportation-related emissions by varying the supply portfolios of the ten destination cities. By our calculations, transportation represents 33% of the total environmental impact of fresh tomatoes delivered to these ten cities. This fact limits the potential for improvement. However, our optimization reduced transportation-related emissions by 20%.

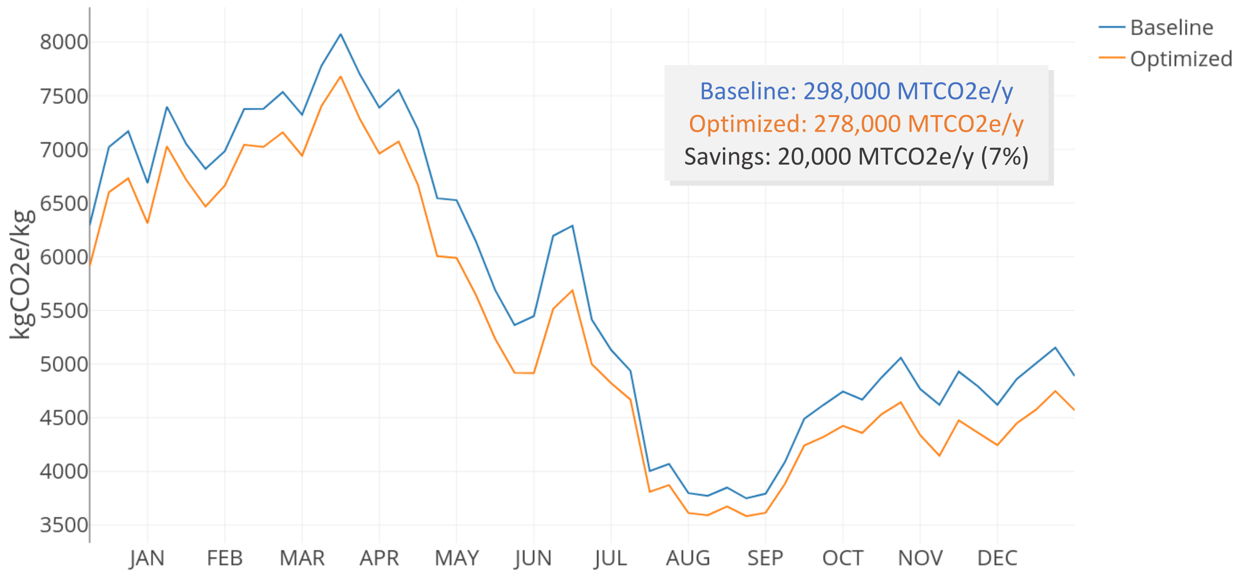

Figure 25. Total environmental impact of fresh tomatoes for all ten U.S. cities (baseline vs. optimized scenario)

4.4 Discussion

Out of ten major metropolitan statistical areas in the United States, Dallas proves to have the lowest-impact tomatoes—0.63 kgCO_2e per kg on average—due to its relatively close proximity to Mexican production. Boston has the highest impact at 0.89 kgCO_2e per kg, an increase of roughly 40%. More significant is the tomato production origin; open-field tomatoes supplied to Philadelphia from Virginia were found to have a carbon footprint of 0.38 kgCO_2e per kg, whereas controlled-environment tomatoes supplied to Philadelphia from Mexico had a carbon footprint of 2.2 kgCO_2e per kg. This discrepancy represents a nearly six-fold increase. The impact of seasonality was minimal; winter, spring, summer, and fall tomatoes for the Philadelphia market were found to have environmental impacts of 0.52, 0.52, 0.55, and 0.57 kgCO_2e per kg, respectively.

Our analysis indicates that the current national tomato distribution scheme is suboptimal. Under the current system, urban markets source tomatoes from a wide variety of production regions, some of which are located at great distances. Under an optimal scenario, each city would source tomatoes from a select subset of production origins, giving preference to local production. Such a scheme could reduce transportation-related life-cycle GHG emissions by 20% and overall cradle-to-market life-cycle GHG emissions by 7%. The potential benefits of the optimization are limited by the fact that transportation accounts for only 33% of the total environmental impact of fresh tomatoes delivered to these ten cities. This is consistent with Weber and Matthews' conclusion that 28% of the carbon footprint of fruits and vegetables is attributable to transportation. Based on these results and the conclusions from Chapter 3, it is likely that transportation mode and growing practices have a more significant impact on the carbon footprint of fresh tomatoes than the supply portfolio.

Before implementing such an optimal allocation scenario in practice, we must consider other factors besides GHG emissions. First, optimizing based on annual GHG emissions may prove economically undesirable. One characteristic of the optimal scenario is that it increases the week-to-week variability in the average environmental impact of tomatoes relative to the baseline. In the case of San Francisco, this variability is as much as a factor of five. The linear optimization algorithm does not impose any penalty to discourage variability. It is therefore conceivable that the optimal scenario could produce significant and undesirable fluctuations in the weekly market price of fresh tomatoes. Perhaps a slightly higher environmental impact is the penalty that we pay for market stability. Second, this analysis assumes that all tomatoes are capable of serving the same purpose, regardless of the production method or geographic region (e.g., an open-field tomato is just as flavorful as a greenhouse-grown tomato). Greenhouse-grown tomatoes are typically costlier and may occupy a different niche than tomatoes produced outdoors. In practice, it may not be realistic to assume, for example, that Philadelphia can make do without any greenhouse-grown or controlled-environment tomatoes.

There are two main sources of uncertainty in this analysis that must be discussed. First, there is some uncertainty in the current city supply portfolio (top panel of Figure 21). Since the USDA movement reports used to develop this figure only include data on the origin—but not the destination—of agricultural shipments, city-level supply matrices had to be estimated by adjusting national-level movement data based on city-level terminal market reports. More information regarding this approach and the associated uncertainty is discussed in Chapter 3 and Appendix B. Second, the analysis uses a single value for each of the protected environment production types—adapted environment, greenhouse, controlled environment—based on the literature. As demonstrated by the literature review in Table 7, there is significant variability even within these sub-classifications. The environmental impact of protected environment systems can vary based on geography and production techniques. The “greenhouse” category is particularly nebulous; the definition of a greenhouse is far from consistent in the literature and can refer to a wide range of production practices and technologies.

4.5 Conclusion

This study presented a comprehensive cradle-to-market environmental model estimating the life-cycle GHG emissions footprint of fresh tomatoes for ten of the largest metropolitan statistical areas in the United States. Our analysis demonstrated that the current fresh tomato distribution scheme is suboptimal. Simply reallocating tomato supplies could decrease the overall environmental impact of tomatoes—and likely other fresh fruits and vegetables—in the United States. However, the results also suggest that geography and production practices may play a more significant role in mitigating the environmental cost of fresh fruits and vegetables than the allocation portfolio or the seasonality. The accuracy of these results, as well as the applicability of this systems-level approach to other commodities and regions, could be greatly improved by the adoption of a universal framework for agricultural data collection and reporting. Such a framework would allow for the development of regionally- and temporally-specific carbon footprinting of agricultural commodities, and would lay the groundwork for optimal decision-making at the nexus of food, energy, and water.

Chapter 5.

Conclusions and Future Work

5.1 Key Conclusions and Recommended Actions

Conclusion: The environmental impact of high-value produce can never be represented by one number; it varies geographically and temporally, and is influenced by different production and supply practices.

Associated action: Develop a comprehensive program for agricultural data collection, encompassing a range of geographic areas and production practices.

As demonstrated both by the existing literature and our own analysis, there is rarely one carbon footprint that can accurately characterize the environmental impact of a crop. Tabatabaie and Murthy, 2016, found that the cradle-to-farm gate carbon footprint of strawberries produced in North Carolina was three times higher than those produced in California. Such variation can be attributed to differences in production practices as well as regional climate and soil conditions, which can affect the environmental impact of agricultural inputs and alter output yield. In Chapter 2, we demonstrate that irrigation practices can significantly influence the energy use footprint, carbon footprint, and production cost of fresh produce in Southern California, particularly if desalination is used. In Chapter 3, we find that the cradle-to-market carbon footprint of oranges delivered to New York City can vary by a factor of three depending on the production origin. Furthermore, the cradle-to-market carbon footprint of oranges is strongly influenced by the transportation mode. A literature review performed in Chapter 4 reveals an order-of-magnitude difference in the cradle-to-farm gate carbon footprint of tomatoes produced by conventional methods compared with those produced in conditioned greenhouses. The carbon footprint of crops can also vary temporally, although the difference appears less pronounced than in the case of geography, production practices, or supply practices. In Chapter 3, we calculate that “out-of-season” oranges in New York City have an average carbon footprint roughly 30% higher than “in-season” oranges. In Chapter 4, however, we find essentially no difference in the seasonal cradle-to-market carbon footprint of fresh tomatoes delivered to Philadelphia.

To better understand the range of environmental impacts of high-value crops, it is necessary to pursue a standardized program of agricultural data collection. USDA currently publishes data on crop production and yields at the state level, but more varied and granular data are needed to fully capitalize on this type of systems-level planning and analysis. Such a program might incentivize growers to share data on production inputs including energy use, water use, and material inputs.

Conclusion: Recycled water has the potential to be used for agricultural irrigation in Southern California and similar growing regions (e.g., Arizona, Texas) without significantly increasing the environmental and economic costs of high-value produce, at least in some cases.

Associated action: Prioritize the use of recycled water for agricultural irrigation in regions of high water stress where high-value crops are in relatively close proximity to urban water treatment facilities. Conduct crop-specific and location-specific analysis of recycled water systems.

In Chapter 2, we explore agricultural water reuse as a potential food-energy-water system synergy. We conclude that a complete switch from conventional irrigation with groundwater and surface water to recycled water would increase the life-cycle greenhouse gas emissions associated with strawberry, lemon, celery, and avocado production in Ventura County by approximately 14%, 7%, 59%, and 9%, respectively. Economic production costs would likely increase by 7%, 22%, 25%, and 34%, respectively. These values are not outside the realm of possibility for growers, particularly in the case of strawberries,[9] and particularly if multiple sources of water are blended. In fact, strawberry packaging was found to have a greater impact on environmental and economic costs than water use.

There are many other regions in the United States of high agricultural significance that experience water stress, including Arizona and Texas. Water reuse has proved effective in Monterey, California, at mitigating water shortages, and in both Monterey and parts of Florida at mitigating saltwater intrusion. Capitalizing on recycled water in regions of high water stress where high-value crops are in relatively close proximity to urban water treatment facilities has positive potential both environmentally and economically. However, crop-specific and location-specific analysis must be conducted. In the case of Oxnard, California, the secondary effluent from the conventional wastewater treatment plant is sufficient in quality for use on several crops grown in Ventura County. Barriers exist in the form of swaying public opinion, convincing growers to purchase recycled water, and constructing distribution infrastructure.

[9] A complete switch to recycled water for irrigation would effectively increase the production cost of strawberries from \$1.63 per kilogram to \$1.74 per kilogram. For context, the wholesale price of California strawberries delivered to New York City was roughly \$5 per kilogram in 2017 [USDA, 2017d].

Conclusion: There are numerous suppliers and supply chains for high-value produce. This diversity presents opportunities to reduce the environmental impact of fresh produce.

Associated action: Conduct systems-level analysis of agricultural production and supply chains for optimal decision making.

In Chapter 3, we show that during the course of a typical year, New York City receives significant quantities of oranges from at least seven different production regions, ranging in distance from 1,900 km (Florida) to 19,000 km (Australia). These various supply chains encompass multiple transportation modes (truck, rail, containership). In Chapter 4, we show that fresh tomatoes in the United States come primarily from any of six production regions and four different production systems (open-field, adapted environment, greenhouse, controlled environment). This wide variety of suppliers and supply chains presents opportunities to minimize the environmental or economic costs. For example, the GHG emissions associated with transporting fresh oranges by rail from Florida to New York City are roughly five times lower per kilogram of oranges than by truck. Mode-switching or integrating emerging transportation technologies have the potential to mitigate the environmental costs of our food system. In Chapter 4, we determine that transportation-related GHG emissions associated with urban fresh tomato supply can be cut by 20% simply by reallocating the supplies. Modeling agricultural production and supply systems allows us to meet consumer demand while minimizing the damage to our natural resources.

Conclusion: Consumers have considerable influence when it comes to reducing the environmental impact of our food system.

Associated action: Develop an outreach program (e.g., performance-based ecolabel) to help consumers make informed choices.

Numerous studies have demonstrated that dietary choices have the potential to significantly mitigate the environmental impact of our food system [Weber and Matthews, 2008; Heller and Keoleian, 2014; Tom et al., 2015; Benis and Farao, 2017; Clune at al., 2017]. The fact that numerous suppliers and supply chains of fresh produce exist means that consumers have choices. Developing an outreach program to communicate information regarding the environmental impact of consumer choices could help to dispel some common misconceptions regarding food. For example, organic and local produce is not necessarily “environmentally friendly” from the standpoint of global climate change. A performance-based ecolabel for resource-efficient crops may help consumers to make informed choices.

5.2 Research Contributions

Advancing urban water and food sector integration and reinvention by quantifying the impacts of switching to future sources of irrigation water.

This research addresses the production of high-value produce at the nexus of food, energy, and water. In Chapter 2, we show that water use, groundwater depletion, and saltwater intrusion can be potentially mitigated by reintroducing wastewater into the food sector as a useful input. We quantify the cradle-to-farm gate energy use footprints, GHG emissions footprints, and operational costs associated with conventional irrigation, irrigation with recycled municipal water, and irrigation with desalinated water. Our results suggest that integrating recycled municipal water with periurban agricultural production has the potential to mitigate regional water stress and other environmental concerns in Ventura County, California.

Creating life-cycle footprints for high-value crops that are regionally and seasonally specific using granular data.

In Chapter 2 we calculate life-cycle energy use and GHG emissions footprints for strawberries, lemons, celery, and avocados using highly localized data. Data are unique to Ventura County, and, in the case of water, are unique to the specific farm. In Chapter 3, we calculate the cradle-to-farm gate life-cycle GHG emissions footprint of fresh oranges delivered to market in four major U.S. cities as a function of both production region and season. We show that the average environmental impact of a given agricultural commodity delivered to market is not static; it can vary throughout the year. We perform a similar analysis in Chapter 4 for fresh tomatoes delivered to ten major U.S. cities. The high level of regional and seasonal specificity used in our research is both unique and necessary.

Developing a model that integrates growing practices, water use, and embedded energy. Expanding this model beyond the farm gate to the wholesale market.

In Chapter 2 we develop a holistic model that joins together different agricultural growing practices, irrigation water sources, and energy sources. In Chapters 3 and 4 we extend this model to the wholesale market by incorporating transportation and spoilage. While the majority of existing life-cycle assessment studies in the literature terminate at the farm gate, our research finds that transportation and logistics are important to assess for complete environmental performance.

Applying optimization to minimize the life cycle environmental impact of fresh produce at the national scale.

This research is the first of its kind in the literature to combine life-cycle assessment of high-value produce with optimization in order to minimize the environmental impact of a given agricultural commodity at a national level. The results presented in Chapter 4 indicate that this type of analysis has the potential to mitigate adverse environmental outcomes while satisfying consumer demand.

5.3 Future Work

Expand model to other high-value crops and geographic regions.

This research assessed the cradle-to-farm gate impact of strawberries, lemons, celery, and avocados; the cradle-to-market impact of oranges delivered to four cities; and the cradle-to-market impact of tomatoes delivered to ten cities. There is plenty of opportunity to expand this model and this type of analysis to other high-value crops and geographic regions, and to explore other environmental problems in this research space.

Explore opportunities for other system synergies.

In Chapter 2, we consider water reuse for irrigation of edible crops as a food-energy-water system synergy, but there are numerous other potential synergies to explore. A few intriguing possibilities include: using waste CO_2 from fossil-fuel combustion to fertilize greenhouse crops; using waste heat from combined heat and power systems to condition greenhouses; and using biodegradable waste to generate biogas through anaerobic digestion. Table 1 lists some other FEWS synergies.

Research environmental impact of non-conventional growing practices, such as protected agriculture and emerging systems and technologies.

This research primarily focused on conventional open-field production (Chapter 2, Chapter 3), while only scratching the surface on protected agriculture (Chapter 4). Protected agriculture such as greenhouse production of tomatoes has expanded in recent years. Emerging technologies and growing systems such as urban rooftop farming, vertical farming, “smart” greenhouses, and “freight farms” have piqued the interest of amateur and professional growers alike. Whether such technologies and systems hold up to the rigor of life-cycle assessment is an important question to be answered in the future.

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Appendix A.

Addendum to Chapter 2

This appendix contains supporting information for Chapter 2: Environmental Evaluation of High-value Agricultural Produce with Diverse Water Sources: Case Study from Southern California.

- Section A1 includes a map and corresponding list of the top ten agricultural counties in California.
- Section A2 includes the calculation methodology for estimating the proportion of Ventura County's irrigation demand represented by the four crops studied.
- Section A3 includes a literature review.
- Section A4 includes a list of the production inputs and returns for each of the four crops studied.
- Section A5 includes additional details regarding the electricity life-cycle energy and GHG emission factors used in this analysis.
- Section A6 includes maps of the irrigation sheds used in this analysis and additional information regarding the assumed piping distribution networks.
- Section A7 includes an additional graph depicting the life-cycle carbon footprint of each of the four crops.
- Section A8 includes additional information regarding uncertainty, including a discussion of adjustments made for custom/contract work, a data quality assessment matrix, a discussion of any inputs excluded from the analysis, additional details regarding the Monte Carlo uncertainty assessment, and a comparison with the existing literature.

Appropriate references for all sections are included at the end of this appendix.

A.1 Top Ten Agricultural Counties in California, 2014

Figure A1. Top Ten Agricultural Counties in California, 2014

Table A1. Top Ten Agricultural Counties in California, 2014 [1]

Rank	Name	Value ($1,000)
1	Tulare	8,084,478
2	Kern	7,552,160
3	Fresno	7,037,175
4	Monterey	4,493,427
5	Merced	4,429,987
6	Stanislaus	4,397,286
7	San Joaquin	3,234,705
8	Kings	2,471,746
9	Madera	2,265,641
10	Ventura	2,133,589

A.2 Calculation of Applied Irrigation Water for Four Ventura County Crops

The applied water by crop and month (in units of acre-in per acre) was determined from the UC Davis cost and return studies [2-5]. Converting from acre-in to million gallons yields the following:

Table A2. Applied water by crop and month for Ventura County in million gallons per acre

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Strawberries	0.03	0.03	0.05	0.08	0.11	0.11	0.00	0.00	0.11	0.00	0.16	0.08	0.76
Lemons	0.02	0.00	0.00	0.08	0.11	0.14	0.17	0.17	0.11	0.06	0.02	0.02	0.89
Celery	0.07	0.15	0.22	0.15	0.07	0.00	0.00	0.07	0.15	0.22	0.15	0.07	1.30
Avocados	0.00	0.00	0.00	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.00	0.00	0.78
Total	0.12	0.18	0.27	0.42	0.39	0.36	0.28	0.35	0.48	0.39	0.33	0.17	

Multiplying by the total acreage for each crop, as determined by the GIS shapefiles from the Ventura County Resource Management Agency [6], and dividing by the number of days in each month gives the average daily water applied in each month:

Table A3. Average applied water by crop and month for Ventura County in million gallons per day

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Acres
Strawberries	9.9	11.0	19.8	30.8	39.7	41.0	0.0	0.0	41.0	0.0	61.5	29.8	23.6	11,328
Lemons	11.6	0.0	1.2	51.6	64.9	87.7	99.8	99.8	67.1	34.9	12.3	12.1	45.5	18,624
Celery	6.3	15.0	19.4	13.5	5.8	0.0	0.0	6.3	14.0	19.4	13.5	5.8	9.9	2,761
Avocados	0.0	0.0	0.0	79.7	77.1	79.7	77.1	77.1	79.7	77.1	0.0	0.0	45.8	21,516
Total	27.8	26.0	40.4	175.5	187.5	208.4	176.9	183.2	201.7	131.4	87.3	47.6	124.8	
Days in month	31	28	31	30	31	30	31	31	30	31	30	31		

The total irrigation demand for Ventura County is as follows, per 2010 USGS data [7]:

Irrigation, Crop self-supplied groundwater withdrawals for crops, fresh, in MGD	158.33
Irrigation, Crop self-supplied surface-water withdrawals for crops, fresh, in MGD	58.56
Irrigation, Crop total self-supplied withdrawals for crops, fresh, in MGD	216.89

Note: Public-supplied irrigation water negligible.

From these data, we can estimate the proportion of Ventura County's total crop irrigation demand represented by these four crops:

$$\frac{124.8}{216.89} \times 100 = 58\%$$

Taking into account landscape irrigation does not change the result significantly. This includes large irrigation accounts but not residential irrigation. Total landscape irrigation for Ventura County was 9.20 million gallons per day (MGD), per 2010 USGS data [7]:

$$\frac{124.8}{216.89 + 9.20} \times 100 = 55\%$$

A.3 Literature Review

Table A4. Literature review

<table>
<tr><th>Publication</th><th>Description</th><th>Results</th></tr>
<tr><td>Clune et. al. (2017)</td><td>Systematic literature review of cradle-to-farm gate GHG footprints for various food categories. Reviewed 369 published studies containing 1718 GWP values for 168 varieties of fresh produce. European studies account for 68% of the reported GWP values (including all of the values for lemons, celery, and avocados).</td><td>GHG footprints [kgCO2e/kg produce]
• Strawberries
median: 0.58, mean: 0.65, stdev: 0.36, min: 0.20, max: 1.50, No. studies: 15
• Lemons and limes
median: 0.26, mean: 0.30, stdev: 0.06, min: 0.18, max: 0.45, No. studies: 2
• Celery
median: 0.18, No. studies: 1
• Avocados
median: 1.30, No. studies: 2</td></tr>
<tr><td>Heller and Keoleian (2014)</td><td>Employs a “meta-analysis approach of published LCA data to arrive at representative CF [carbon footprint] values.” Not a comprehensive database. Based on ~25 studies representing a variety of countries and climatic conditions.</td><td>GHG footprints [kgCO2e/kg produce]
• Strawberries
avg: 0.35, min: 0.16, max: 0.55, No. studies: 3
• Citrus
avg: 0.50, min: 0.25, max: 1.07, No. studies: 5
• Avocados
avg: 1.27, min: 0.65, max: 1.56, No. studies: 1</td></tr>
<tr><td>Gonzalez et. al. (2011)</td><td>Calculates energy and GHG footprint for strawberries grown in the United States. Includes both production and transportation to Sweden.</td><td>Energy footprints [MJ/kg produce]
• Strawberries – 5.4

GHG footprints [kgCO2e/kg produce]
• Strawberries – 0.55</td></tr>
</table>

Table A4. Literature review

Publication	Description	Results
Mekonnen and Hoekstra (2011)	Quantifies the green, blue, and grey water footprint for 126 crops using a high-resolution grid-based dynamic water balance model. Analysis includes California-specific estimates for strawberries, lemons/limes, celery, and avocados.	**Blue water footprints [L applied/kg produce]** • Strawberries – 82 • Lemons and limes – 90 • Celery – 15 • Avocados – 618
Tabatabaie and Murthy (2016)	Conducts cradle-to-farm gate LCAs for strawberries produced in California, Florida, North Carolina, and Oregon. Found strong dependence on yield. Concluded that materials contributed more than half of the GHG footprint for all four states. Based on 2011 UC Davis cost and return study for Santa Barbara/San Luis Obispo.	**GHG footprints [kgCO2e/kg produce]** • CA strawberries – 1.75 • FL strawberries – 2.50 • NC strawberries – 5.48 • OR strawberries – 2.21
Venkat (2012)	Conducts cradle-to-farm gate LCAs for organic and conventional strawberries in California. Footprint for conventional strawberries based on 2006 UC Davis cost and return study for Santa Barbara/San Luis Obispo. Does not account for materials.	**GHG footprints [kgCO2e/kg produce]** • Conventional strawberries – 0.337 • Organic strawberries – 0.234

A.4 Production Inputs and Returns

Table A5. Production inputs and returns per hectare

Category	Unit/ha/y	Strawberries	Lemons	Celery	Avocados
Applied Water	**L**	**7,111,994**	**8,345,798**	**6,095,995**	**7,267,216**
- Drip Irrigation	*L*	*4,825,996*	*8,345,798*	*4,571,996*	*197,555*
- Micro Sprinkler Irrigation	*L*	-	-	-	*7,069,660*
- Sprinkler Irrigation	*L*	*2,285,998*	-	*1,523,999*	-
Biocides	**kg**	**321**	**35**	**9**	**65**
- Fungicides	*kg*	*303*	*21*	*4*	*26*
- Herbicides	*kg*	*1*	*9*	*3*	*1*
- Insecticides	*kg*	*17*	*5*	*2*	*39*
Direct Electricity (excluding electricity used for pumping of water)	**kWh**	**3,769**	**-**	**4,910**	**-**
- Cooling	*kWh*	*3,769*	-	*4,910*	-
Direct Fuel (excluding fuel used for pumping of water)	**L**	**2,936**	**2,059**	**1,387**	**485**
- Diesel	*L*	*2,867*	*582*	*1,367*	*41*
- Gasoline	*L*	*69*	*86*	*20*	*312*
- Jet Fuel	*L*	-	-	-	*132*
- Propane	*L*	-	*1,391*	-	-
Fertilizers	**-**	**-**	**-**	**-**	**-**
- Nitrogen (as N)	*kg*	*156*	*133*	*173*	*167*
- Phosphorus (as P_2O_5*)*	*kg*	*119*	-	*73*	-
- Potassium (as K_2O*)*	*kg*	*45*	-	*31*	*28*
Materials	**-**	**-**	**-**	**-**	**-**
- Clamshells (1-lb)	*#*	*112,668*	-	-	-
- Mulch 1.5 mil (plastic)	*m^2*	*15,010*	-	-	-
- T-Tape	*m*	*12,311*	-	-	-
- Nursery plants	*#*	*72,896*	-	*111,197*	-
- Saplings	*#*	-	*7*	-	*13*
- Tree wraps	*#*	-	*7*	-	-
- Beehives	*#*	-	-	-	*5*
- Mulch	*m^3*	-	-	-	*21*
- Rodent bait and traps	*$*	-	-	-	*$26.52*
Nutrients/Growth Regulators	**kg**	**-**	**4**	**-**	**58**
Labor	**hrs**	**3,943**	**1,577**	**1,035**	**437**
Yield	**kg**	**63,882**	**42,874**	**83,223**	**12,224**

Notes:

i. The data presented in the table above originate from the UC Davis cost and return studies [2-5], but have been adjusted to account for work performed by contractors/custom operators. Refer to Section A8 for additional details regarding this approach.

ii. Due to a lack of reliable data, nursery plants, saplings, tree wraps, beehives, mulch, and rodent bait and traps were not included in the life-cycle energy and GHG footprints. Refer to section A8 for a description of inputs excluded from the analysis.

A.5 Electricity Life-cycle Energy and GHG Emission Factors

The electricity generation portfolio used in the analysis is based on the 2015 Power Content Label for Southern California Edison, the local electricity supplier for Oxnard, published by the California Energy Commission.

Table A6. Southern California Edison and California-wide electricity mixes [14]

Generation source	Southern California Edison 2015 Power Mix	California Average 2015 Power Mix
Eligible Renewable	25%	22%
Biomass & biowaste	*1%*	*3%*
Geothermal	*9%*	*4%*
Eligible hydro	*0%*	*1%*
Solar	*7%*	*8%*
Wind	*8%*	*6%*
Coal	0%	6%
Large hydro	2%	5%
Natural gas	26%	44%
Nuclear	6%	9%
Other	0%	0%
Unspecified	41%	14%
TOTAL	100%	100%

"Unspecified" power refers to electricity from transactions that are not traceable to specific generation sources. To account for the 41% of power designated as unspecified, the California average power mix was applied, resulting in the following distribution which was used in the analysis:

Table A7. Adjusted electricity mix for Southern California Edison

Generation source	Southern California Edison 2015 Power Mix (adjusted)
Eligible Renewable	35%
Biomass & biowaste	*2%*
Geothermal	*11%*
Eligible hydro	*0%*
Solar	*11%*
Wind	*11%*
Coal	3%
Large hydro	4%
Natural gas	47%
Nuclear	10%

Other	0%
TOTAL	100%

The following life-cycle energy and GHG emission factors were then applied to each generation source, and a weighted average was calculated to determine the overall life-cycle energy and GHG emission factors.

Table A8. Life-cycle energy and GHG emissions factors by generation source [15].

Generation source	MJ/kWh	gCO2e/kWh
Biomass	16	-380
Geothermal	22	76
Hydro	0.12	25
Solar	1.7	90
Wind	0.23	18
Coal	11	900
Natural gas	8.8	500
Nuclear	11	17

A.6 Irrigation Sheds and Distribution Network for Future Water Sources

Secondary Recycled Water

This analysis assumes that 21.3 MGD of secondary effluent are available from Oxnard's wastewater treatment plant (WWTP) for use in the irrigation of lemons and avocados, and that the lowest-elevation fields are supplied with water first. Irrigation continues until all of the available water has been used (Figure A2). Since elevation increases monotonically with distance from the WWTP, this approach was the most logical. Irrigation demand is based on an "average day," as calculated by dividing the crop-specific annual water demand by 365 days. Using this method, it was determined that 6,400 acres of lemon orchards and 2,400 acres of avocado orchards could be irrigated, on average, using effluent from Oxnard's WWTP (Table A9). This scenario would require the water to be pumped to a maximum elevation of 300 feet relative to the WWTP.

The results account for the energy, GHG emissions, and costs associated with distributing the secondary effluent from Oxnard's WWTP to the nearest fields and the construction of the distribution system (Figure A3). All scenarios assume the same on-farm irrigation energy use within each crop type, although on-farm irrigation energy use varies slightly from crop to crop.

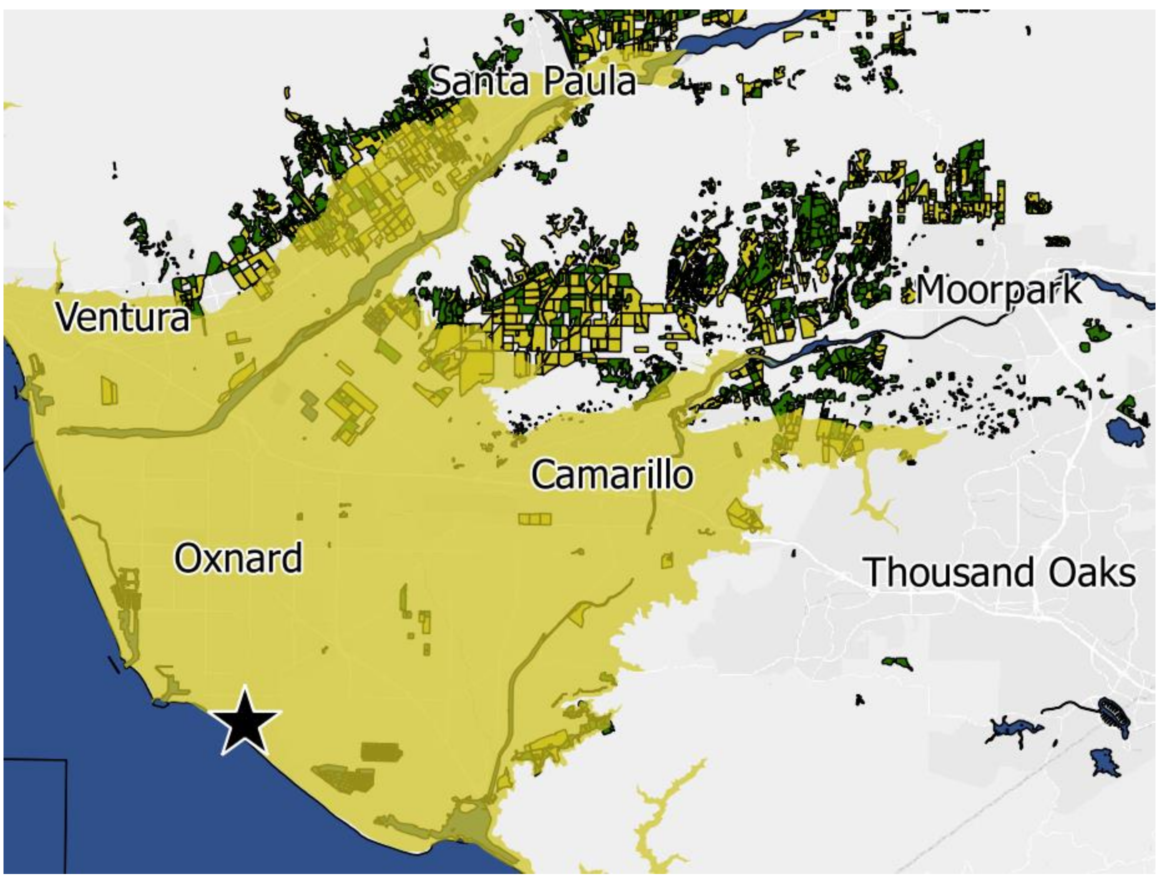

Figure A2. Irrigation shed for secondary recycled water (lemons & avocados)

Table A9. Irrigation shed for secondary recycled water (lemons & avocados) on average day

Maximum elevation	300 ft
Water available	21 MGD
Acres of lemons irrigated	6,400
Acres of avocados irrigated	2,400

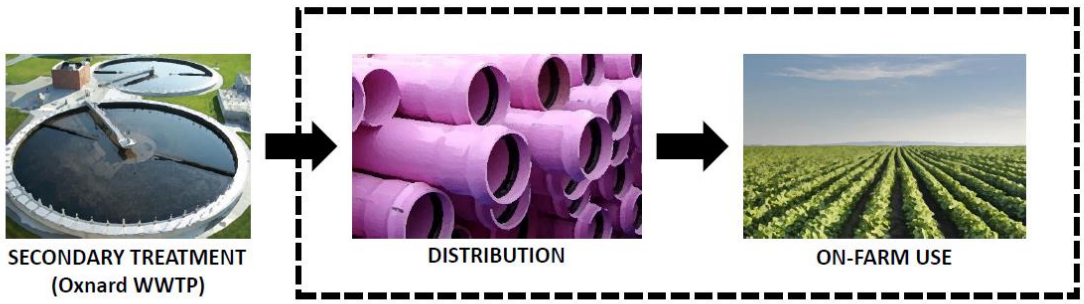

Figure A3. Schematic for irrigation with secondary effluent
Note: Processes within dashed box are accounted for in estimates of energy, GHG emissions, and costs.

In order to distribute the recycled water back to the fields, a simplified piping network was developed (Figure A4). The embedded energy and GHG emissions associated with the piping network were estimated from the literature, and the impacts were allocated per unit of water delivered, assuming a 50-year infrastructure lifetime [16]. The piping material was assumed to be polyvinyl chloride. Although the piping network illustrated below is clearly suboptimal, our analysis indicates that the network itself is responsible for less than one percent of the embedded energy and emissions per unit of water delivered. The purchase price of the water was assumed to be \$0.77 per cubic meter [17]. This estimate assumes that the secondary effluent itself is free; the only costs are associated with distribution.

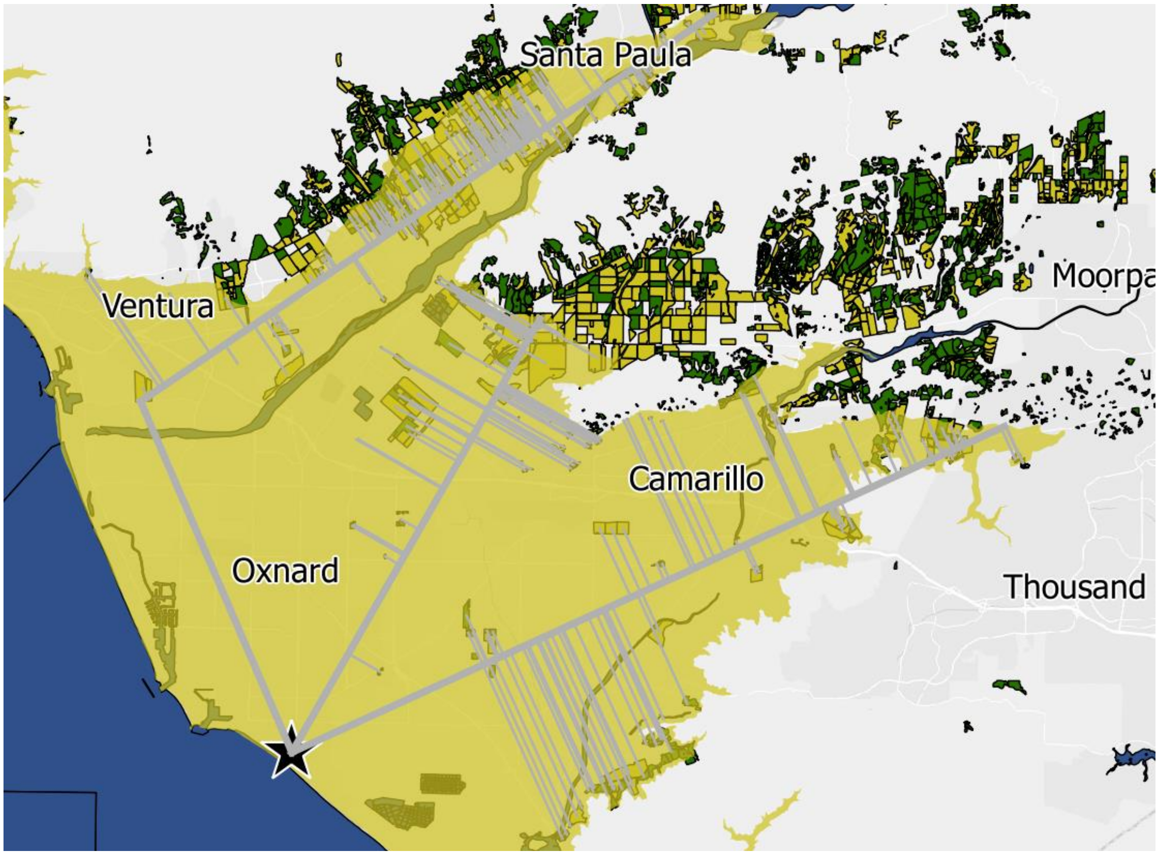

Figure A4. Distribution network for secondary recycled water (lemons & avocados)

The embedded energy, in MJ/m^3, required to pump the water from the treatment facility to each of the fields is given by the following equation:

$$E = \rho g(EL + HL)/\eta$$

Where: *ρ = density of water = 999 kg/m^3 (freshwater at 60°F) [18]*
g = gravitational constant = 9.81 m/s^2
EL = elevation gain between the treatment facility and the field, in meters
HL = head loss, in meters
η = pump and drive efficiency

Head loss was calculated per the Darcy-Weisbach Equation:

$$HL = {flv^2}/{2Dg} \quad [18]$$

Where: *f = friction factor = $64/Re$ (for laminar flow), Re = ${\rho v D}/{\mu}$ [18]*
μ = dynamic viscosity = 1.12e-3 Ns/m^2 (freshwater at 60°F) [18]
l = length of the pipe, in meters

v = velocity of water in pipe, in meters per second
D = diameter of pipe, in meters

Advanced Recycled Water

This analysis assumes that 16.2 MGD of advanced effluent are available from Oxnard's expanded advanced water purification facility (AWPF) for use in the irrigation of strawberries and celery and that the lowest-elevation fields are supplied with water first. Irrigation continues until all of the available water has been used (Figure A5). Irrigation demand is based on an "average day," as calculated by dividing the crop-specific annual water demand by 365 days. Using this method, it was determined that 5,400 acres of strawberry fields and 1,500 acres of celery fields could be irrigated, on average, using water from Oxnard's AWPF (Table A10). This scenario would require the water to be pumped to a maximum elevation of 40 feet relative to the AWPF.

The results presented herein account for the energy, GHG emissions, and costs associated with the construction of an expanded AWPF, incremental treatment required to bring the secondary effluent from Oxnard's WWTP up to an advanced level, the distribution of the advanced effluent from Oxnard's AWPF to the nearest fields, and the construction of the distribution system (Figure A7). All scenarios assume the same on-farm irrigation energy use within each crop type, although on-farm irrigation energy use varies slightly from crop to crop.

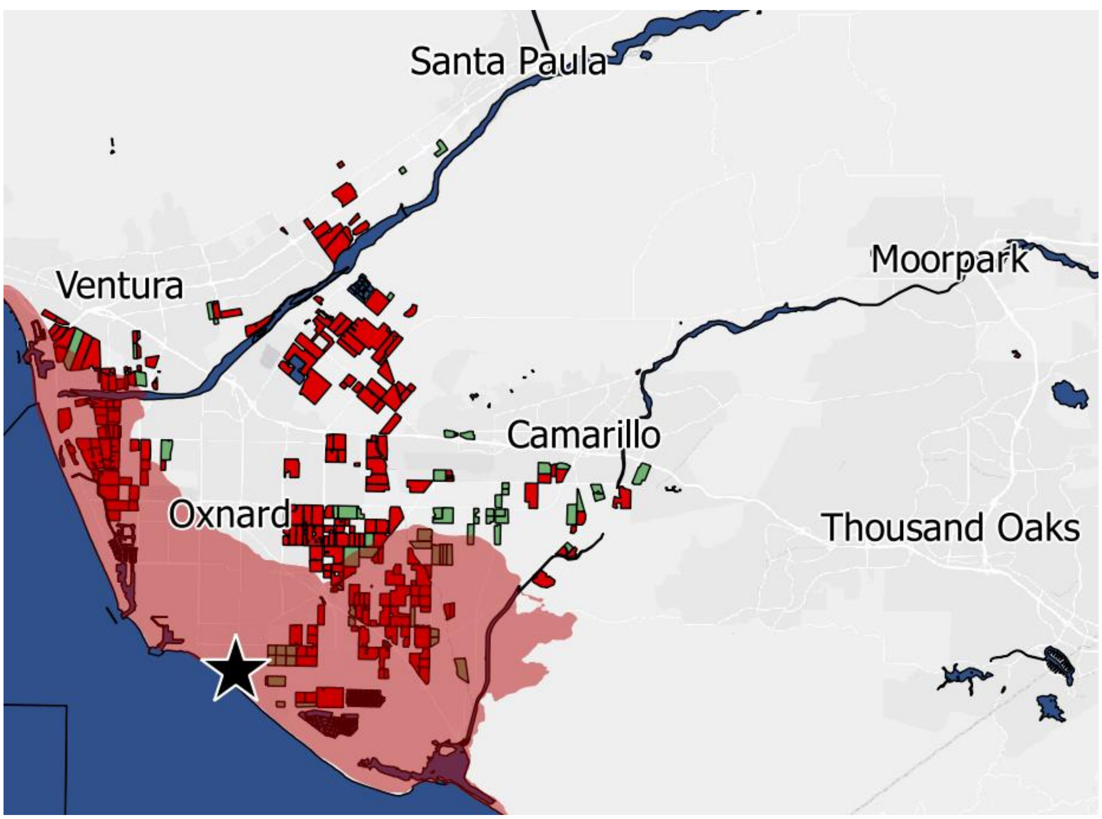

Figure A5. Irrigation shed for advanced recycled water (strawberries & celery)

Table A10. Irrigation shed for advanced recycled water (strawberries & celery) on average day

Maximum elevation	40 ft
Water available	16 MGD
Acres of strawberries irrigated	5,400
Acres of celery irrigated	1,500

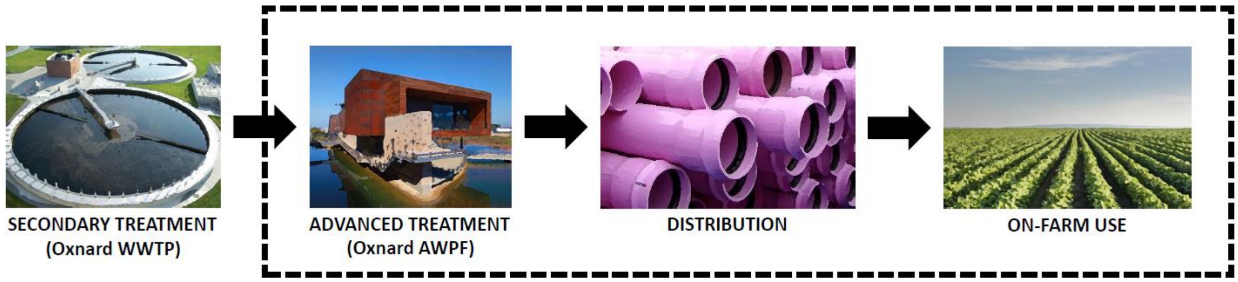

Figure A6. Schematic for irrigation with advanced effluent
Note: Processes within dashed box are accounted for in estimates of energy, GHG emissions, and costs.

As in the case of lemons and avocados, a simplified piping network was developed (Figure A7). Although the piping network illustrated below is clearly suboptimal, our analysis indicates that the network itself is responsible for less than one percent of the embedded energy and emissions per unit of water delivered. The purchase price of the water was assumed to be $1.15 per cubic meter, per the City of Oxnard's current rate for recycled water for irrigation [19]. This estimate assumes that rates would remain more or less unchanged by the proposed expansion. The literature suggests that a slightly higher rate of $1.25 per cubic meter is typical for recycled water projects [17].

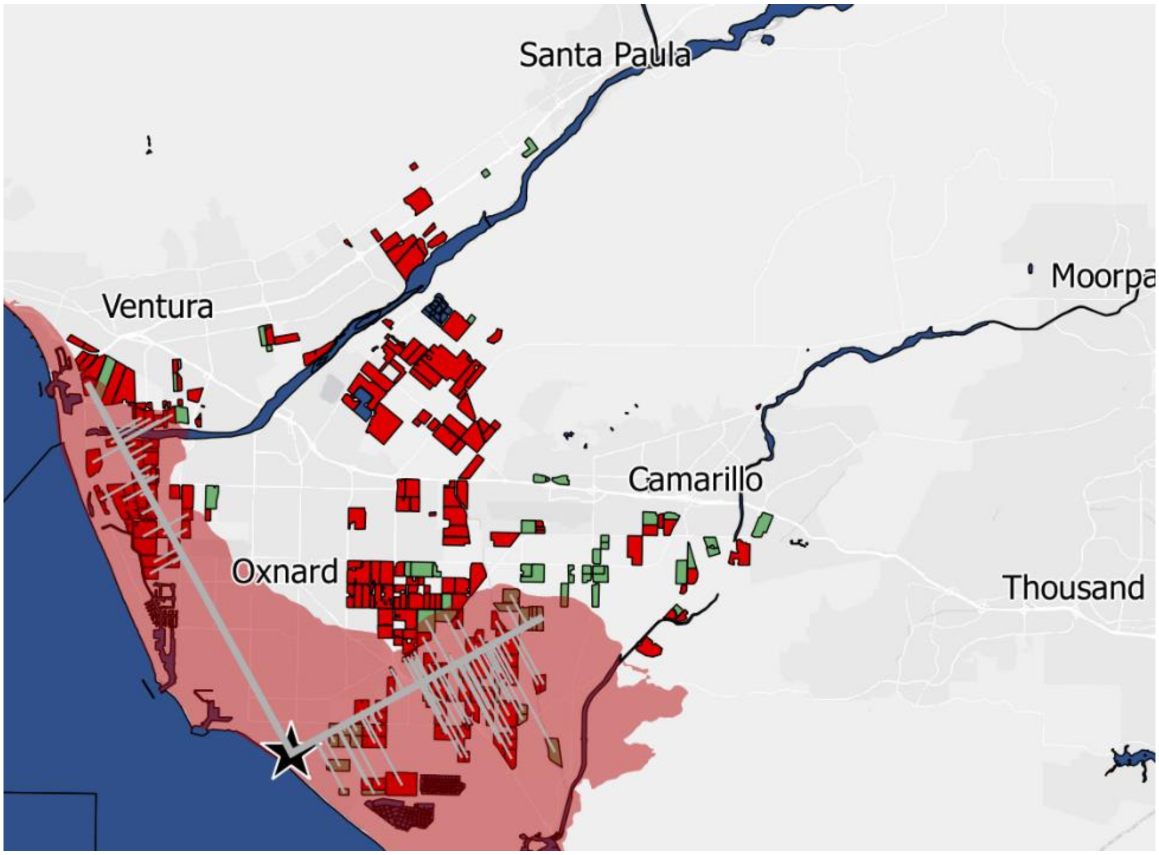

Figure A7. Distribution network for advanced recycled water (strawberries & celery)

Desalinated Water

In order to draw a fair comparison across all three potential water sources, all scenarios are calculated based on the same group of fields. As a result, the desalination scenario assumes the same distribution networks as in the recycled water scenario. The desalination scenario assumes that the seawater reverse osmosis plant is constructed in approximately the same location as Oxnard's WWTP and AWPF with the capability to provide roughly the same quantity of water as in the recycled scenario.

The results presented herein account for the energy, GHG emissions, and costs associated with the construction of the desalination plant, the treatment stage, the distribution of the effluent from desalination plant to the nearest fields, and the construction of the distribution system (Figure A8). All scenarios assume the same on-farm irrigation energy use within each crop type, although on-farm irrigation energy use varies slightly from crop to crop.

Figure A8. Schematic for irrigation with desalinated water
Note: Processes within dashed box are accounted for in estimates of energy, GHG emissions, and costs.

The purchase price of the water was assumed to be \$2.31 per cubic meter [17]. This estimate assumes \$1.54 per cubic meter for treatment and \$0.77 per cubic meter for distribution [17].

A.7 Graph of GHG Emissions

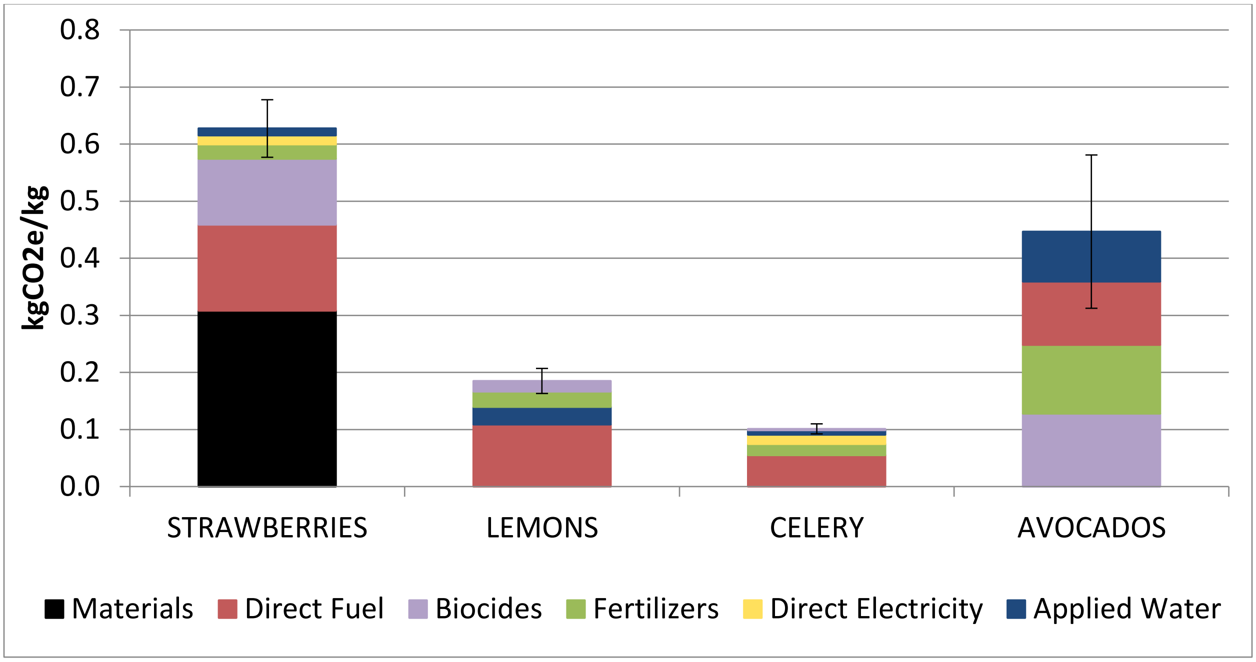

Figure A9. Baseline cradle-to-farm gate life-cycle GHG emissions for four crops
Notes: The “Direct Electricity” and “Direct Fuel” categories exclude electricity and fuel used for irrigation water, which are included in the “Applied Water” category. Uncertainty bars represent one standard deviation as determined using a Monte Carlo simulation. The intent of this figure is to establish baseline GHG emissions values for each crop, rather than advocate for dietary substitution or provide a cross-crop comparison.

A.8 Uncertainty

Adjustments for custom/contract work

As described by the UC Davis cost and return studies, certain agricultural processes are conducted by a contractor or custom operator. Where custom/contract work is performed, the cost and return studies report the total cost associated with the process, but do not break down the cost into individual categories (e.g., labor, materials). Where custom/contract work appears, the following procedure was applied:

a. A proxy cost and return study was identified where the same (or similar) procedure is conducted in house, rather than by a contractor. This proxy cost and return study may apply to: the same crop but a different growing region (e.g., strawberries produced in Santa Barbara County v. strawberries produced in Ventura County), or a different crop with similar growing practices (e.g., lemons v. oranges).
b. The proportion of costs attributable to labor, fuel, lube/repairs, and materials was determined based on the proxy cost and return study.
c. The same proportions are applied to the original total cost.

The table below indicates the amount of custom/contract work performed for each of the four crops, as a percentage of the total operational costs per acre.

Table A11. Amount of custom/contract work as percentage of total operational costs, by crop [2-5]

Strawberries	Lemons	Celery	Avocados
23%	85%	9%	6%

The proportion of custom/contract work seems particularly high for lemons due to the fact that lemon harvesting is performed by a contractor. Since labor does not contribute to the energy and carbon footprints of the crops, it is important to consider the non-labor operation costs per acre.

Table A12. Amount of custom/contract work as percentage of non-labor operational costs, by crop [2-5]

Strawberries	Lemons	Celery	Avocados
26%	20%	56%	7%

- *Example: Strawberry fumigation* -

The 2011 Ventura County cost and return study for strawberries (used as the basis for the life-cycle footprints developed in this analysis) reports that fumigation of strawberry beds is performed by a contractor with a total cost of $1,350 per acre [2].

An earlier cost and return study for Santa Barbara County reports that fumigation was performed in house with the following costs [20]:

Table A13. Cost breakdown for strawberry fumigation (Santa Barbara County) [20]

	Labor Cost	Fuel	Lube & Repairs	Material Cost	Total Cost
Cost	$111.00	$16.80	$4.20	$1,138.00	$1,270.00
% of total	9%	1%	0%	90%	100%

The same proportions are then applied to the original cost from the 2011 Ventura County cost and return study, as follows:

Table A14. Adjusted cost breakdown for strawberry fumigation (Ventura County)

	Labor Cost	Fuel	Lube & Repairs	Material Cost	Total Cost
Cost	$117.99	$17.86	$4.46	$1,209.69	$1,350.00
% of total	9%	1%	0%	90%	100%

Data quality assessment matrix

Table A15. Scoring rubric for data quality matrix

Category	1	2	3	4	5
Acquisition method	Data directly measured/collected by local agency or research group	Data estimated based on direct measurements with some assumptions and calculations	Data based on peer-reviewed journal, published textbook, or model	Data based on non-peer-reviewed report or other publication	Data estimated based on journal, report, or other publication with significant assumptions and calculations
Technological correlation	Data applies to exact system, product, or technology under study (e.g., Oxnard's AWPF)	Data applies to same type of system, product, or technology under study (e.g., a similar-sized water reuse facility with same treatment train)	Data applies to similar system, product, or technology under study (e.g., a water reuse facility with slightly different treatment train or size)	Data estimated based on similar system, product, or technology with some assumptions and calculations	Data estimated based on dissimilar system, product, or technology with significant assumptions and calculations

Table A15. Scoring rubric for data quality matrix

Category	1	2	3	4	5
Geographical correlation	Data from area under study (i.e., Ventura County)	Average data from larger area in which the area under study is included (e.g., California, United States)	Data from area with similar conditions	Data from area with slightly similar conditions	Data from unknown area or area with very different conditions
Temporal correlation	Less than three years of difference to year of study	Less than five years of difference	Less than 10 years of difference	Less than 20 years of difference	Age unknown or more than 20 years of difference

Table A16. Data quality matrix

Data item	Acquisition method	Technological correlation	Geographical correlation	Temporal correlation
Strawberries - production practices and costs	2	1	1	3
Lemons - production practices and costs	2	2	3	1
Celery - production practices and costs	2	1	1	2
Avocados - production practices and costs	2	1	1	3
Biocides - embedded energy and GHG emissions	3	3	2	1
Electricity - embedded energy and GHG emissions	5	2	1	3
Fossil fuel - embedded energy and GHG emissions	3	1	2	1
Fertilizer - embedded energy and GHG emissions	3	3	2	1
Materials - embedded energy and GHG emissions	3	4	5	3
Groundwater depths	1	1	1	1
Location and acreage of fields	1	1	1	2
On-farm pumping energy	4	4	5	4
Piping embedded energy and GHG emissions	5	4	2	1
Treatment - recycled water	3	2	3	1
Treatment - desalinated water	3	3	3	3
Recycled and desalinated water costs	4	3	2	1

Completeness of life-cycle energy and carbon footprints

Due to lack of reliable data, several inputs were excluded from the energy and GHG footprints developed in this analysis. The tables below outline the excluded inputs, by crop, as well as their relative percentages of operational and non-labor operational costs.

Table A17. Inputs excluded from analysis and relative percentage of costs

Strawberries

Production input	% of operational cost	% of non-labor operational cost
Nursery plants	8.2%	14%
Combined total	8.2%	14%

Lemons

Production input	% of operational cost	% of non-labor operational cost
Saplings	0.31%	2.0%
Tree wraps	0.016%	0.10%
Combined total	0.32%	2.1%

Celery

Production input	% of operational cost	% of non-labor operational cost
Nursery plants	9.3%	19%
Combined total	9.3%	19%

Avocados

Production input	% of operational cost	% of non-labor operational cost
Beehives	2.6%	6.5%
Rodent bait and traps	0.24%	0.61%
Saplings	3.6%	9.0%
Mulch	0.63%	1.6%
Combined total	7.0%	18%

Biocides

There is a wide range of life-cycle energy and GHG emission factors for biocides in the literature. The table below presents some of these estimates.

Table A18. Life-cycle energy and GHG emission factors for biocides

		Fungicides	Herbicides	Insecticides	Notes
CA-GREET 2.0	[MJ/kg]	-	280	335	Used in this analysis.
	[kgCO2e/kg]	-	21	25	
Tabatabaie, 2016	[MJ/kg]	115	275	313	Herbicides and insecticides from CA-GREET 1.8. Fungicides from Tabar, 2010.
	[kgCO2e/kg]	-	-	-	
Tabar, 2010	[MJ/kg]	115	295	58	Study from Iran. Fungicides, herbicides, and insecticides based on three older studies.
	[kgCO2e/kg]	-	-	-	
Ecoinvent, 2010	[MJ/kg]	164	164	258	Fungicides, herbicides, and insecticides based on European data.
	[kgCO2e/kg]	11	10	17	
Venkat, 2012	[MJ/kg]	387	589	488	Reverse-engineered from results.
	[kgCO2e/kg]	26	36	30	

Range [MJ/kg]:	115-387	164-589	58-488
Range [kgCO2e/kg]:	11-26	10-36	17-30

While there is a great deal of uncertainty regarding the life-cycle energy and GHG emission factors for biocides, biocides represent a relatively small proportion of the life-cycle energy for each crop, as shown in the table below.

Table A19. Biocides as a proportion of life-cycle energy

	Strawberries	Lemons	Celery	Avocados
All biocides	13%	8%	2%	26%
Fungicides only	12%	5%	1%	10%

Monte Carlo Uncertainty Assessment

In order to determine uncertainty ranges for the life-cycle energy and GHG emissions of the four crops, a Monte Carlo uncertainty assessment was performed using Oracle's Crystal Ball software. The most significant parameters were varied, including crop yields as well as energy and GHG emission factors for all of the major inputs, as summarized in the table below.

Table A20. Probability distribution functions for Monte Carlo assessment

Parameter	Units	Lower bound	Upper bound	Distribution shape	Notes
Strawberry yield	kg/ha	-7%	+7%	Normal	USDA NASS 10-year average
Lemon yield	kg/ha	-11%	+11%	Normal	USDA NASS 10-year average
Celery yield	kg/ha	-7%	+7%	Normal	USDA NASS 10-year average

Table A20. Probability distribution functions for Monte Carlo assessment

Parameter	Units	Lower bound	Upper bound	Distribution shape	Notes
Avocado yield	kg/ha	-26%	+26%	Normal	USDA NASS 10-year average
Electricity	MJ/kWh	-20%	+20%	Uniform	
Electricity	kgCO2e/kWh	-40%	+5%	Uniform	California GHG reduction laws
Fungicides	MJ/kg	-60%	+30%	Uniform	Literature review
Fungicides	kgCO2e/kg	-50%	+10%	Uniform	Literature review
Herbicides	MJ/kg	-40%	+100%	Uniform	Literature review
Herbicides	kgCO2e/kg	-50%	+90%	Uniform	Literature review
Insecticides	MJ/kg	-80%	+50%	Uniform	Literature review
Insecticides	kgCO2e/kg	-30%	+20%	Uniform	Literature review
Fertilizer (N)	MJ/kg	-20%	+20%	Uniform	
Fertilizer (N)	kgCO2e/kg	-20%	+20%	Uniform	
Fertilizer (P)	MJ/kg	-20%	+20%	Uniform	
Fertilizer (P)	kgCO2e/kg	-20%	+20%	Uniform	
Fertilizer (K)	MJ/kg	-20%	+20%	Uniform	
Fertilizer (K)	kgCO2e/kg	-20%	+20%	Uniform	
Diesel	MJ/L	-10%	+10%	Uniform	
Diesel	kgCO2e/L	-10%	+10%	Uniform	
Gasoline	MJ/L	-10%	+10%	Uniform	
Gasoline	kgCO2e/L	-10%	+10%	Uniform	
Jet fuel	MJ/L	-10%	+10%	Uniform	
Jet fuel	kgCO2e/L	-10%	+10%	Uniform	
Propane	MJ/L	-10%	+10%	Uniform	
Propane	kgCO2e/L	-10%	+10%	Uniform	
PET clamshells	MJ/#	-10%	+5%	Uniform	Value could be slightly overestimated due to differences in transportation distances
PET clamshells	kgCO2e/#	-10%	+5%	Uniform	Value could be slightly overestimated due to differences in transportation distances

Comparison with existing literature

- *Strawberries* -

Our value for the life-cycle GHG footprint of strawberries (0.63 kgCO2e/kg) is extremely close to the mean value from the systematic literature review conducted by Clune et. al. 2017 (0.65 kgCO2e/kg). Some studies, including Venkat 2012, did not consider impacts from materials, resulting in lower estimates (0.337 kgCO2e/kg for Venkat). The study conducted by Tabatabaie and Murthy 2016 was not included in Clune's literature review, and found a significantly higher GHG footprint relative to other comparable studies (1.75 kgCO2e/kg), roughly three quarters of which was attributed to materials. Our analysis found that materials contributed to roughly half of the GHG footprint.

Our analysis indicates that roughly 100 L of applied water (i.e., blue water) is needed to produce 1 kg of strawberries. This represents a typical average for Ventura County. The actual quantity of water needed will vary from year to year based on rainfall (i.e., green water). Mekonnen and Hoekstra 2011 found a California average of 82 L of applied water per 1 kg. It seems logical that more water would need to be applied in Southern California relative to the California average, due to the infrequency of rainfall in Southern California relative to Northern California. Mekonnen and Hoekstra estimated a combined blue and green water footprint of 107 L/kg, much closer to our estimate.

- *Lemons* -

Our value for the life-cycle GHG footprint of lemons (0.19 kgCO2e/kg) is comparable to the mean value from Clune et. al. 2017 (0.30 kgCO2e/kg). The mean value from Clune is based on only two published studies, neither of which are specific to the United States. Any variation is likely due differences in climate, production practices, and yields.

Our analysis indicates that roughly 200 L of applied water is needed to produce 1 kg of lemons. Mekonnen and Hoekstra 2011 calculated a California average of only 90 L/kg. This discrepancy is likely due to the variation in rainfall between Northern and Southern California. Mekonnen and Hoekstra estimated a combined blue and green water footprint of 176 L/kg, much closer to our estimate.

- *Celery* -

Our value for the life-cycle GHG footprint of celery (0.10 kgCO2e/kg) is comparable to the median value from Clune et. al. 2017 (0.18 kgCO2e/kg). The value from Clune is based on only one published study from Australia. Any variation is likely due differences in climate, production practices, and yields.

Our analysis indicates that roughly 100 L of applied water is needed to produce 1 kg of celery. Mekonnen and Hoekstra 2011 calculated a California average of only 15 L/kg. This discrepancy is likely due to the variation in rainfall between Northern and Southern California. Mekonnen and Hoekstra estimated a combined blue and green water footprint of 83 L/kg, much closer to our estimate.

- *Avocados* -
Our value for the life-cycle GHG footprint of avocados (0.45 kgCO2e/kg) is significantly lower than the mean value found by Clune et. al. (1.30 kgCO2e/kg). The mean value from Clune is based on only two published studies, neither of which are specific to the United States. It is possible that some of the variation is due differences in climate, production practices, and yields. In addition, there were several material inputs excluded from our analysis of avocados (e.g., beehives, saplings), amounting to approximately 18% of non-labor operational costs. As a result, it is likely that the true GHG footprint of avocados is slightly higher than our analysis indicates.

Our analysis indicates that roughly 600 L of applied water is needed to produce 1 kg of avocados. This is comparable to the California-average value found by Mekonnen and Hoekstra 2011 (618 L/kg).

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Appendix B.

Addendum to Chapter 3

This appendix contains supporting information for Chapter 3: Modeling the Carbon Footprint of Fresh Produce: Effects of Transportation, Localness, and Seasonality on U.S. Orange Markets.

- Section B1 of contains a literature review of existing orange life cycle assessment studies.
- Sections B2 though B5 include additional data and assumptions for the production, post-harvest processing, packaging, and transportation modeling stages, respectively.
- Section B6 includes additional details regarding the estimation of the weekly weighted-average environmental impact.
- Sections B7 though B9 contain underlying data for the results of the New York City oranges case study.
- Section B10 describes the details of the uncertainty assessment.
- Section B11 includes results for oranges supplied to Los Angeles, Chicago, and Atlanta.

Appropriate references for all sections are included at the end of this appendix.

B.1 Literature Review

Table B1: Summary of literature review for life cycle assessment of oranges [1-9]

Source	Geographic region	GHG emissions per orange [kgCO_2e/kg]	GHG emissions per hectare [kgCO_2e/ha]	Yield [kg/ha]
Audsley, 2009	Europe	0.09	1,500	17,000
Beccali, 2009	Sicily	0.10	2,090	20,400
Dwivedi, 2012	Florida	0.31	7,820	25,100
Gonzalez, 2011	United States	0.28[a]	-	-
Jungbluth, 2013	Spain	0.07	3,422	48,200
Knudsen, 2011	Brazil	0.11	2,240	20,000
Pergola, 2013	Sicily	0.13	3,590	26,900
Ribal, 2017[b]	Spain	0.31	5,570	33,352
Yan, 2016[c]	China	0.14	7,100	56,000

[a] Modified from the original reported value to subtract transportation emissions from Florida to Gothenburg, Sweden.
[b] Results represent the average of 124 individual orchards with an average size of 3.5 hectares.
[c] Results represent the average of 7 individual orchards.

B.2 Production

Table B2: Annual yields and GHG emissions from production of fresh oranges

Production region	Annual yield		GHG emissions from production	
	Value [kg/ha]	Source	Value [$kgCO_2e/kg$]	Source
Australia	19,890	[11,12]	0.28	calculated
California	28,945	[10]	0.19	calculated
Chile	13,680	[11,12]	0.41	calculated
Florida	27,216	[10]	0.20	calculated
Mexico	11,868	[11,12]	0.47	calculated
Morocco	13,990	[11,12]	0.40	calculated
Peru	11,883	[11,12]	0.47	calculated
South Africa	23,520	[11,12]	0.24	calculated
Texas	21,112	[10]	0.26	calculated

B.3 Processing

Table B3: Processing stages and associated electricity use for fresh oranges

Stage	Electricity use [kWh/metric ton]	Source
Washing, waxing, drying	1.50	[13]
Sorting, grading	1.25	[13]
Packing	1.45	[13]
Short-term cold storage	35.00	[13]
Total	39.20	

Table B4: Assumed electricity portfolio by production region

Production region	Coal	Oil	Gas	Nuclear	Hydro	Biomass	Wind	Solar	Geothermal	Source
Australia	61.2%	2.0%	21.9%	0.0%	7.4%	1.9%	4.0%	1.3%	0.3%	[15]
California	0.4%	0.8%	60.6%	8.6%	8.3%	3.5%	6.6%	5.0%	6.1%	[14]
Chile	35.4%	6.2%	17.0%	0.0%	31.5%	2.5%	5.3%	1.7%	0.4%	[15]
Florida	22.8%	1.4%	61.3%	12.2%	0.1%	2.1%	0.0%	0.1%	0.0%	[14]
Mexico	11.2%	11.0%	57.1%	3.2%	12.9%	1.2%	2.5%	0.8%	0.2%	[15]
Morocco	55.0%	13.1%	19.5%	0.0%	5.7%	1.7%	3.6%	1.2%	0.3%	[15]
Peru	0.7%	1.2%	45.9%	0.0%	48.8%	0.9%	1.8%	0.6%	0.1%	[15]
S. Africa	93.0%	0.1%	0.0%	5.5%	0.4%	0.3%	0.5%	0.2%	0.0%	[15]
Texas	33.9%	0.6%	46.8%	9.0%	0.1%	0.4%	9.1%	0.1%	0.0%	[14]

Table B5: Life-cycle GHG emission factors for electricity production

Production region	Coal	Oil	Gas	Nuclear	Hydro	Biomass	Wind	Solar	Geothermal	Source
gCO_2e/kWh	897	877	497	17	24.5	-384	18.1	90.3	75.8	[16]

Table B6: Calculated life-cycle electricity GHG emission factors and GHG emissions from post-harvest processing of fresh oranges

Production region	Life-cycle electricity GHG emission factors [kgCO_2e/kWh]	GHG emissions from post-harvest processing [kgCO_2e/kg oranges]
Australia	672	0.026
California	312	0.012
Chile	458	0.018
Florida	515	0.020
Mexico	481	0.019
Morocco	702	0.028
Peru	255	0.010
South Africa	835	0.033
Texas	544	0.021

B.4 Packaging

Since the majority of oranges shipped within the United States are packaged in 4/5-bushel or 7/10-bushel cartons, this case study assumes the following packaging configuration for all orange shipments:

Length:	0.40 m
Width:	0.30 m
Height:	0.25 m
Thickness:	3.2 mm

Figure B1: Assumed packaging and dimensions for orange packaging stage [17]

Assuming a conservative density of 90 kg per cubic meter of cardboard and a life-cycle GHG emissions footprint of 1.01 kgCO_2e/kg of cardboard, the result is 0.17 kgCO_2e/box. Assuming 18 kg of oranges per box, this equates to roughly 9 gCO_2/kg of oranges due to packaging.

B.5 Transportation

Table B7: Supply-by-mode (SM_{ij}) matrix for transportation stage, U.S. average [18]

Production region	Truck	Rail	Containership
Australia	0.0%	0.0%	100.0%
California	0.0%	100.0%	0.0%
Chile	0.0%	0.0%	100.0%
Florida	99.9%	0.1%	0.0%
Mexico	100.0%	0.0%	0.0%
Morocco	0.0%	0.0%	100.0%
Peru	0.0%	0.0%	100.0%
South Africa	0.0%	0.0%	100.0%
Texas	100.0%	0.0%	0.0%

Table B8: Transportation distances between orange production regions and Hunt's Point Cooperative Market in New York City [km]

Production region	Truck1[a]	Rail[b]	Containership[c]	Truck2[a]
Australia	744	-	18,427	28
California	43	4,850	-	6
Chile	101	-	8,630	28
Florida (T)	1,899	-	-	-
Florida (R)	94	1,893	-	6
Mexico	3,832	-	-	-
Morocco[d]	N/A	N/A	N/A	N/A
Peru[d]	N/A	N/A	N/A	N/A
South Africa	1,428	-	12,568	28
Texas	3,180	-	-	-

[a] Determined from Google Maps.
[b] Determined from GIS datasets of intermodal rail hubs and U.S. Department of Transportation railroad lines [19,20]
[c] Determined based on tables of nautical shipping distances between major ports [21]
[d] Transportation distances from Morocco and Peru were not calculated because terminal market shipping data indicate that New York City did not receive any shipments from these regions between 2012 and 2016.

Table B9: Transportation emissions matrix (TR_{ij}) for transportation between orange production regions and Hunt's Point Cooperative Market in New York City [$kgCO_2e$/kg oranges]

Production region	Truck	Rail	Containership
Australia	-	-	0.15
California	-	0.07	-
Chile	-	-	0.05
Florida	0.16	0.03	-
Mexico	0.33	-	-
Morocco[a]	N/A	N/A	N/A
Peru[a]	N/A	N/A	N/A
South Africa	-	-	0.18
Texas	0.27	-	-

[a] Transportation emissions from Morocco and Peru were not calculated because terminal market shipping data indicate that New York City did not receive any shipments from these regions between 2012 and 2016.

Table B10: Mode-weighted transportation emissions matrix (TR_{AVGi}) for transportation between orange production regions and Hunt's Point Cooperative Market in New York City

Production region	[$kgCO_2e$/kg oranges]
Australia	0.15
California	0.07
Chile	0.05
Florida	0.16
Mexico	0.33
Morocco[a]	N/A
Peru[a]	N/A
South Africa	0.18
Texas	0.27

[a] Transportation emissions from Morocco and Peru were not calculated because terminal market shipping data indicate that New York City did not receive any shipments from these regions between 2012 and 2016.

B.6 Weekly Weighted-Average Environmental Impact

Weekly shipping data for fresh produce were only available at the national level. In order to estimate shipping data at the city level, weekly U.S.-level orange movement reports were combined with weekly terminal market data for New York City. The following section describes the methodology used for this approach.

Figure B2 and Figure B3 were generated from USDA Agricultural Marketing Service (AMS) custom movement reports for fresh oranges. These reports describe the quantity, transportation mode, origin, and packaging of common crops shipped within the U.S. The figures are based on a five-year average from 2012-2016. Any production regions individually accounting for less than 0.1% of the U.S.'s total annual supply were excluded from the analysis. These regions include Argentina, Arizona, Brazil, the Dominican Republic, Ecuador, Greece, Israel, Italy, Jamaica, Panama, Spain, and Uruguay. Collectively, these 12 regions account for only 0.27% of the U.S.'s total annual supply.

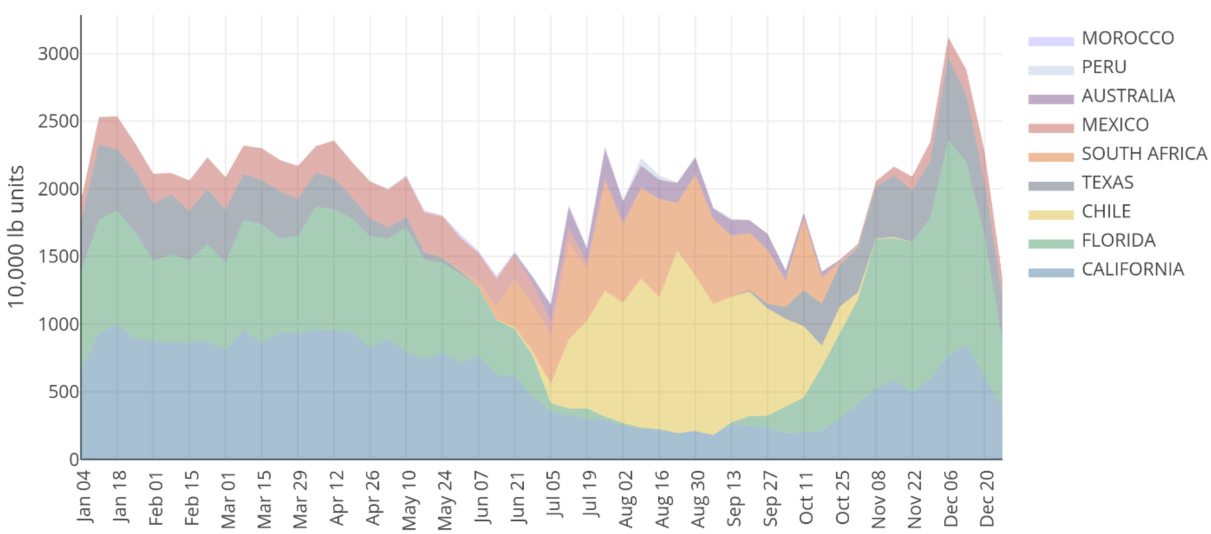

Figure B2: United States fresh orange supply by weight (2012-2016 average)
Generated from USDA AMS movement reports [18]

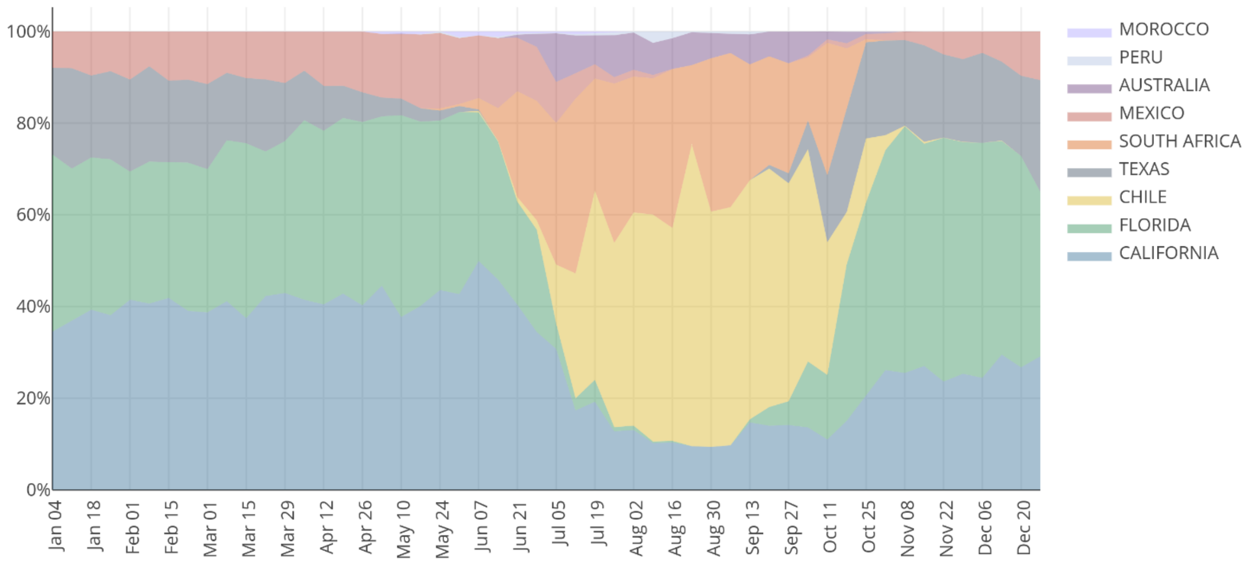

Figure B3: United States fresh orange supply by proportion (2012-2016 average)
Generated from USDA AMS movement reports [18]

Table B11: United States fresh orange "supply-by-week matrix" (2012-2016 average) [18].

Week of	CALIF.	FLORI.	CHILE	TEXAS	S. AFR.	MEXI.	AUST.	PERU	MORO.
4-Jan	35%	39%	0%	19%	0%	8%	0%	0%	0%
11-Jan	37%	33%	0%	22%	0%	8%	0%	0%	0%
18-Jan	39%	33%	0%	18%	0%	10%	0%	0%	0%
25-Jan	38%	34%	0%	19%	0%	9%	0%	0%	0%
1-Feb	41%	28%	0%	20%	0%	10%	0%	0%	0%
8-Feb	41%	31%	0%	21%	0%	8%	0%	0%	0%
…	…	…	…	…	…	…	…	…	…

The USDA also maintains terminal market reports for all major U.S. cities. These reports declare data on the origin and price—but not the quantity—of fresh oranges on a weekly basis [22]. These reports were used to determine whether or not a shipment occurred from a given production region to the city in question. A matrix of ones and zeros was then developed, as shown in Table B12.

Table B12: New York City fresh orange shipments by week (2012-2016 average) [22]

Week of	CALIF.	FLORI.	CHILE	TEXAS	S. AFR.	MEXI.	AUST.	PERU	MORO.
4-Jan	1	1	0	0	0	0	0	0	0
11-Jan	1	1	0	0	0	0	0	0	0
18-Jan	1	1	0	0	0	0	0	0	0
25-Jan	1	1	0	0	0	0	0	0	0
1-Feb	1	1	0	0	0	0	0	0	0
8-Feb	1	1	0	0	0	0	0	0	0
…	…	…	…	…	…	…	…	…	…

By performing a bit-wise multiplication of the matrices in Table B11 and Table B12, and redistributing the remaining production regions in proportion to their national significance, it is possible to estimate the weekly city-level fresh orange supply, as shown in Figure B4 and Table B13.

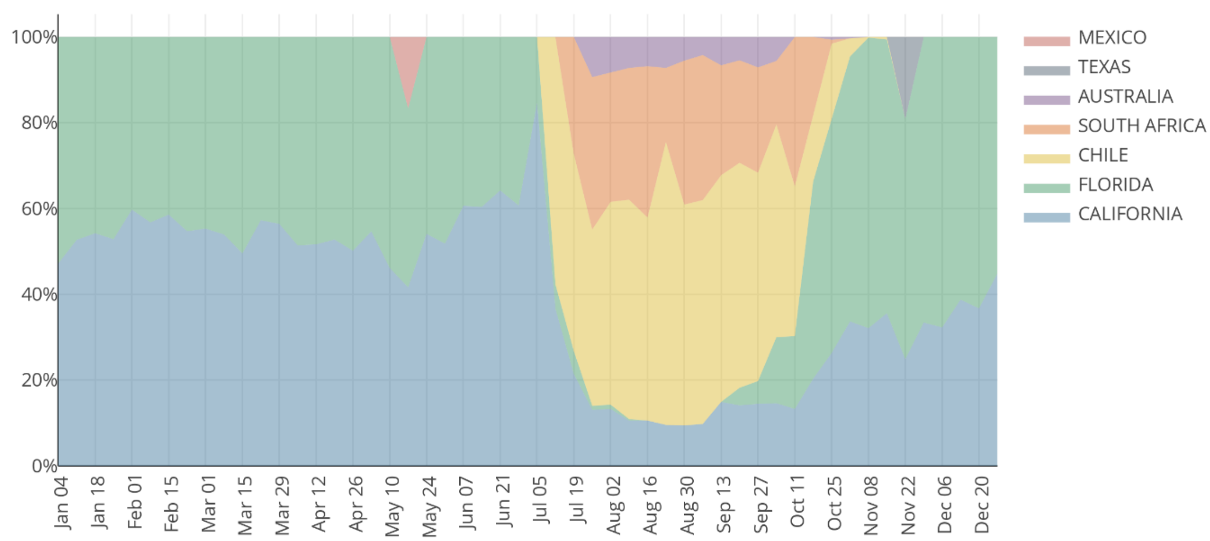

Figure B4: New York City fresh orange supply (2012-2016 average)

Table B13: New York City fresh orange shipments by week (2012-2016 average)

Week of	CALIF.	FLORI.	CHILE	S. AFR.	AUST.	MEXI.	TEXAS
4-Jan	47%	53%	0	0	0	0	0
11-Jan	53%	47%	0	0	0	0	0
18-Jan	54%	46%	0	0	0	0	0
25-Jan	53%	47%	0	0	0	0	0
1-Feb	60%	40%	0	0	0	0	0
8-Feb	57%	43%	0	0	0	0	0
…	…	…	…	…	…	…	…

Since New York City never receives shipments from Peru or Morocco, these regions were eliminated from the analysis.

B.7 Underlying Data for Figure 17

The following table presents the data underlying Figure 17 from Chapter 3:

Table B14: Underlying data for Figure 17

Production region	Truck1	Rail	Containership	Truck2	σ
Australia	0.064	0.000	0.085	0.002	0.045
California	0.004	0.063	0.000	0.001	0.023
Chile	0.009	0.000	0.040	0.002	0.018
Florida (T)	0.163	0.000	0.000	0.000	0.062
Florida (R)	0.008	0.025	0.000	0.001	0.009
Mexico	0.330	0.000	0.000	0.000	0.125
South Africa	0.123	0.000	0.058	0.002	0.054
Texas	0.273	0.000	0.000	0.000	0.104

B.8 Underlying Data for Figure 18

The following table presents the data underlying Figure 18 from Chapter 3:

Table B15: Underlying data for Figure 18

Production region	Production (PD)	Processing (PS)	Packaging (PK)	Transportation (TRavg)	Total	σ
Australia	0.28	0.03	0.01	0.15	0.47	0.27
California	0.19	0.01	0.01	0.07	0.28	0.11
Chile	0.41	0.02	0.01	0.05	0.49	0.39
Florida	0.20	0.02	0.01	0.16	0.40	0.13
Mexico	0.47	0.02	0.01	0.33	0.83	0.47
South Africa	0.24	0.03	0.01	0.18	0.46	0.23
Texas	0.26	0.02	0.01	0.28	0.57	0.18

B.9 Underlying Data for Figure 19

The following table presents the data underlying Figure 19 from Chapter 3:

Table B16: Underlying data for Figure 19

Week of	Production (PD)	Processing (PS)	Packaging (PK)	Transportation (TRavg)	Total	σ
4-Jan	0.20	0.02	0.01	0.12	0.34	0.12
11-Jan	0.20	0.02	0.01	0.11	0.34	0.12
18-Jan	0.20	0.02	0.01	0.11	0.34	0.12
25-Jan	0.20	0.02	0.01	0.11	0.34	0.12
1-Feb	0.20	0.02	0.01	0.11	0.33	0.12
8-Feb	0.20	0.02	0.01	0.11	0.33	0.12
15-Feb	0.20	0.02	0.01	0.11	0.33	0.12
22-Feb	0.20	0.02	0.01	0.11	0.34	0.12
1-Mar	0.20	0.02	0.01	0.11	0.33	0.12
8-Mar	0.20	0.02	0.01	0.11	0.34	0.12
15-Mar	0.20	0.02	0.01	0.12	0.34	0.12
22-Mar	0.20	0.02	0.01	0.11	0.33	0.12
29-Mar	0.20	0.02	0.01	0.11	0.33	0.12
5-Apr	0.20	0.02	0.01	0.12	0.34	0.12
12-Apr	0.20	0.02	0.01	0.11	0.34	0.12
19-Apr	0.20	0.02	0.01	0.11	0.34	0.12
26-Apr	0.20	0.02	0.01	0.12	0.34	0.12
3-May	0.20	0.02	0.01	0.11	0.34	0.12
10-May	0.20	0.02	0.01	0.12	0.35	0.12
17-May	0.24	0.02	0.01	0.15	0.42	0.17
24-May	0.20	0.02	0.01	0.11	0.34	0.12
31-May	0.20	0.02	0.01	0.11	0.34	0.12
7-Jun	0.20	0.02	0.01	0.11	0.33	0.12
14-Jun	0.20	0.02	0.01	0.11	0.33	0.12
21-Jun	0.20	0.02	0.01	0.10	0.32	0.12
28-Jun	0.20	0.02	0.01	0.11	0.33	0.12
5-Jul	0.19	0.01	0.01	0.08	0.30	0.12

Table B16: Underlying data for Figure 19

Week of	Production (PD)	Processing (PS)	Packaging (PK)	Transportation (TRavg)	Total	σ
12-Jul	0.32	0.02	0.01	0.06	0.41	0.26
19-Jul	0.30	0.02	0.01	0.10	0.43	0.24
26-Jul	0.30	0.02	0.01	0.11	0.45	0.24
2-Aug	0.31	0.02	0.01	0.10	0.45	0.25
9-Aug	0.32	0.02	0.01	0.10	0.46	0.26
16-Aug	0.32	0.02	0.01	0.11	0.46	0.26
23-Aug	0.35	0.02	0.01	0.08	0.46	0.30
30-Aug	0.32	0.02	0.01	0.10	0.46	0.27
6-Sep	0.32	0.02	0.01	0.10	0.46	0.27
13-Sep	0.32	0.02	0.01	0.09	0.45	0.27
20-Sep	0.32	0.02	0.01	0.10	0.45	0.26
27-Sep	0.31	0.02	0.01	0.10	0.45	0.25
4-Oct	0.31	0.02	0.01	0.10	0.44	0.25
11-Oct	0.28	0.02	0.01	0.12	0.44	0.22
18-Oct	0.24	0.02	0.01	0.13	0.40	0.16
25-Oct	0.24	0.02	0.01	0.12	0.39	0.16
1-Nov	0.21	0.02	0.01	0.13	0.36	0.13
8-Nov	0.20	0.02	0.01	0.13	0.36	0.12
15-Nov	0.20	0.02	0.01	0.13	0.36	0.12
22-Nov	0.21	0.02	0.01	0.16	0.40	0.13
29-Nov	0.20	0.02	0.01	0.13	0.36	0.12
6-Dec	0.20	0.02	0.01	0.13	0.36	0.12
13-Dec	0.20	0.02	0.01	0.13	0.35	0.12
20-Dec	0.20	0.02	0.01	0.13	0.36	0.12
27-Dec	0.20	0.02	0.01	0.12	0.35	0.12

B.10 Uncertainty Assessment

There are four main sources of uncertainty in this analysis: (i) year-to-year variation in yield, (ii) variation in production practices leading to uncertainty in the carbon impact per unit hectare, (iii) uncertainty in freight emission factors, and (iv) uncertainty regarding city-level produce shipments. Each of these factors was incorporated into a Monte Carlo uncertainty assessment and is discussed in additional detail below.

(i) Yield variation

Crop yields can vary significantly from year-to-year as a result of annual weather conditions. For the domestic production region, annual yield data are available from USDA NASS dating back four decades [10]. Since technological improvements have caused crop yields to increase over time, we chose to focus on the past five years, as we believe recent data are the most representative. Orange yield for California, Florida, and Texas were varied per the data presented in Figure B5 (i.e., 20% probability of each outcome).

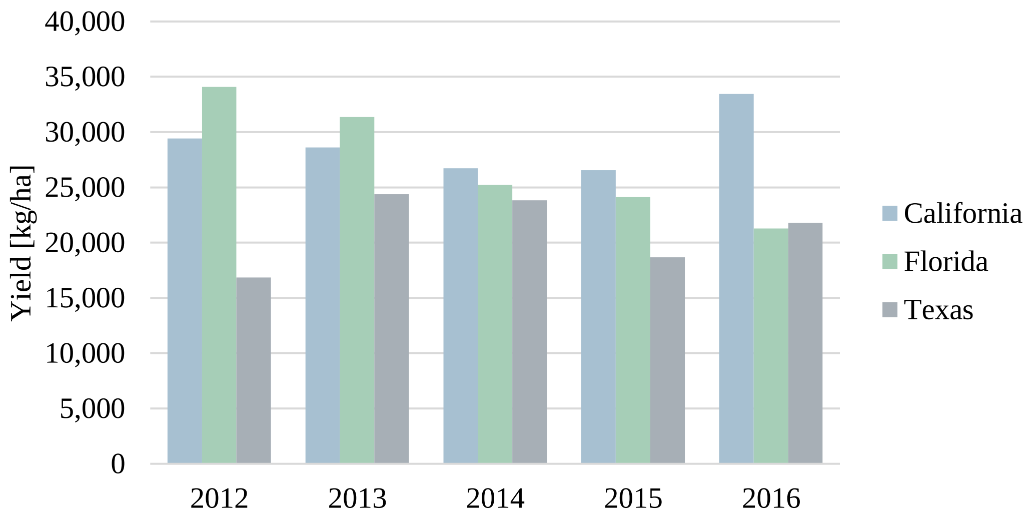

Figure B5: Domestic yield variation (2012-2016)

Since detailed year-by-year yield data were not available for the international region, yield variation had to be estimated from the literature. Each of the international production regions (Australia, Chile, Mexico, South Africa) were varied in a normal distribution with a standard deviation of 30% [8].

(ii) Carbon impact per hectare

Since production practices can vary both between regions and from orchard to orchard within a region, the GHG emissions impact per unit hectare [kgCO_2e/ha] was varied in a normal distribution with a standard deviation of 55% [8].

(iii) Freight emission factors

Freight emission factors may improve somewhat as a result of technological improvements but are not likely to dip significantly below the values used in this analysis. Emission factors may worsen due to inefficient routing or suboptimal loading factors (e.g., if trucks return from market empty). Table B17 summarizes the assumptions used in the Monte Carlo assessment.

(iv) City-level shipping data

The weekly supply of fresh produce at the city-level is a potential source of error in this analysis. To address this issue, a “low emissions” scenario and a “high emissions” scenario were formulated by adjusting the proportion of supply from production regions with relatively low and relatively high overall cradle-to-market emissions. For the “low emissions” scenario, it was assumed that shipments from California are increased by 50% in the “on-season” weeks. Similarly, shipments from South Africa are increased by 50% in the “off-season” weeks. The remaining production regions are decreased proportionally. The resulting supply scheme is illustrated in Figure B6.

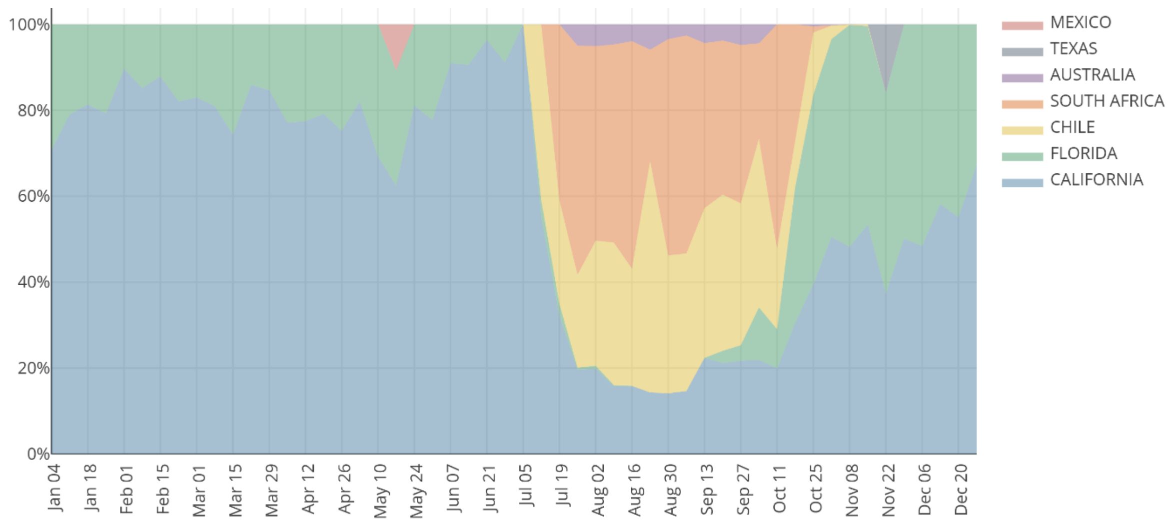

Figure B6: New York City fresh orange supply, “low emissions scenario”

The “high emissions” scenario assumes that shipments from California are decreased by 50% in the “on-season” weeks. Similarly, shipments from South Africa are decreased by 50% in the “off-season” weeks. The remaining production regions are increased proportionally. The resulting supply scheme is illustrated in Figure B7.

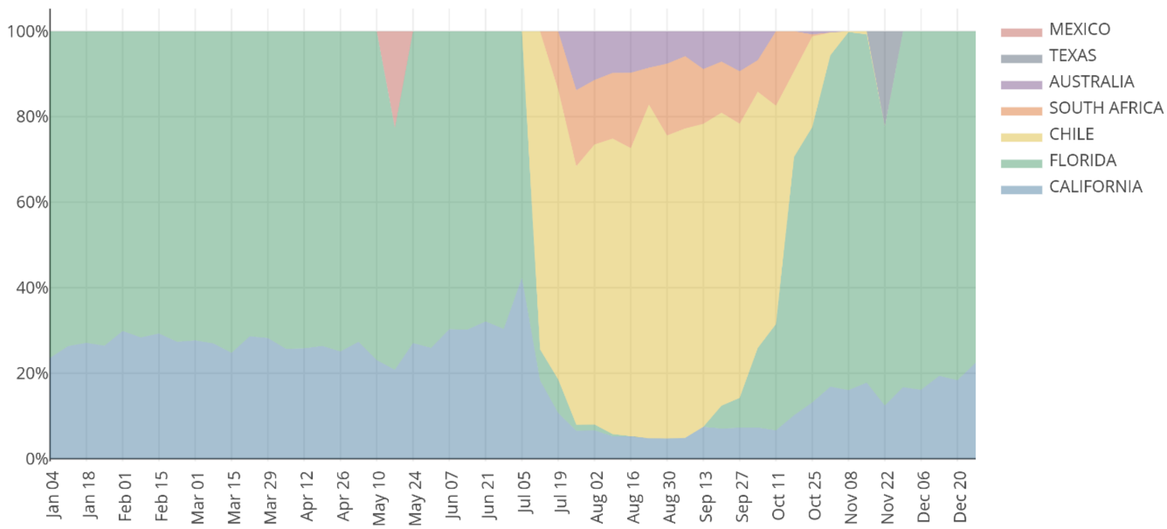

Figure B7: New York City fresh orange supply, "high emissions scenario"

These extreme scenarios were then incorporated into the Monte Carlo simulation by varying the quantity of oranges supplied from California and South Africa by ±50% in a uniform distribution and adjusting shipments from the remaining regions proportionally.

Uncertainty assessment summary

Table B17: Summary of assumptions for Monte Carlo assessment

Factor	Distribution type	Variation	Source
Australia yield	Normal	σ = 30%	[8]
California yield	Discrete	(see Figure B5)	[10]
Chile yield	Normal	σ = 30%	[8]
Florida yield	Discrete	(see Figure B5)	[10]
Mexico yield	Normal	σ = 30%	[8]
South Africa yield	Normal	σ = 30%	[8]
Texas yield	Discrete	(see Figure B5)	[10]
$kgCO_2e$ per ha	Normal	σ = 55%	[8]
Truck EF	Uniform	-69%/+200%	[23]
Rail EF	Uniform	-75%/+200%	[23]
Containership EF	Uniform	-48%/+200%	[23]
California supply	Uniform	±50%	N/A
South Africa supply	Uniform	±50%	N/A

B.11 Additional Results: Los Angeles, Chicago, Atlanta

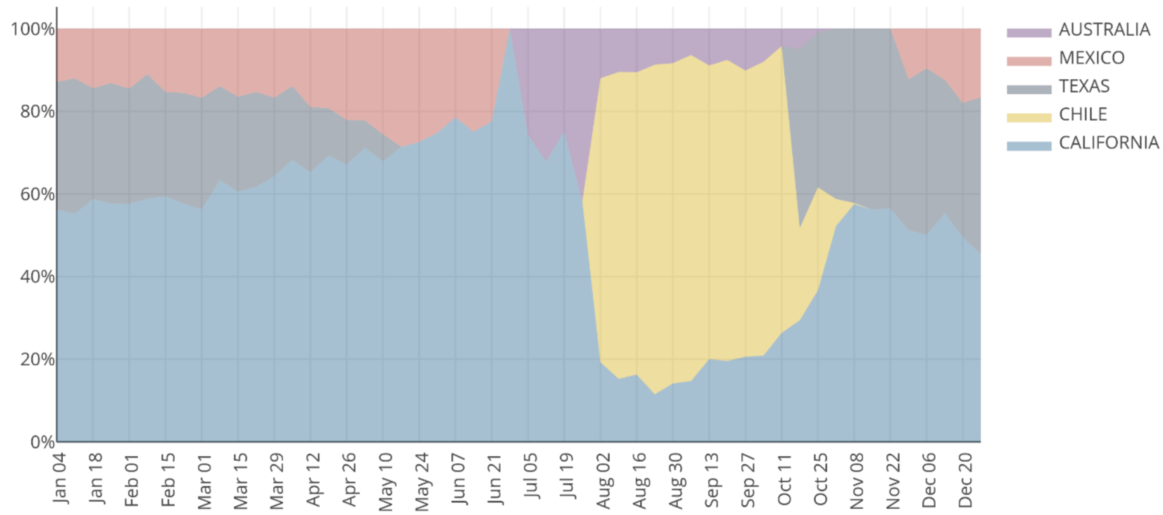

Figure B8: Los Angeles fresh orange supply (2012-2016 average)

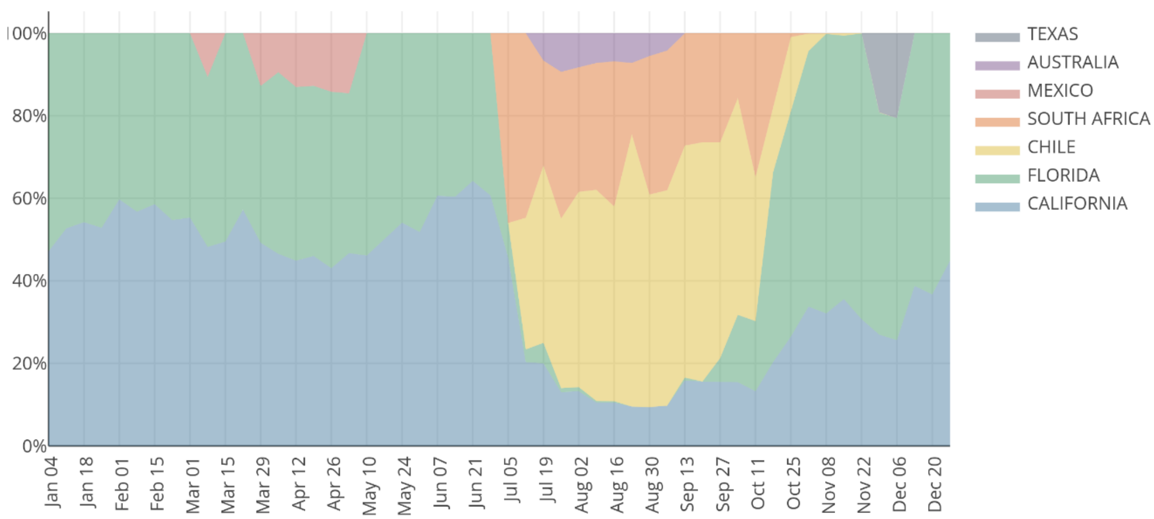

Figure B9: Chicago fresh orange supply (2012-2016 average)

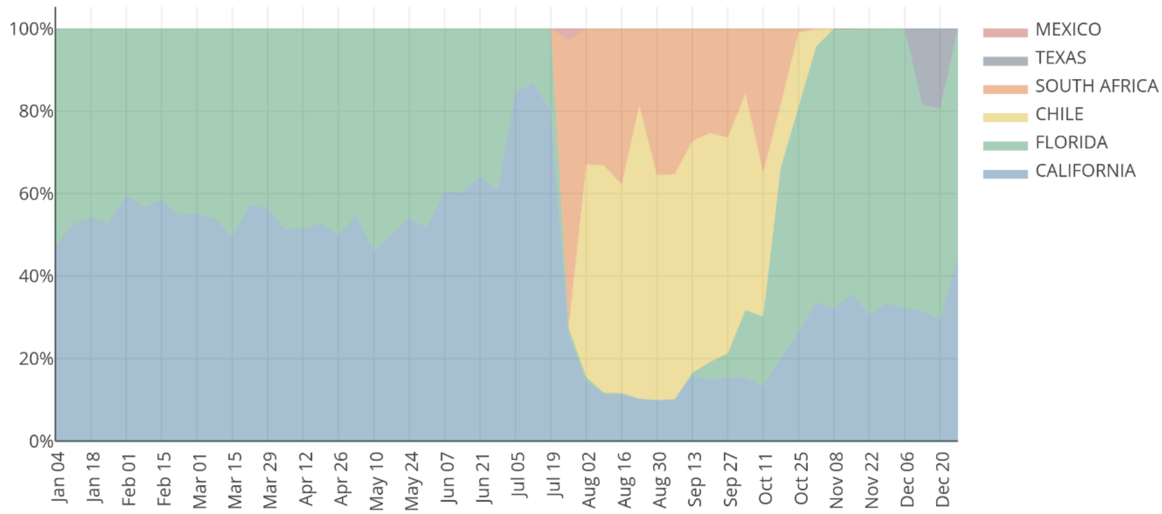

Figure B10: Atlanta fresh orange supply (2012-2016 average)

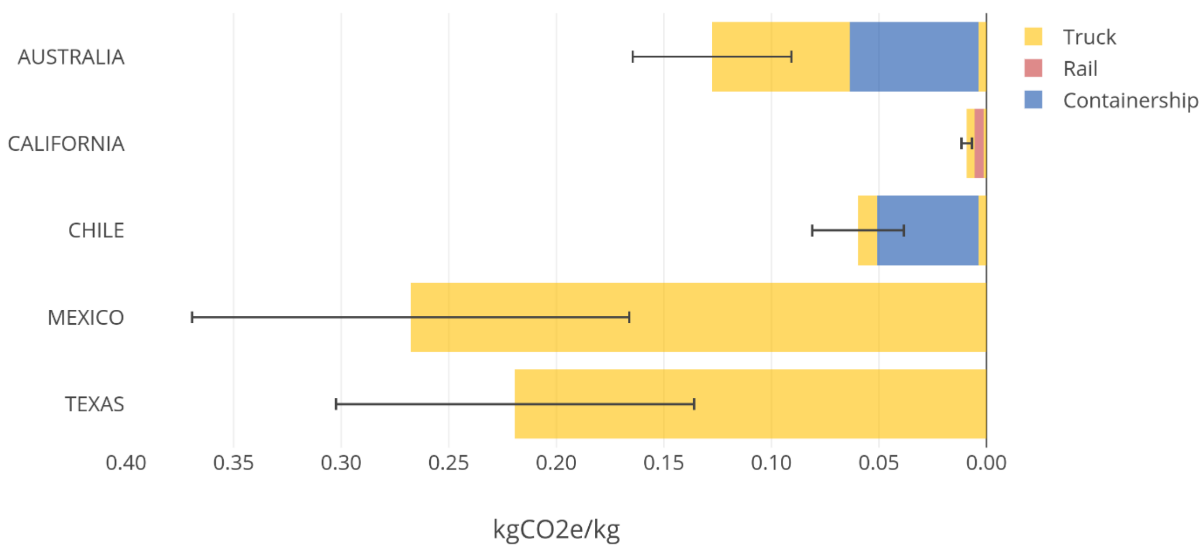

Figure B11: Life-cycle GHG emissions associated with transportation of fresh oranges to Los Angeles by transportation mode

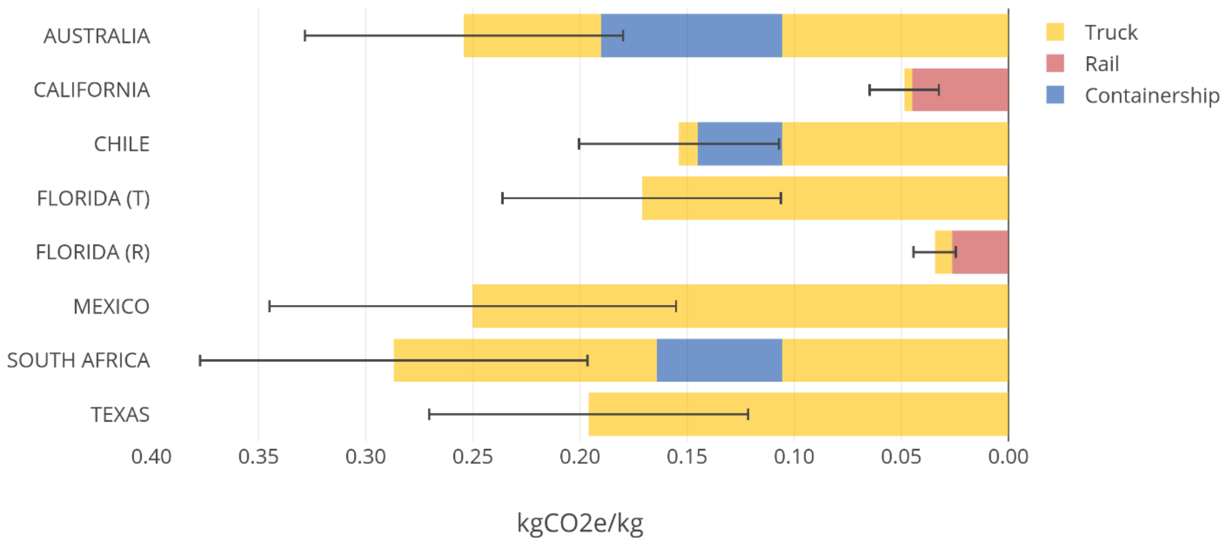

Figure B12: Life-cycle GHG emissions associated with transportation of fresh oranges to Chicago by transportation mode

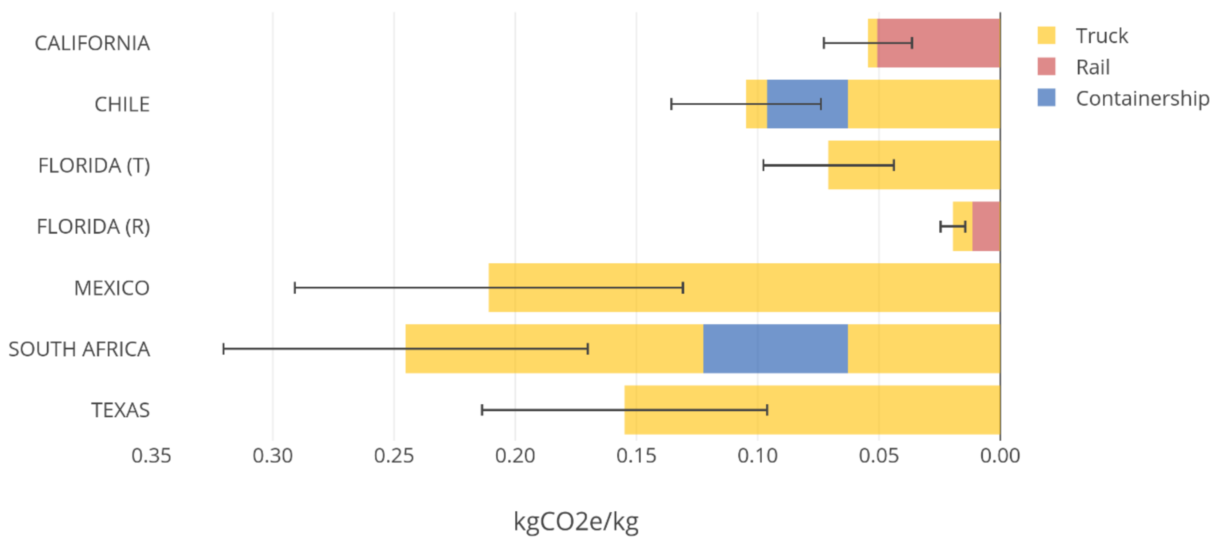

Figure B13: Life-cycle GHG emissions associated with transportation of fresh oranges to Atlanta by transportation mode

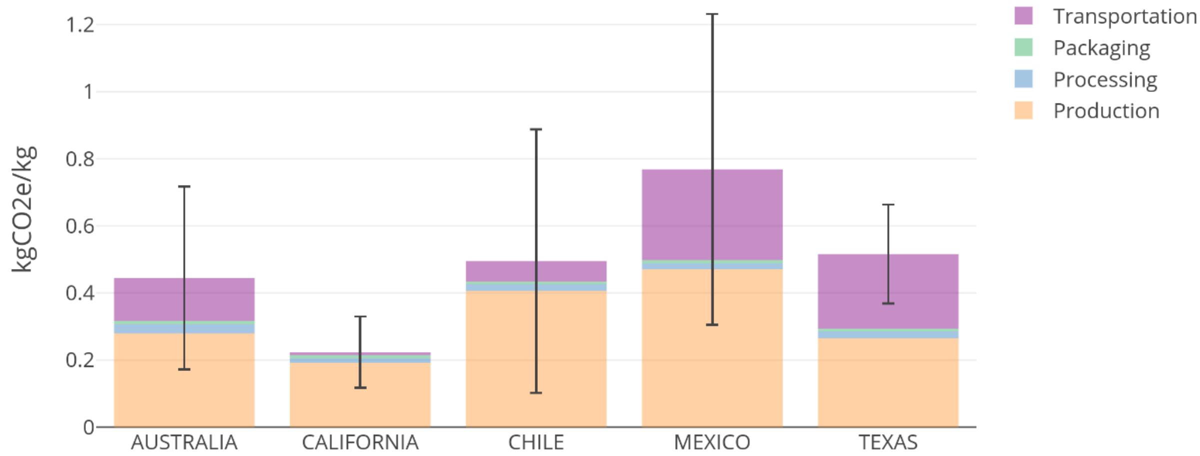

Figure B14: Carbon footprint of fresh oranges supplied to Los Angeles by production region

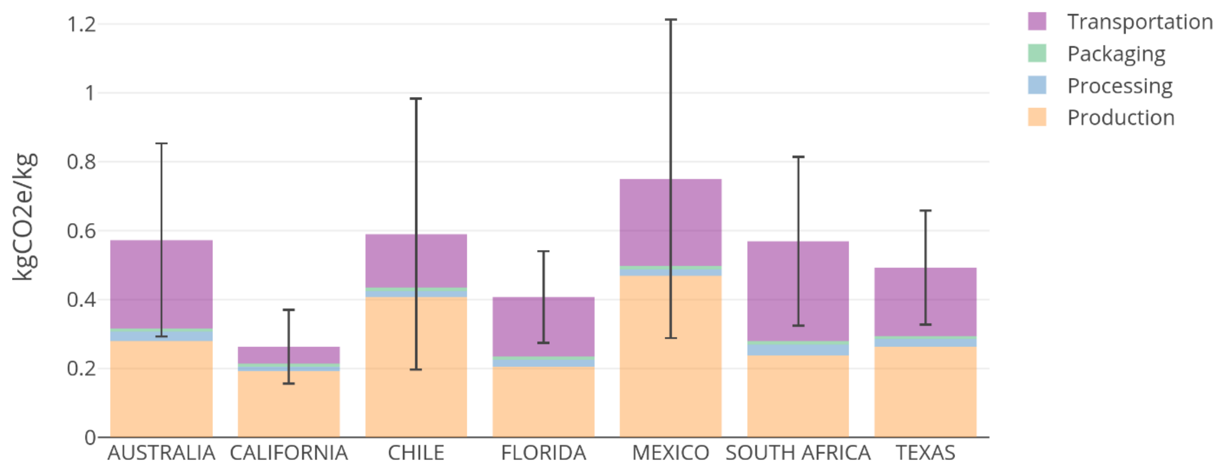

Figure B15: Carbon footprint of fresh oranges supplied to Chicago by production region

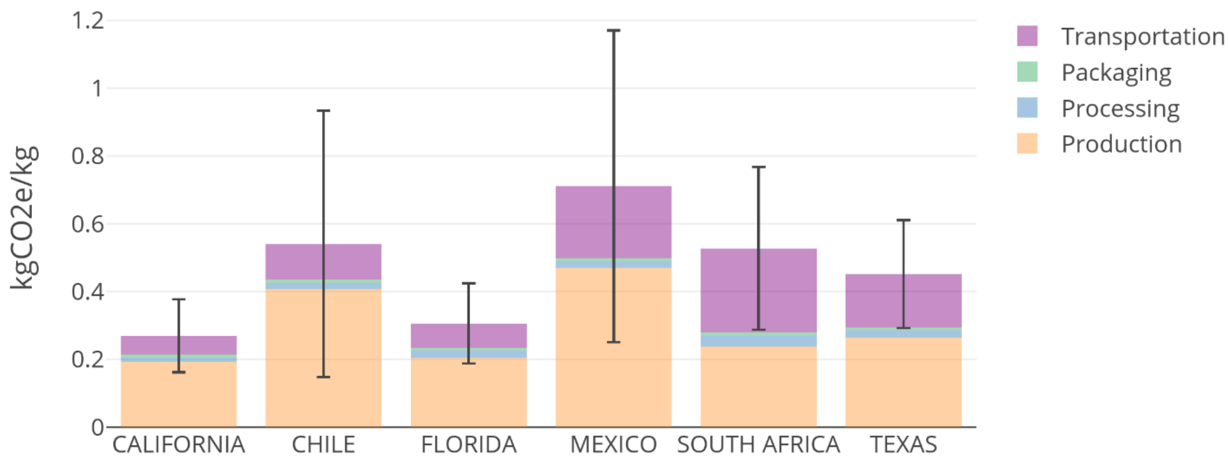

Figure B16: Carbon footprint of fresh oranges supplied to Atlanta by production region

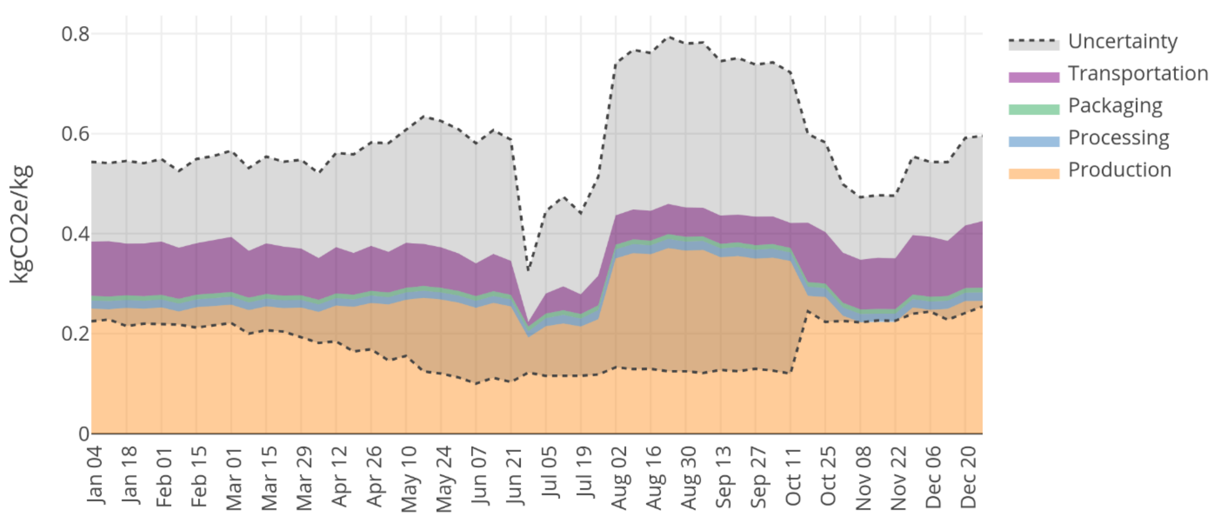

Figure B17: Seasonal variation in the average carbon footprint of oranges supplied to Los Angeles

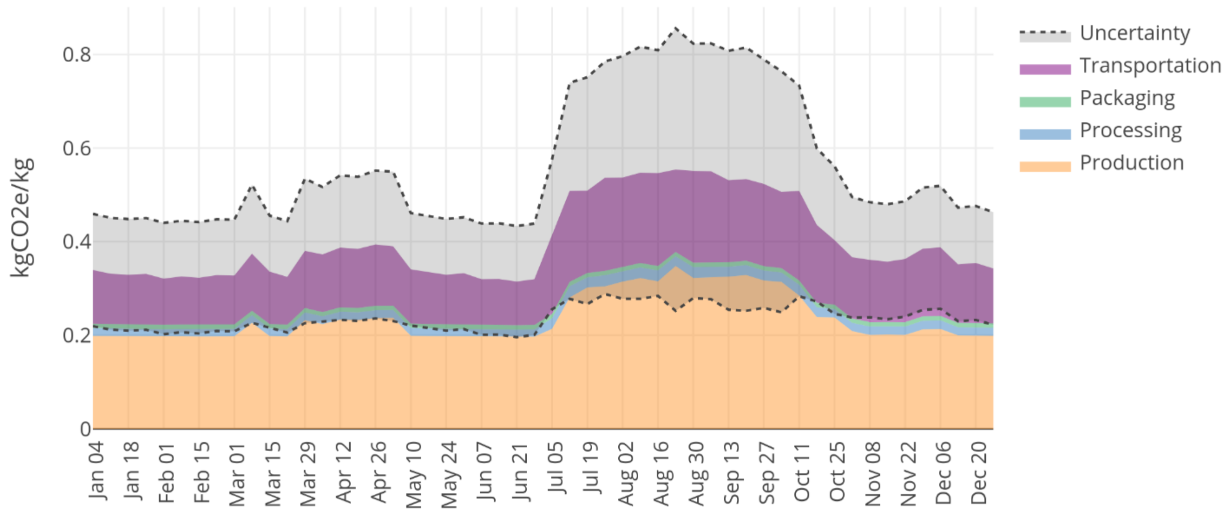

Figure B18: Seasonal variation in the average carbon footprint of oranges supplied to Chicago

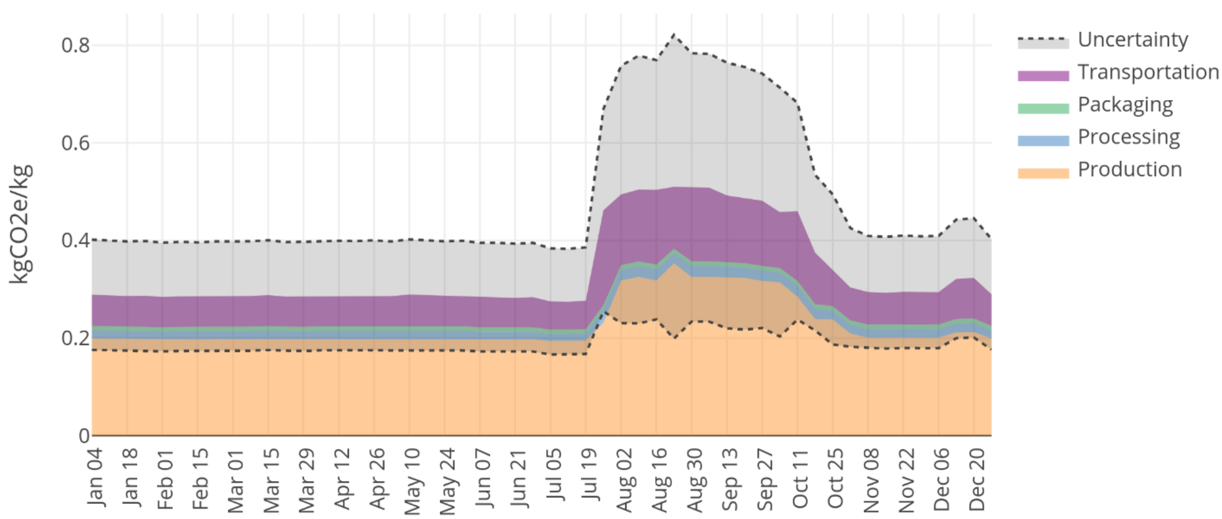

Figure B19: Seasonal variation in the average carbon footprint of oranges supplied to Atlanta

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Appendix C.

Addendum to Chapter 4

This appendix contains supporting information for Chapter 4: Optimal Allocation of Tomato Supply to Minimize Carbon Footprint in Major U.S. Metropolitan Markets.

- Section C1 contains results for the Atlanta tomato market.
- Section C2 contains results for the Boston tomato market.
- Section C3 contains results for the Chicago tomato market.
- Section C4 contains results for the Dallas tomato market.
- Section C5 contains results for the Los Angeles tomato market.
- Section C6 contains results for the Miami tomato market.
- Section C7 contains results for the New York City tomato market.
- Section C8 contains results for the San Francisco tomato market.
- Section C9 contains results for the Washington DC tomato market.

C.1 Results for Atlanta Tomato Market

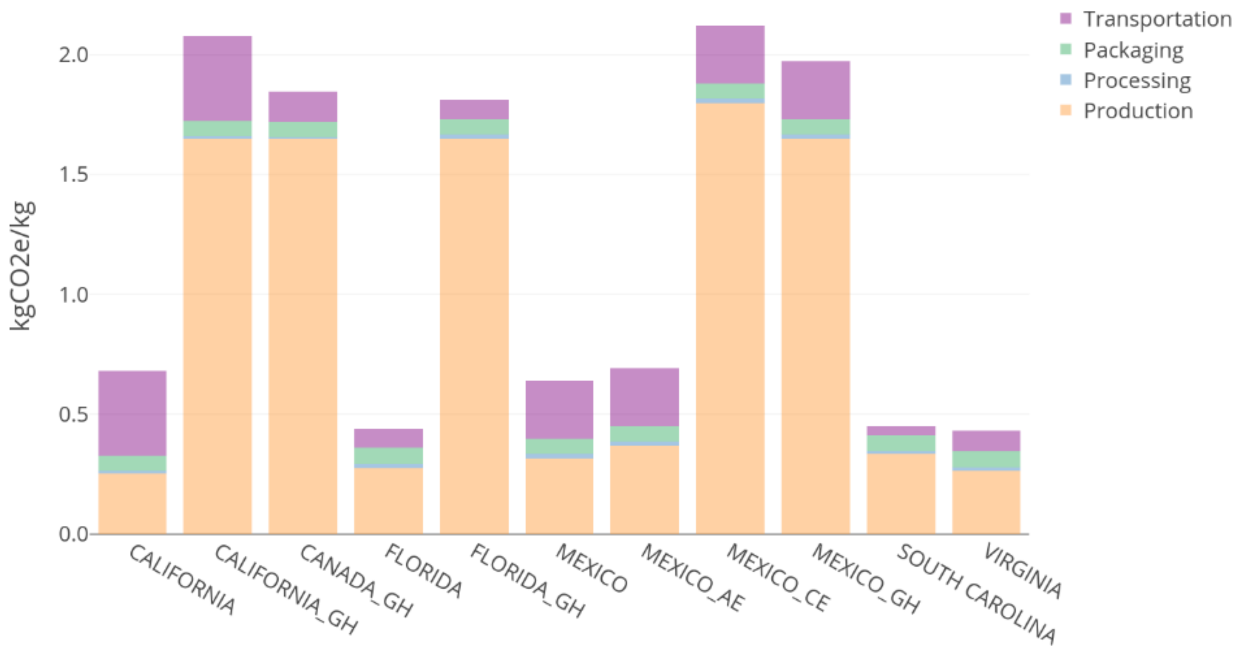


Figure C1: Cradle-to-market life-cycle GHG emissions for Atlanta fresh tomato supply

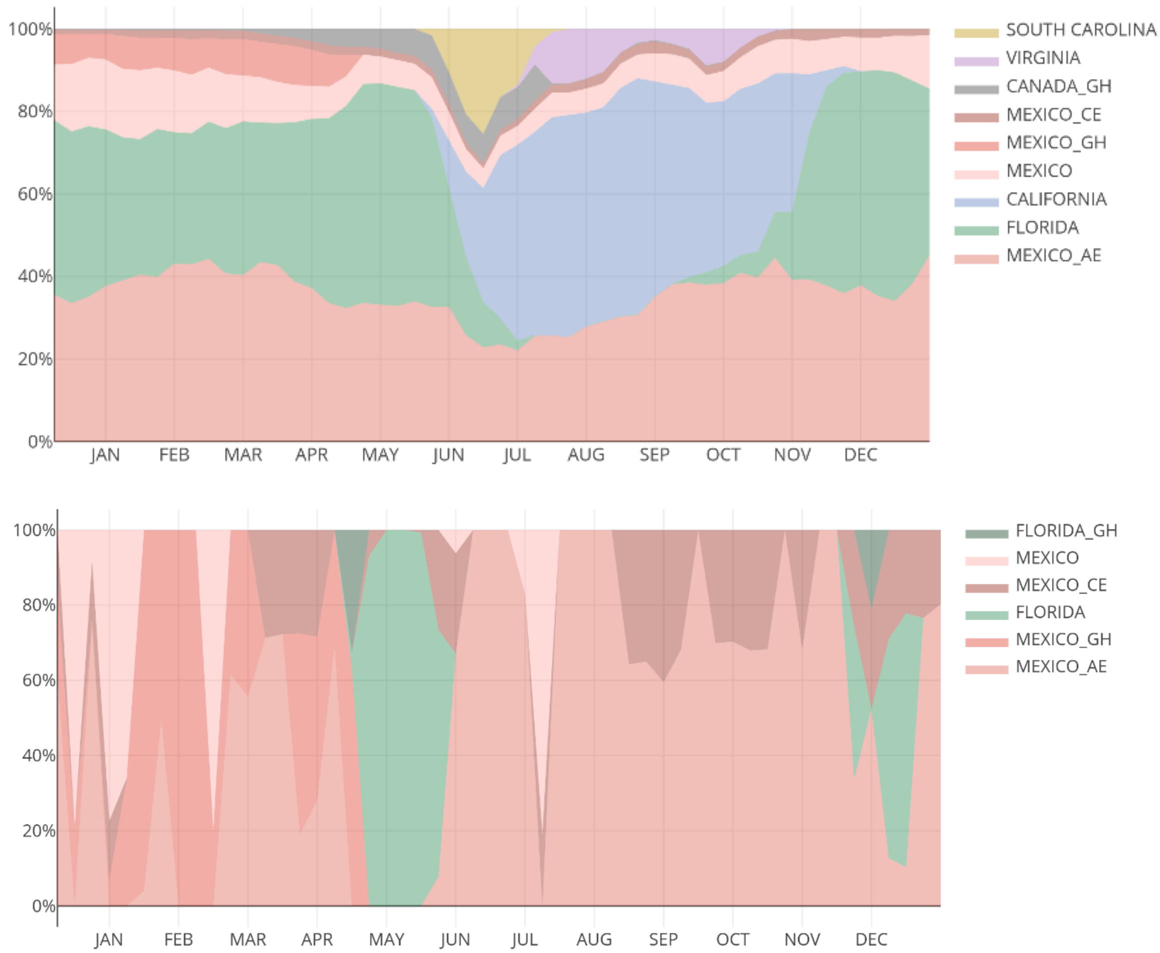


Figure C2: Tomato supply portfolio for Atlanta market under baseline (top) and optimized scenario (bottom)

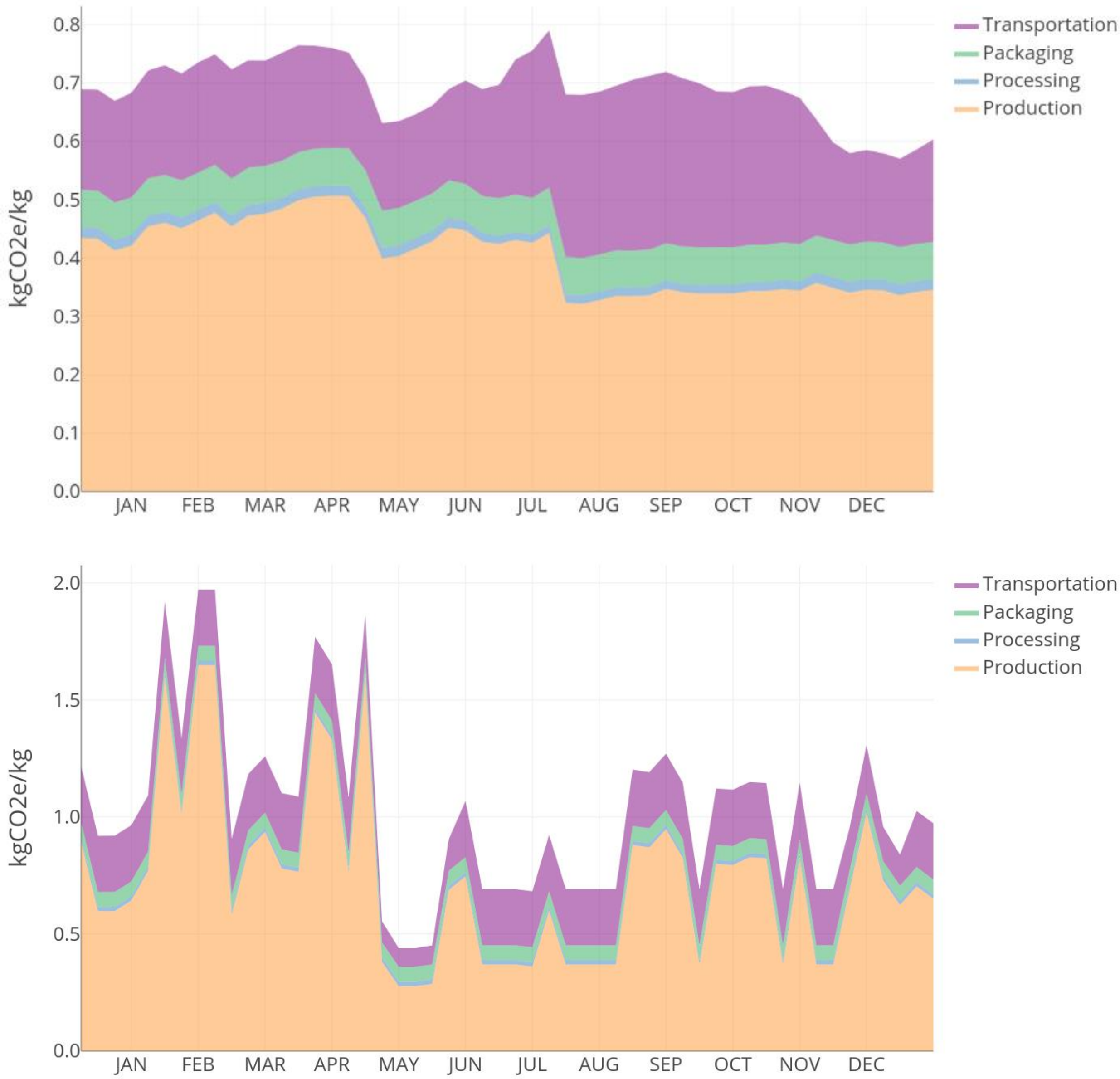


Figure C3: Environmental impact of fresh tomatoes delivered to Atlanta market under baseline (top) and optimized scenario (bottom)

C.2 Results for Boston Tomato Market

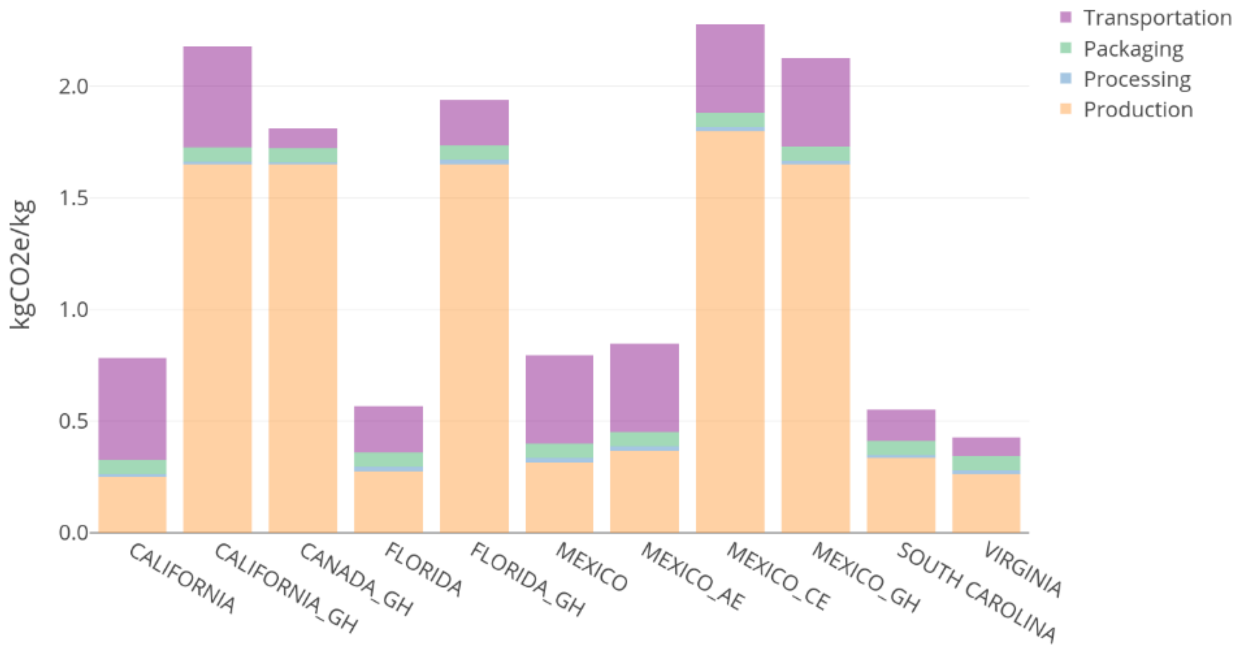


Figure C4: Cradle-to-market life-cycle GHG emissions for Boston fresh tomato supply

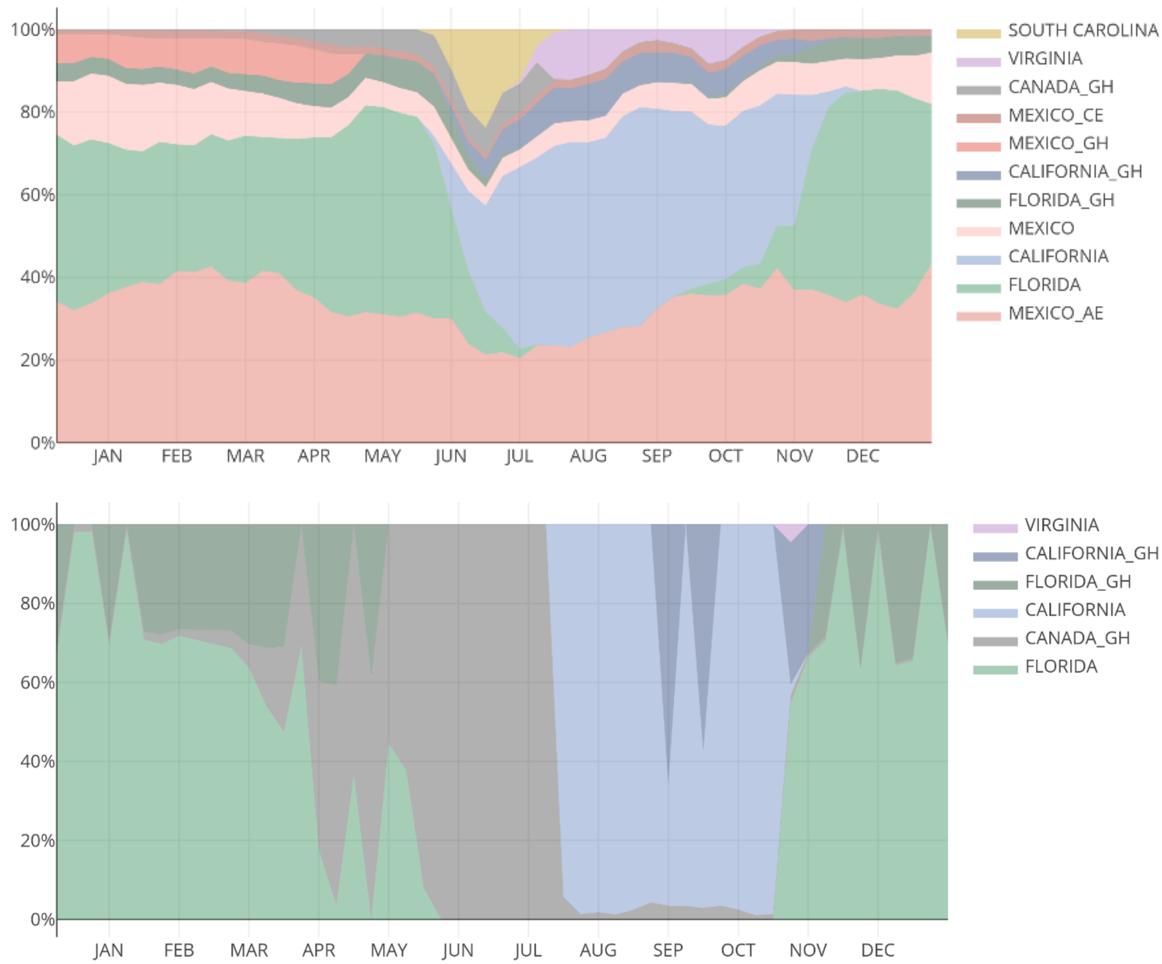


Figure C5: Tomato supply portfolio for Boston market under baseline (top) and optimized scenario (bottom)

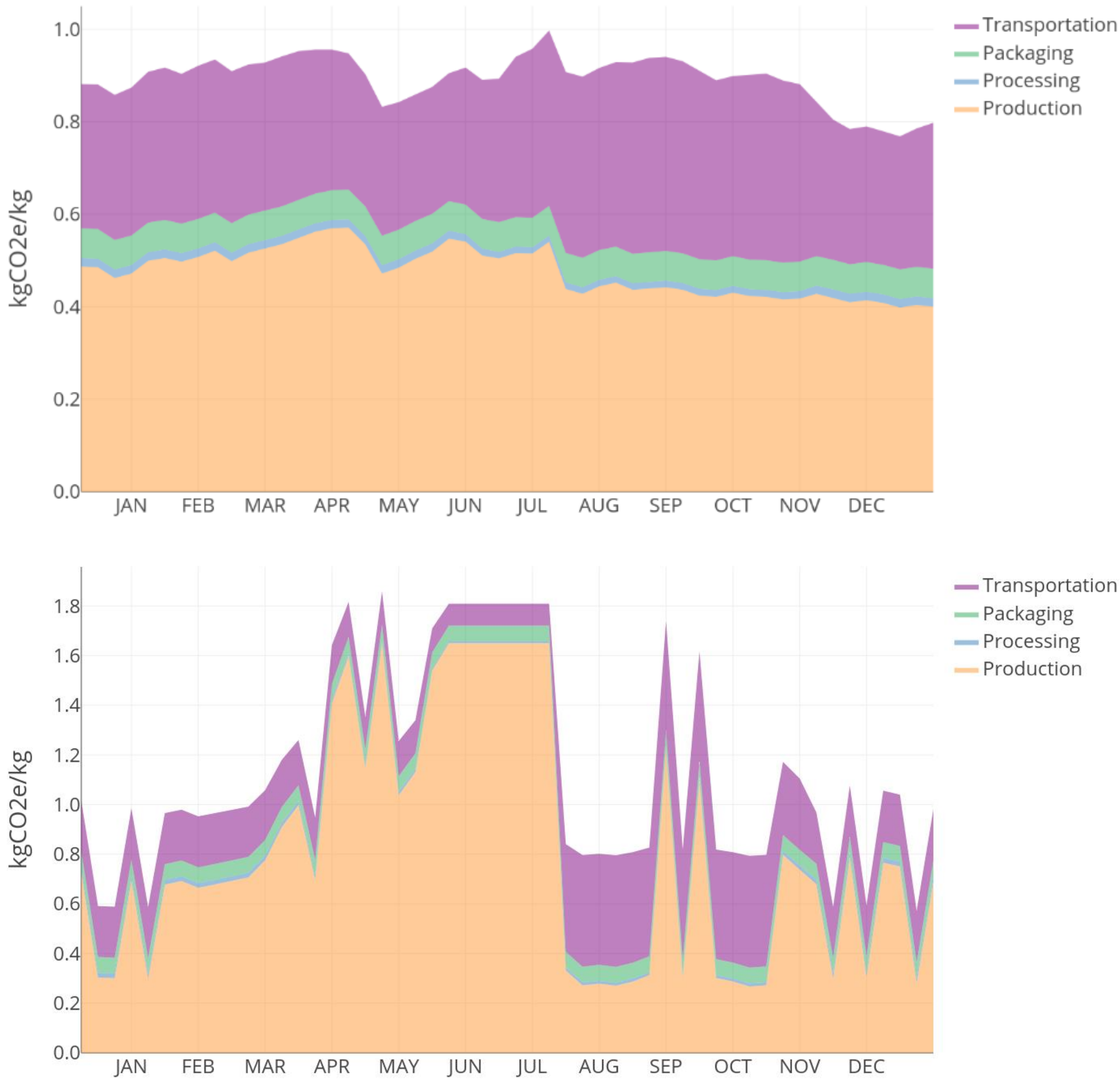


Figure C6: Environmental impact of fresh tomatoes delivered to Boston market under baseline (top) and optimized scenario (bottom)

C.3 Results for Chicago Tomato Market

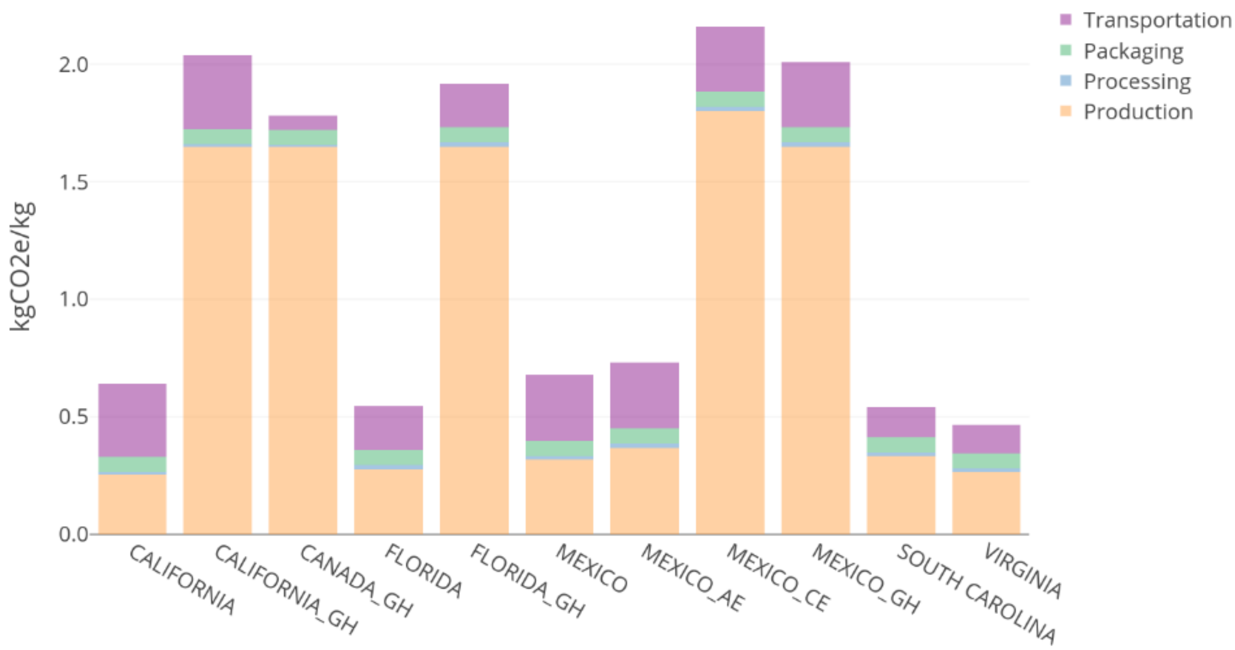


Figure C7: Cradle-to-market life-cycle GHG emissions for Chicago fresh tomato supply

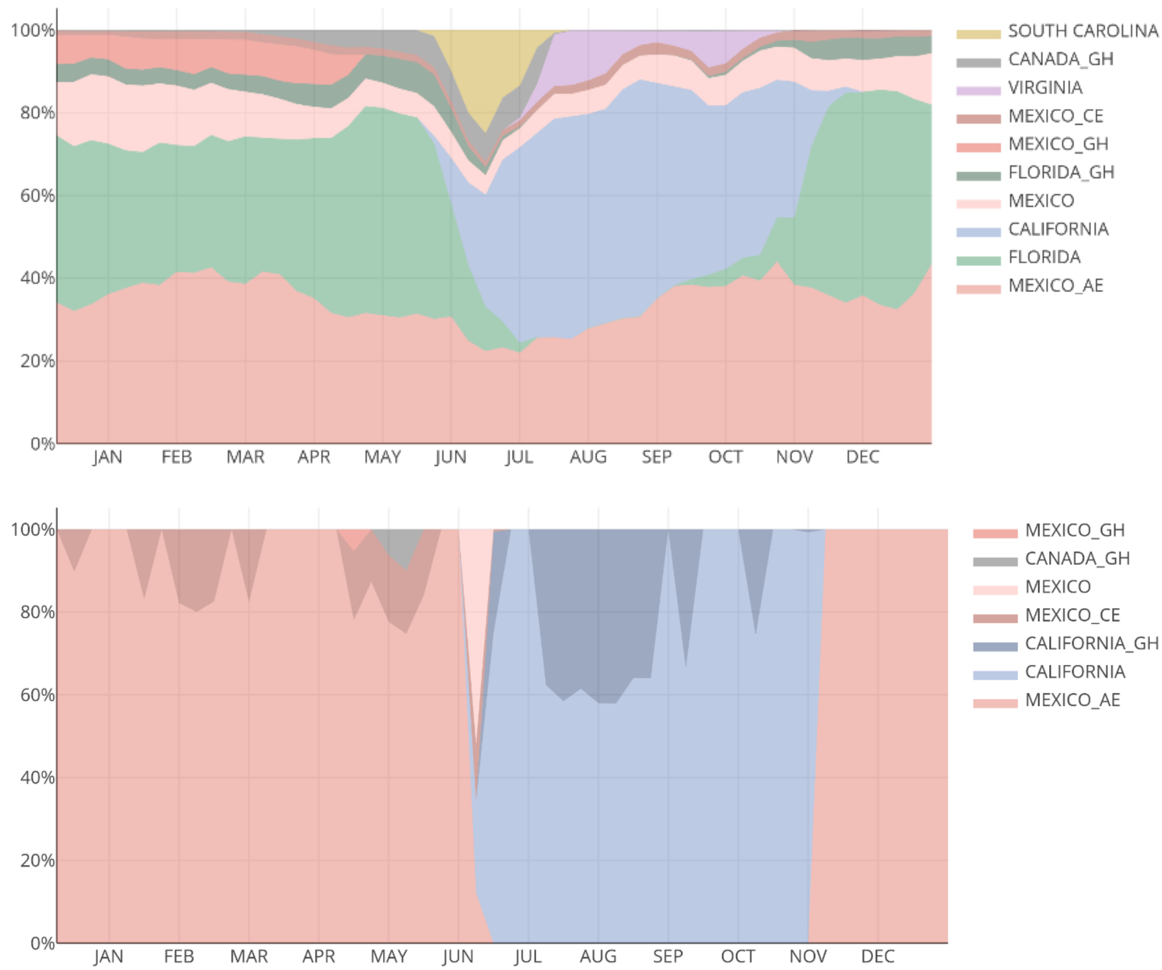


Figure C8: Tomato supply portfolio for Chicago market under baseline (top) and optimized scenario (bottom)

Figure C9: Environmental impact of fresh tomatoes delivered to Chicago market under baseline (top) and optimized scenario (bottom)

C.4 Results for Dallas Tomato Market

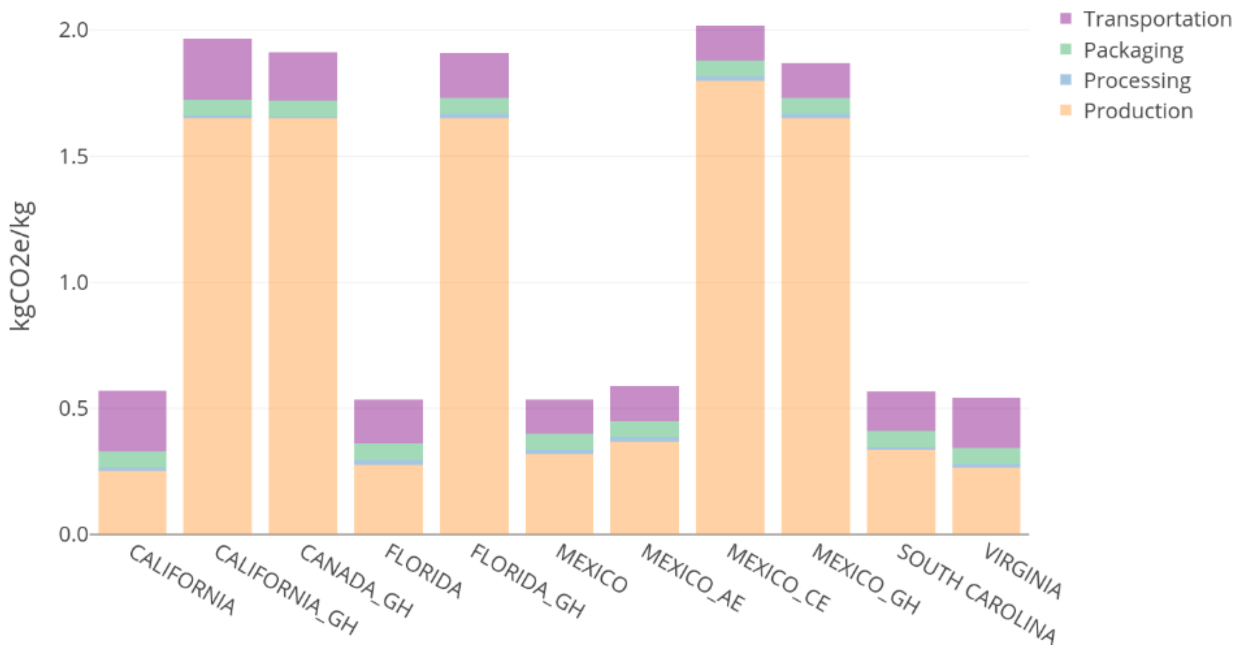
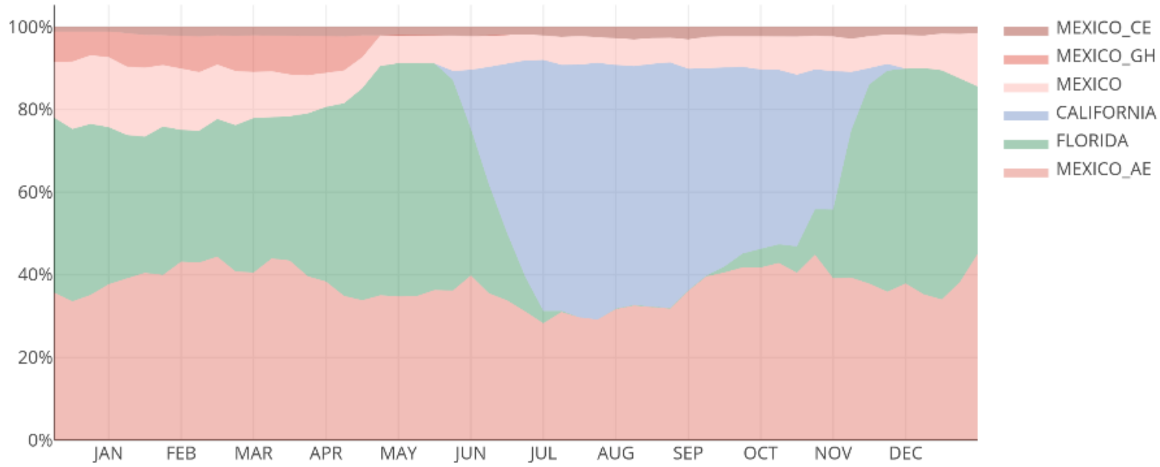


Figure C10: Cradle-to-market life-cycle GHG emissions for Dallas fresh tomato supply



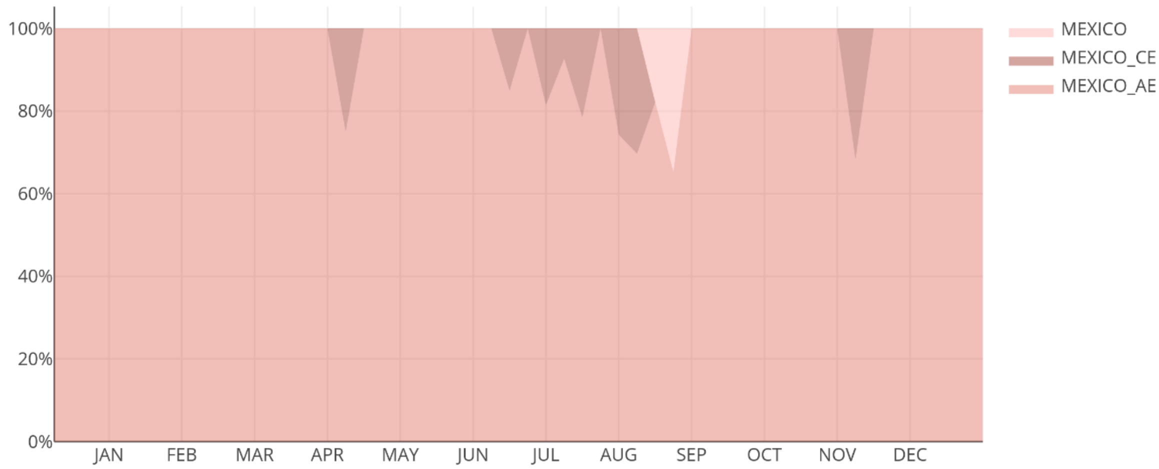


Figure C11: Tomato supply portfolio for Dallas market under baseline (top) and optimized scenario (bottom)

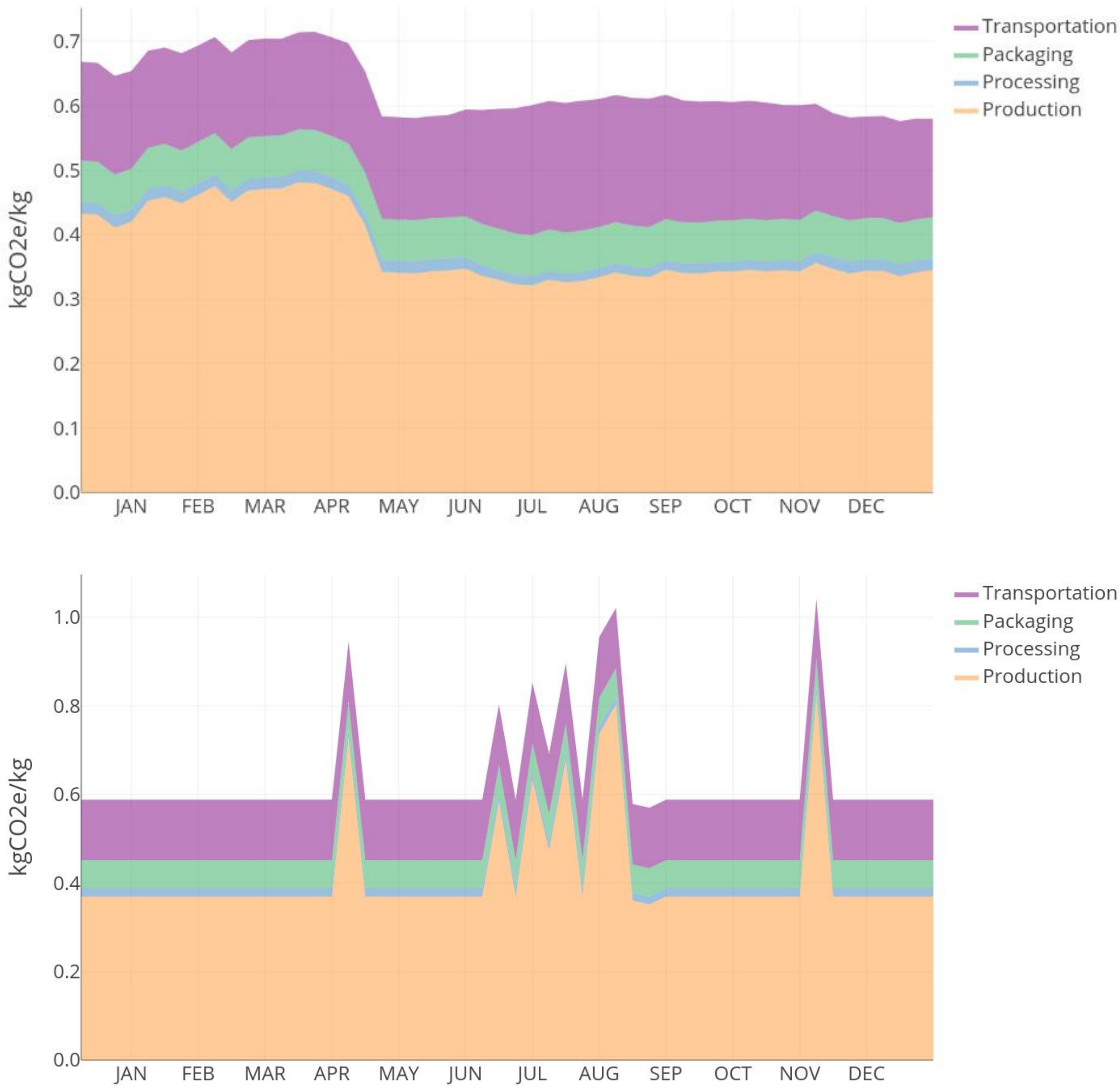


Figure C12: Environmental impact of fresh tomatoes delivered to Dallas market under baseline (top) and optimized scenario (bottom)

C.5 Results for Los Angeles Tomato Market

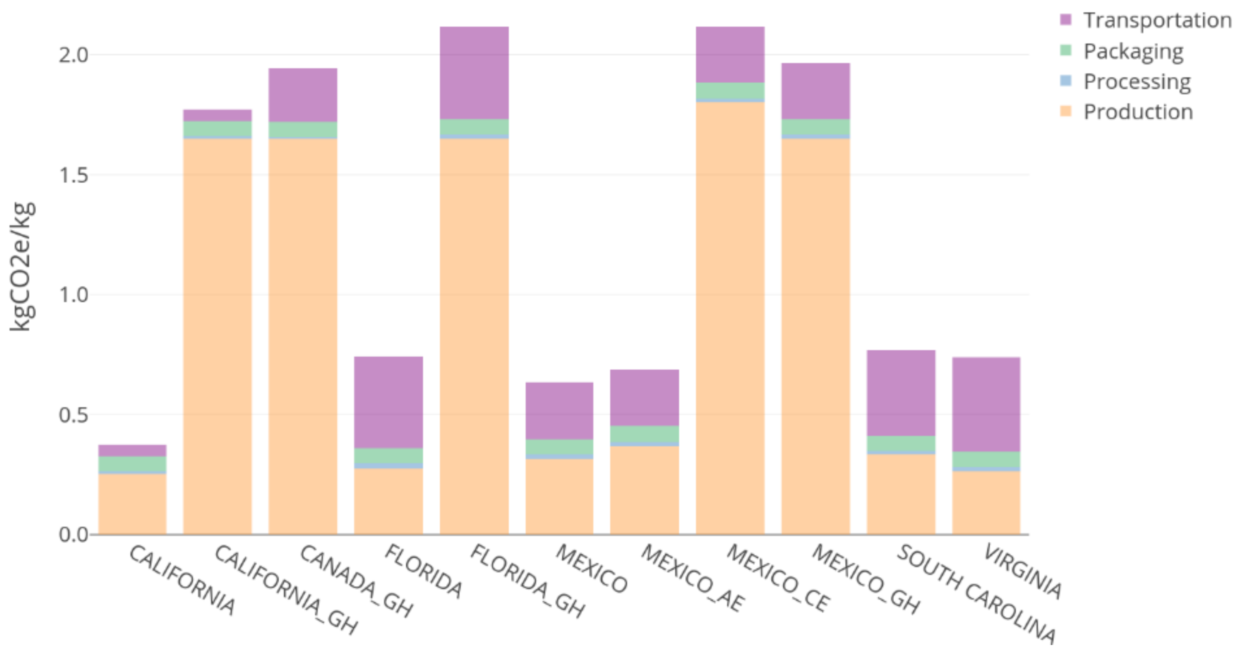


Figure C13: Cradle-to-market life-cycle GHG emissions for Los Angeles fresh tomato supply

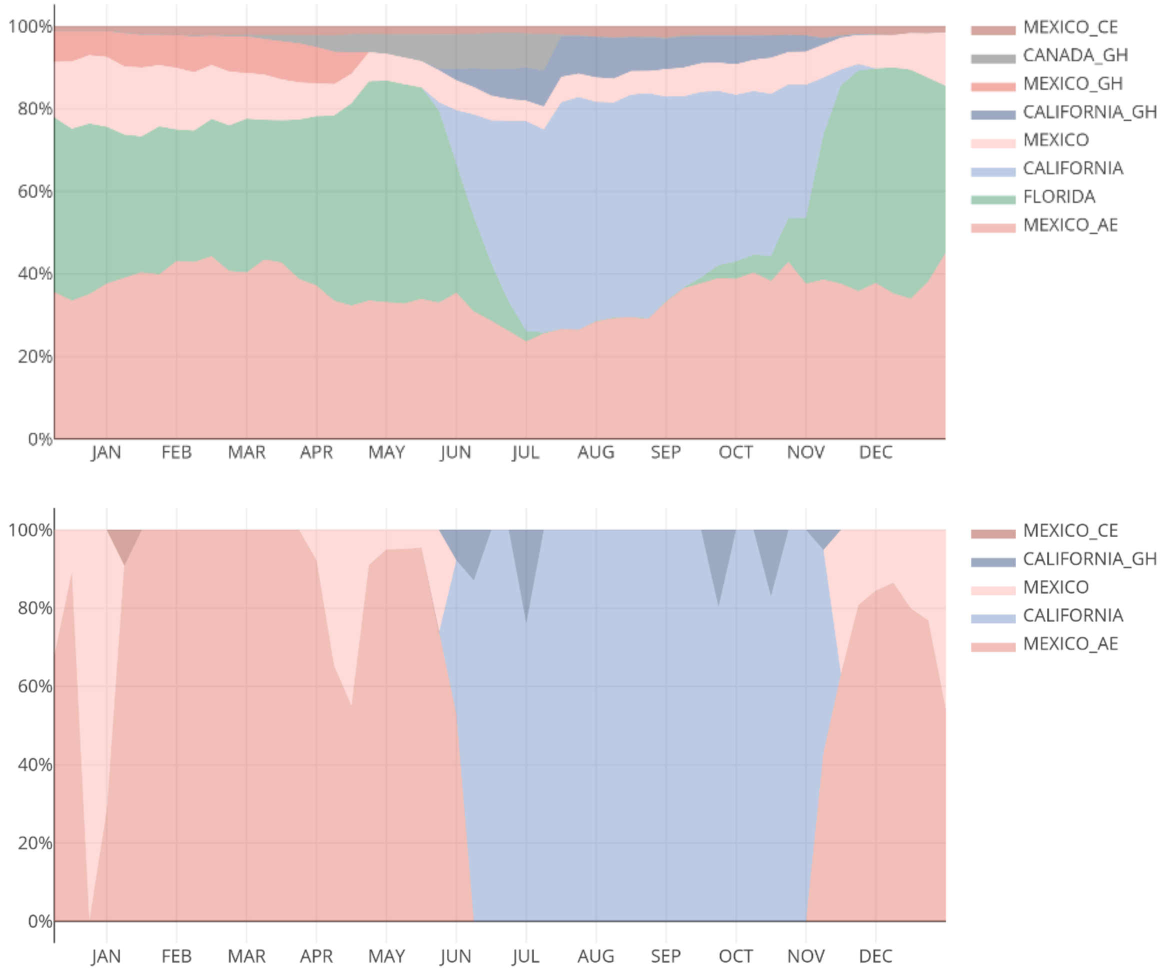


Figure C14: Tomato supply portfolio for Los Angeles market under baseline (top) and optimized scenario (bottom)

Figure C15: Environmental impact of fresh tomatoes delivered to Los Angeles market under baseline (top) and optimized scenario (bottom)

C.6 Results for Miami Tomato Market

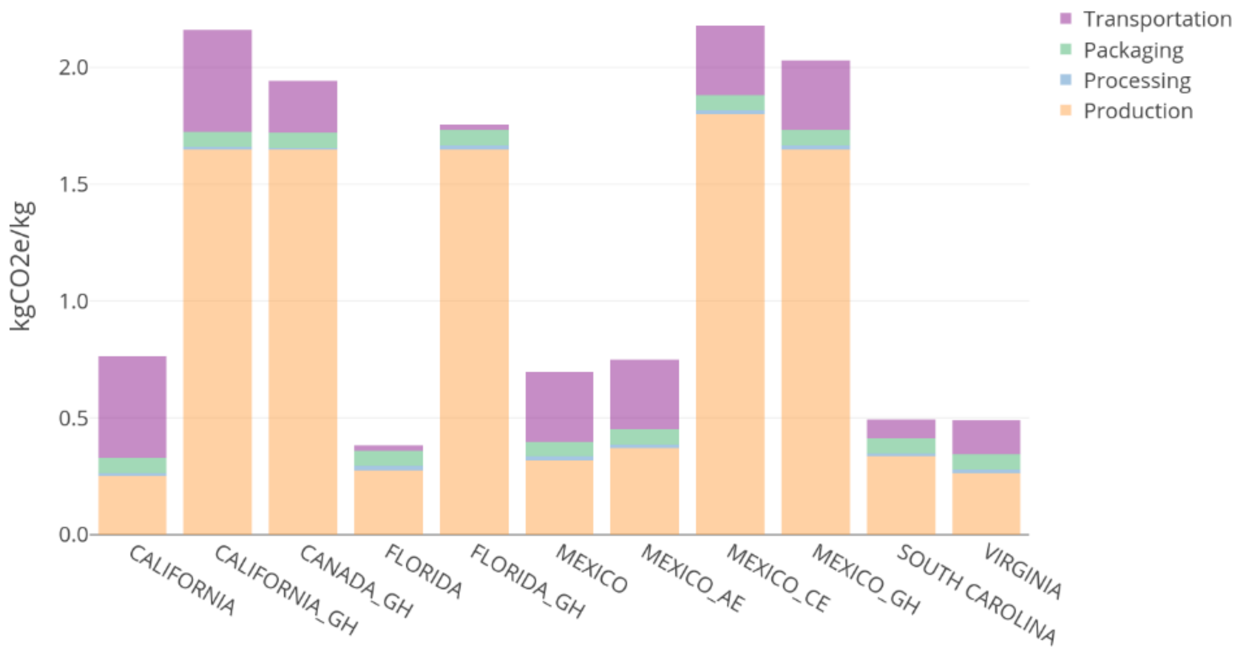


Figure C16: Cradle-to-market life-cycle GHG emissions for Miami fresh tomato supply

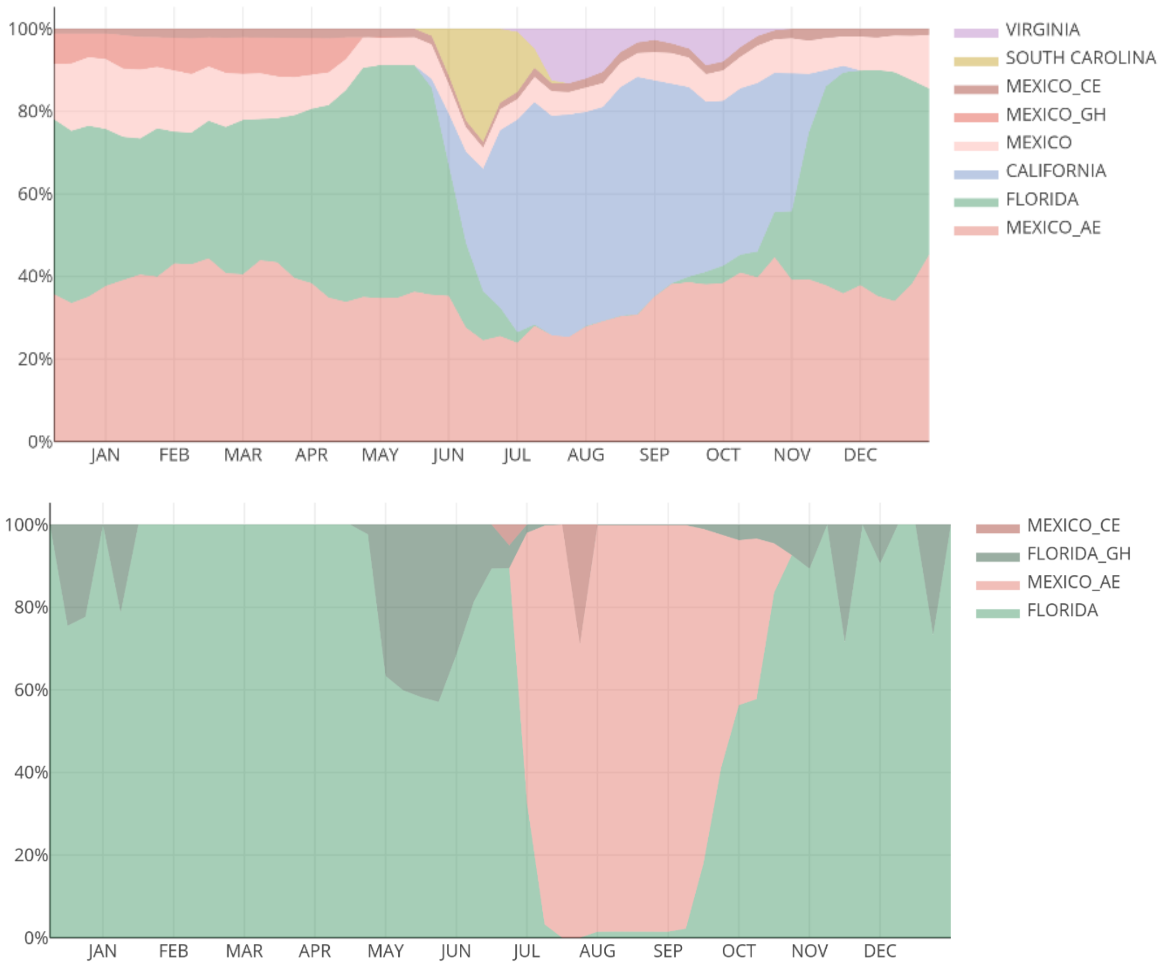


Figure C17: Tomato supply portfolio for Miami market under baseline (top) and optimized scenario (bottom)

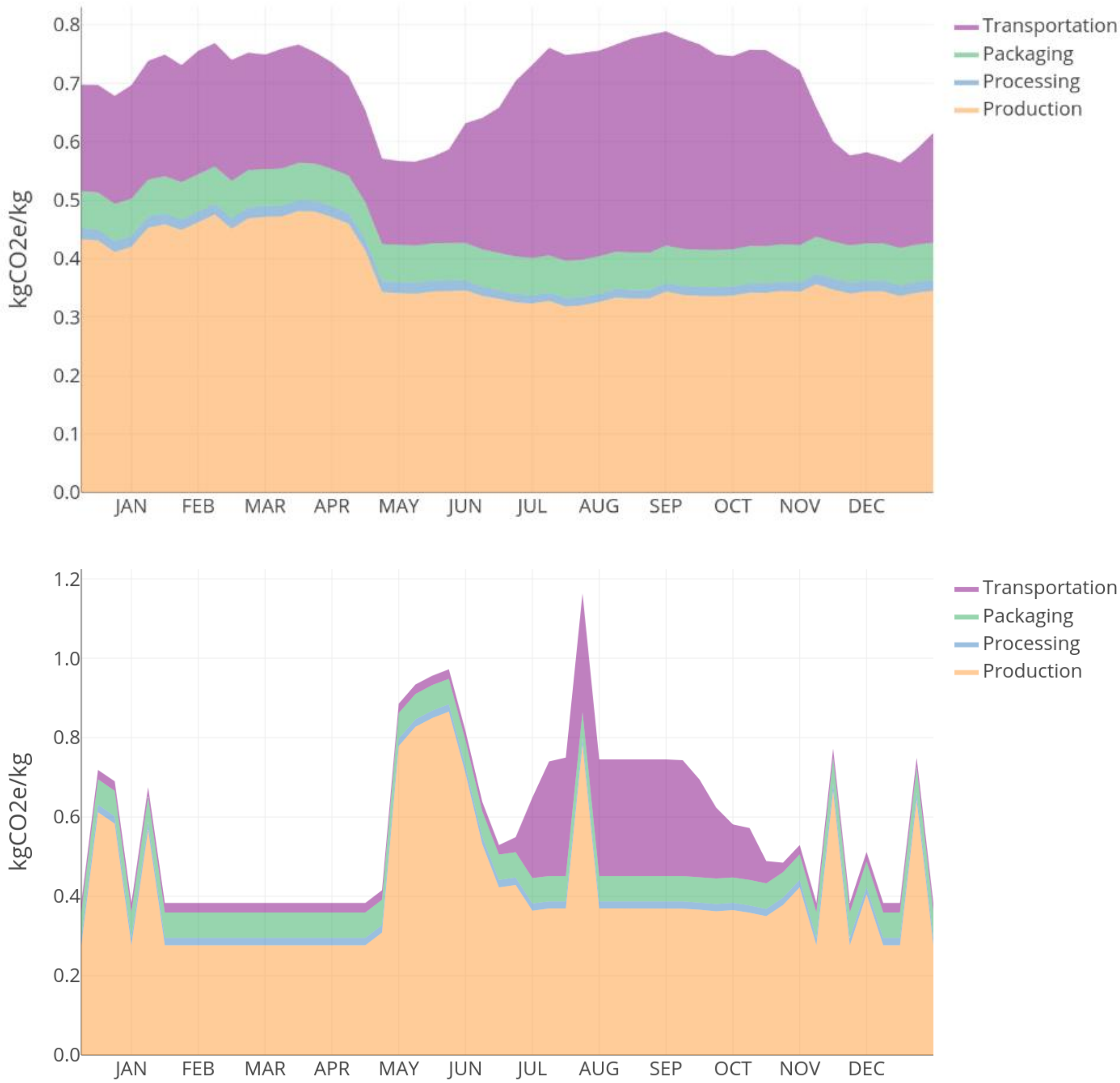


Figure C18: Environmental impact of fresh tomatoes delivered to Miami market under baseline (top) and optimized scenario (bottom)

C.7 Results for New York City Tomato Market

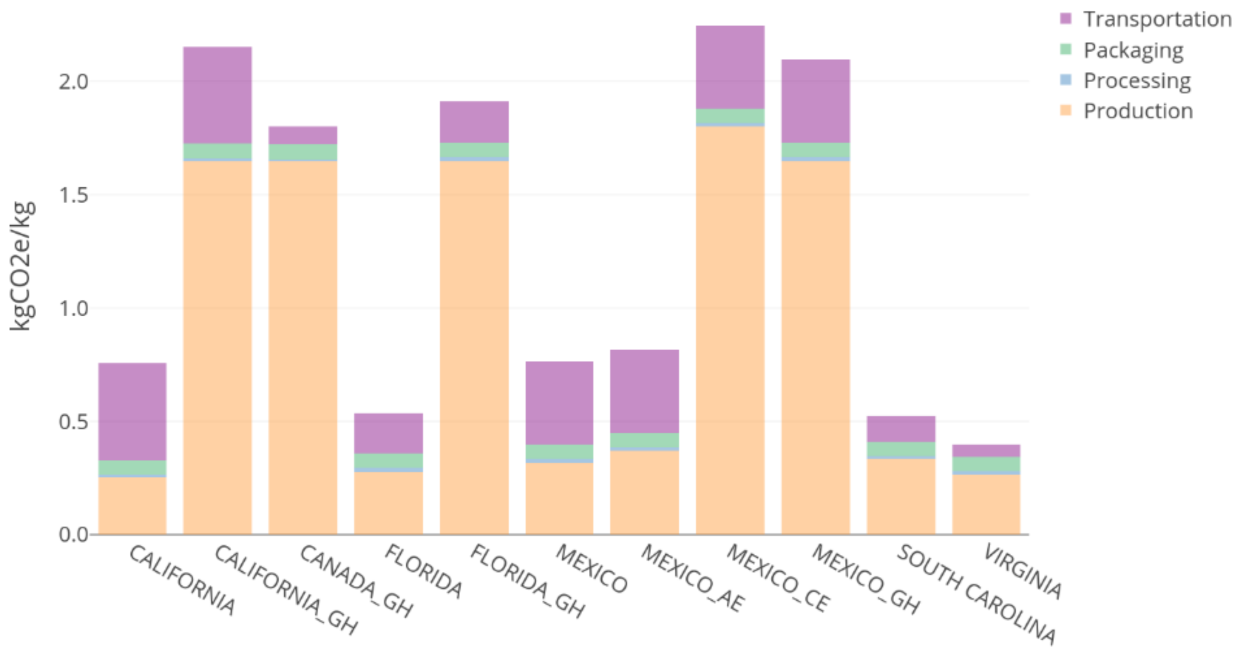


Figure C19: Cradle-to-market life-cycle GHG emissions for New York City fresh tomato supply

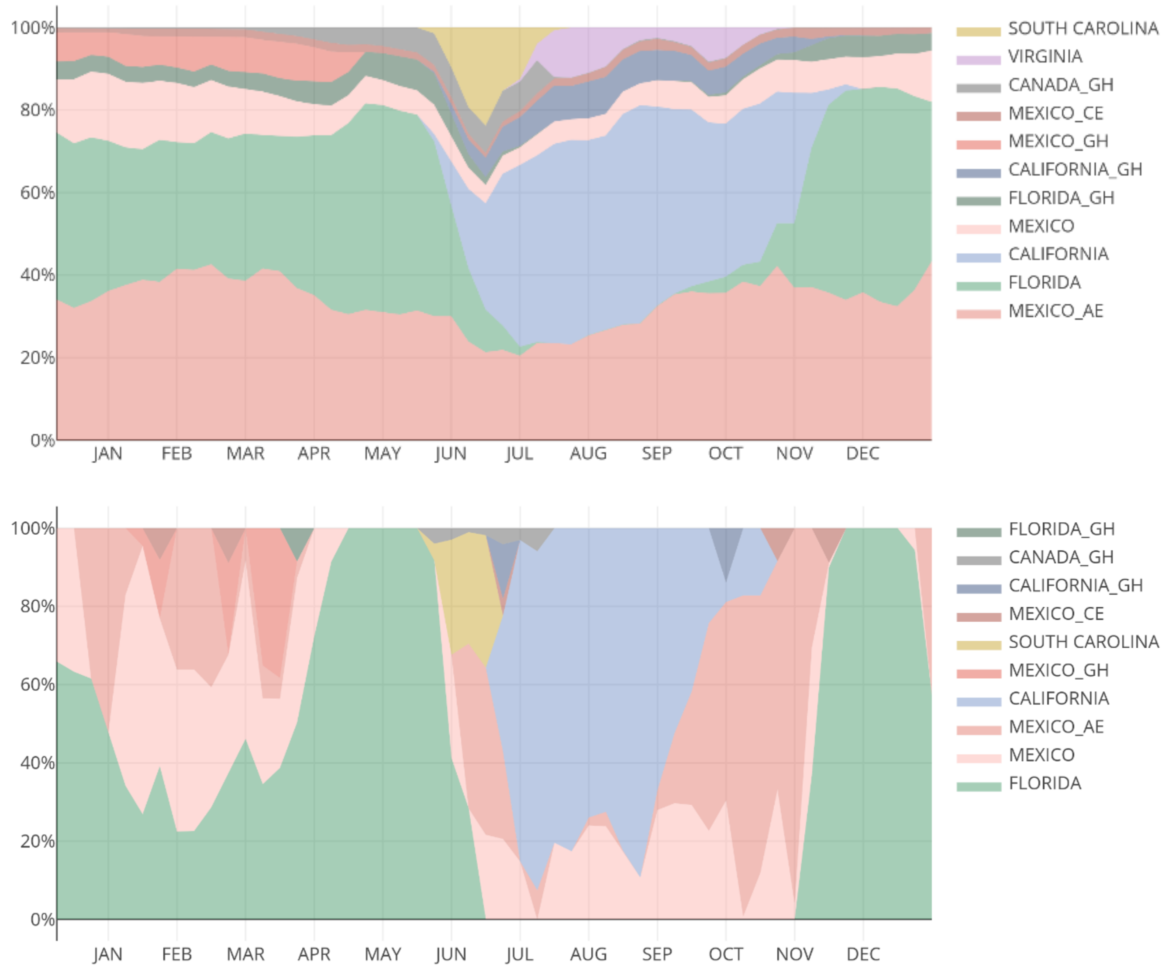


Figure C20: Tomato supply portfolio for New York City market under baseline (top) and optimized scenario (bottom)

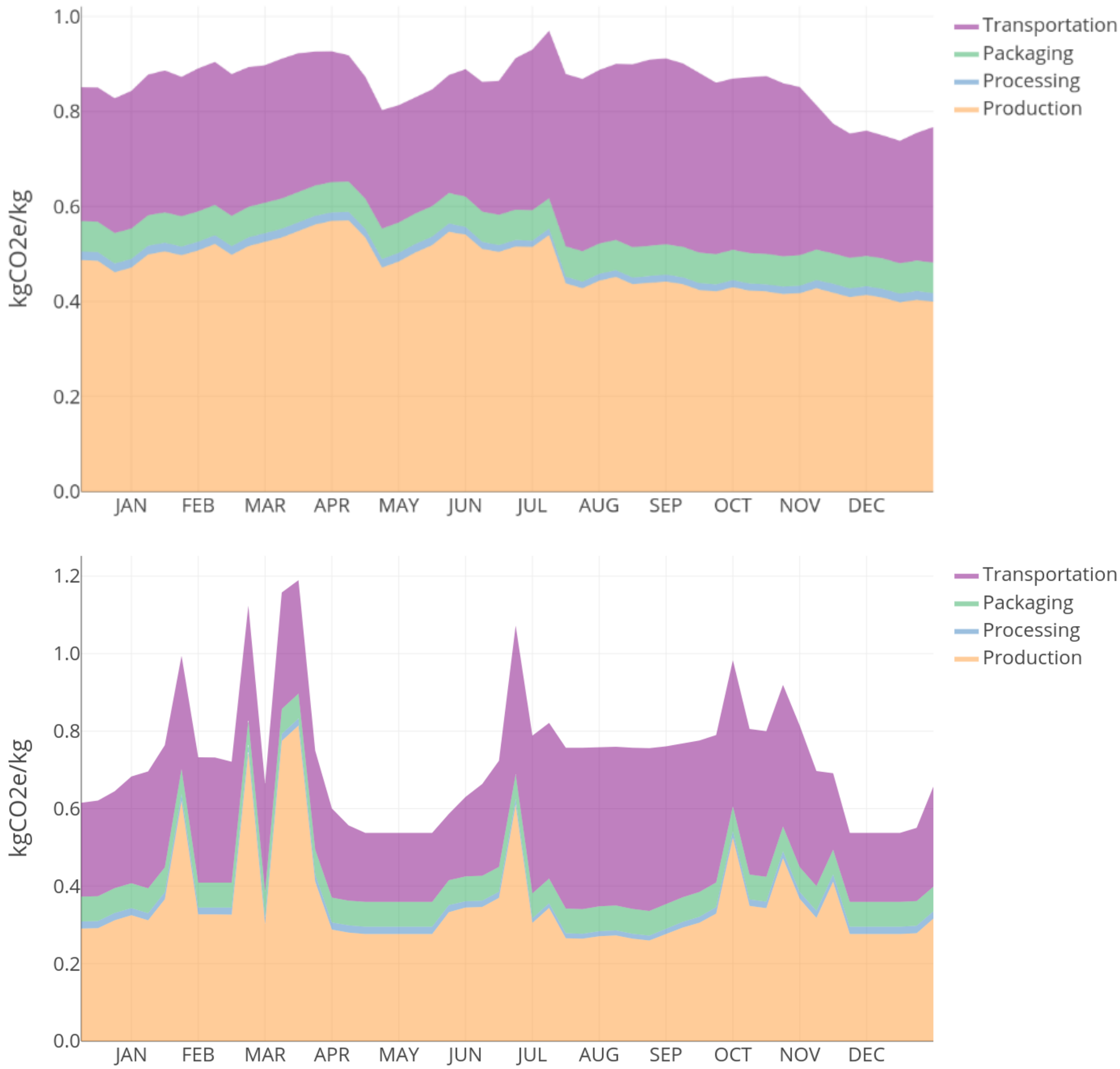


Figure C21: Environmental impact of fresh tomatoes delivered to New York City market under baseline (top) and optimized scenario (bottom)

C.8 Results for San Francisco Tomato Market

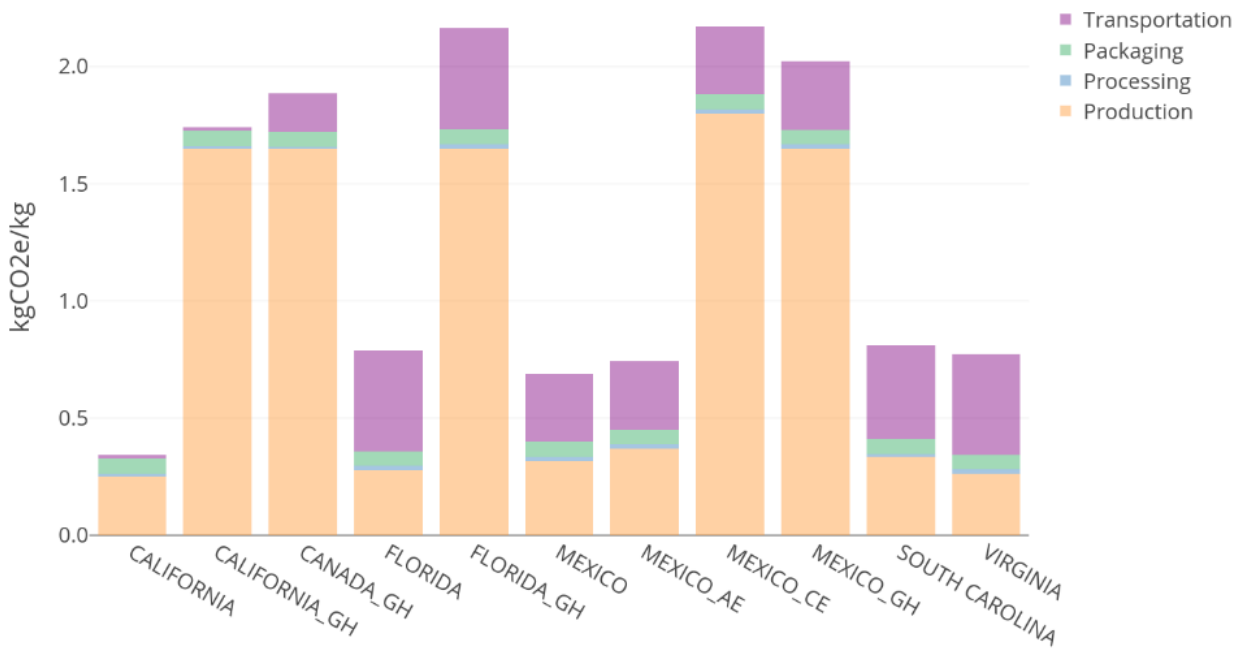


Figure C22: Cradle-to-market life-cycle GHG emissions for San Francisco fresh tomato supply

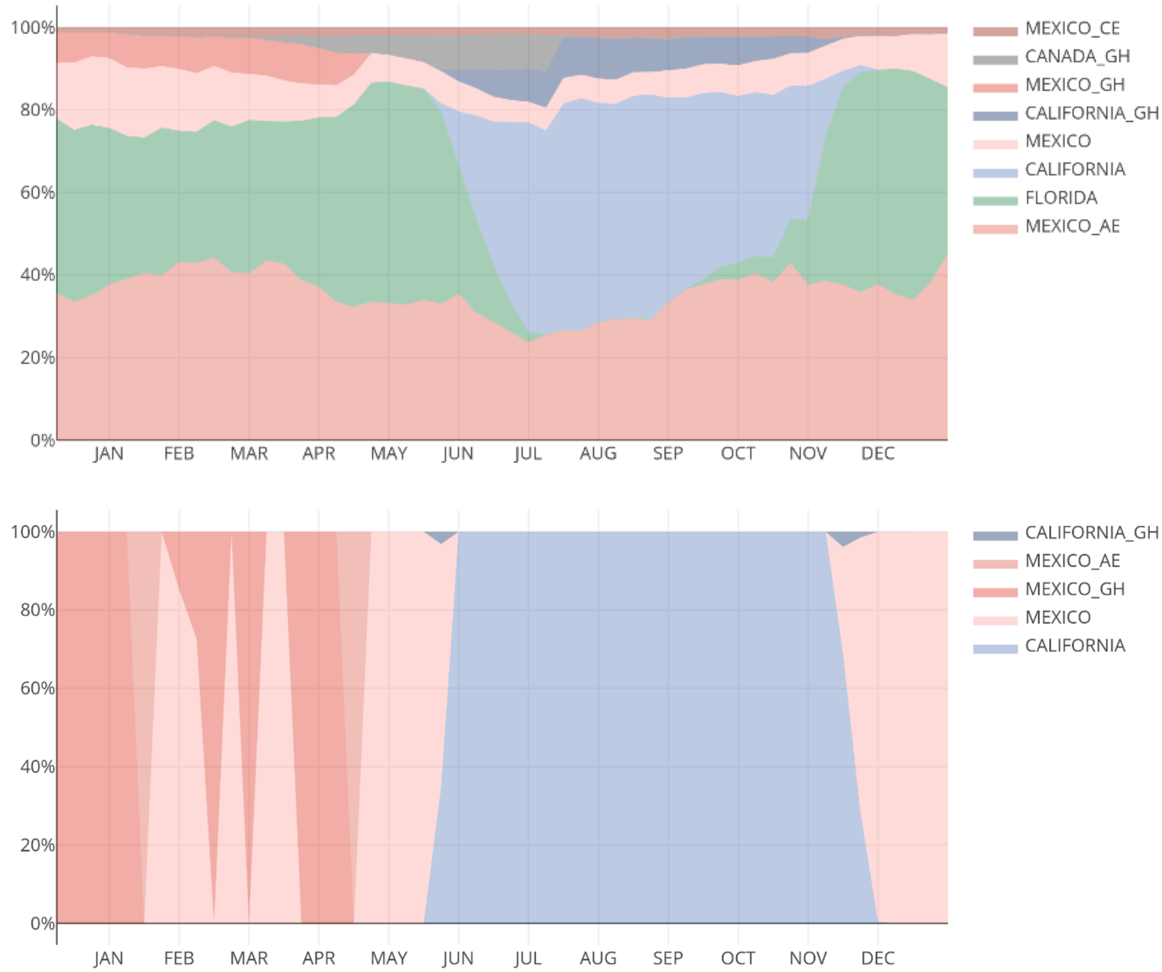


Figure C23: Tomato supply portfolio for San Francisco market under baseline (top) and optimized scenario (bottom)

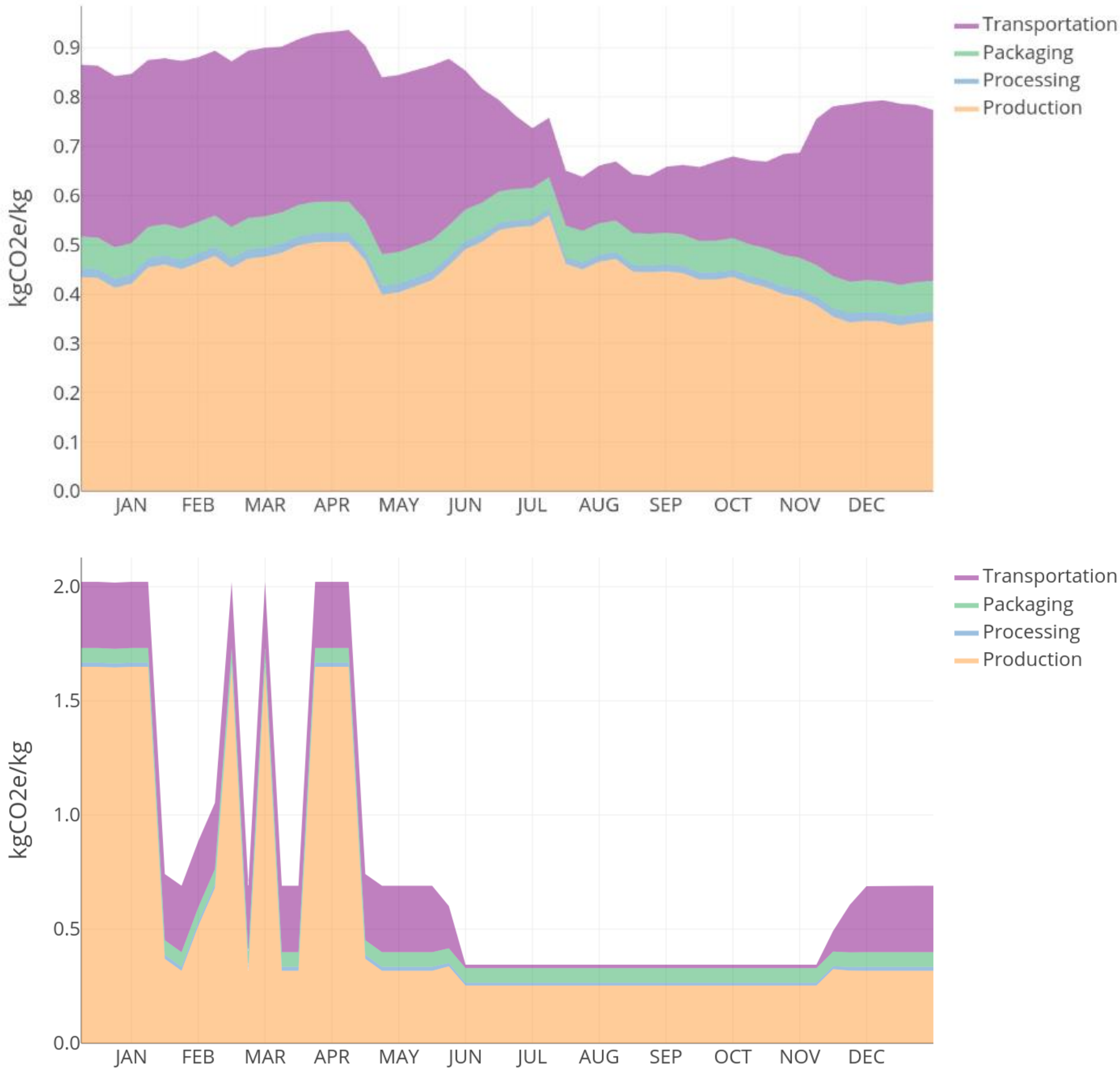


Figure C24: Environmental impact of fresh tomatoes delivered to San Francisco market under baseline (top) and optimized scenario (bottom)

C.9 Results for Washington DC Tomato Market

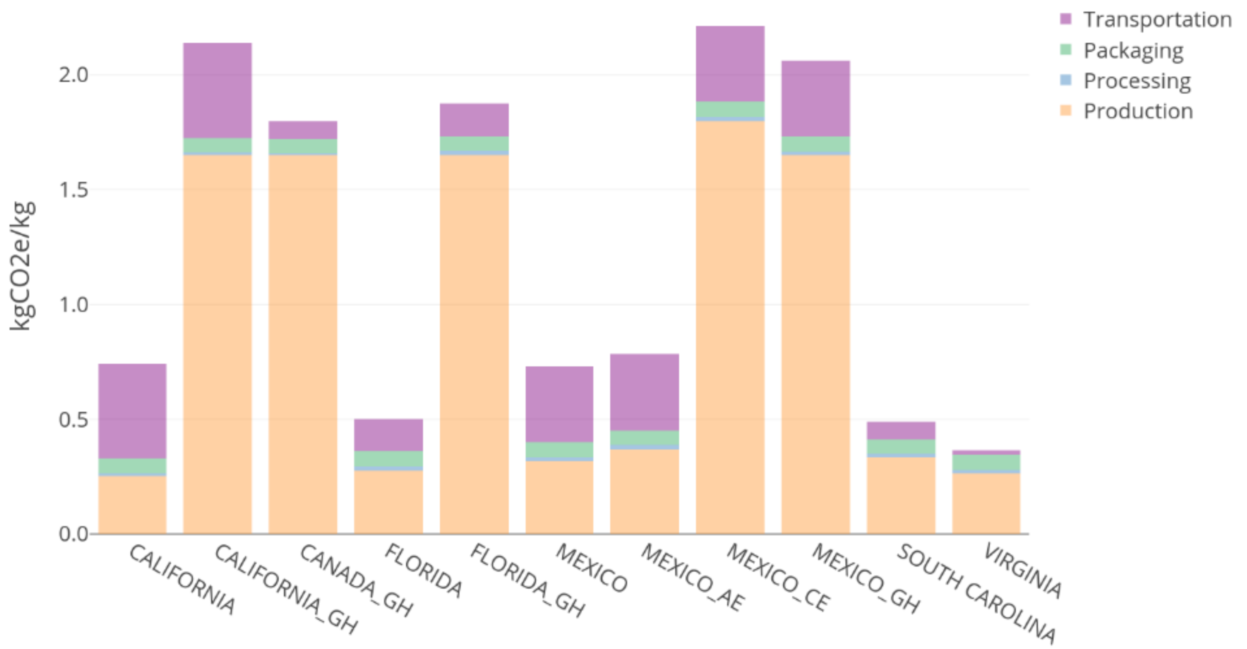


Figure C25: Cradle-to-market life-cycle GHG emissions for Washington DC fresh tomato supply

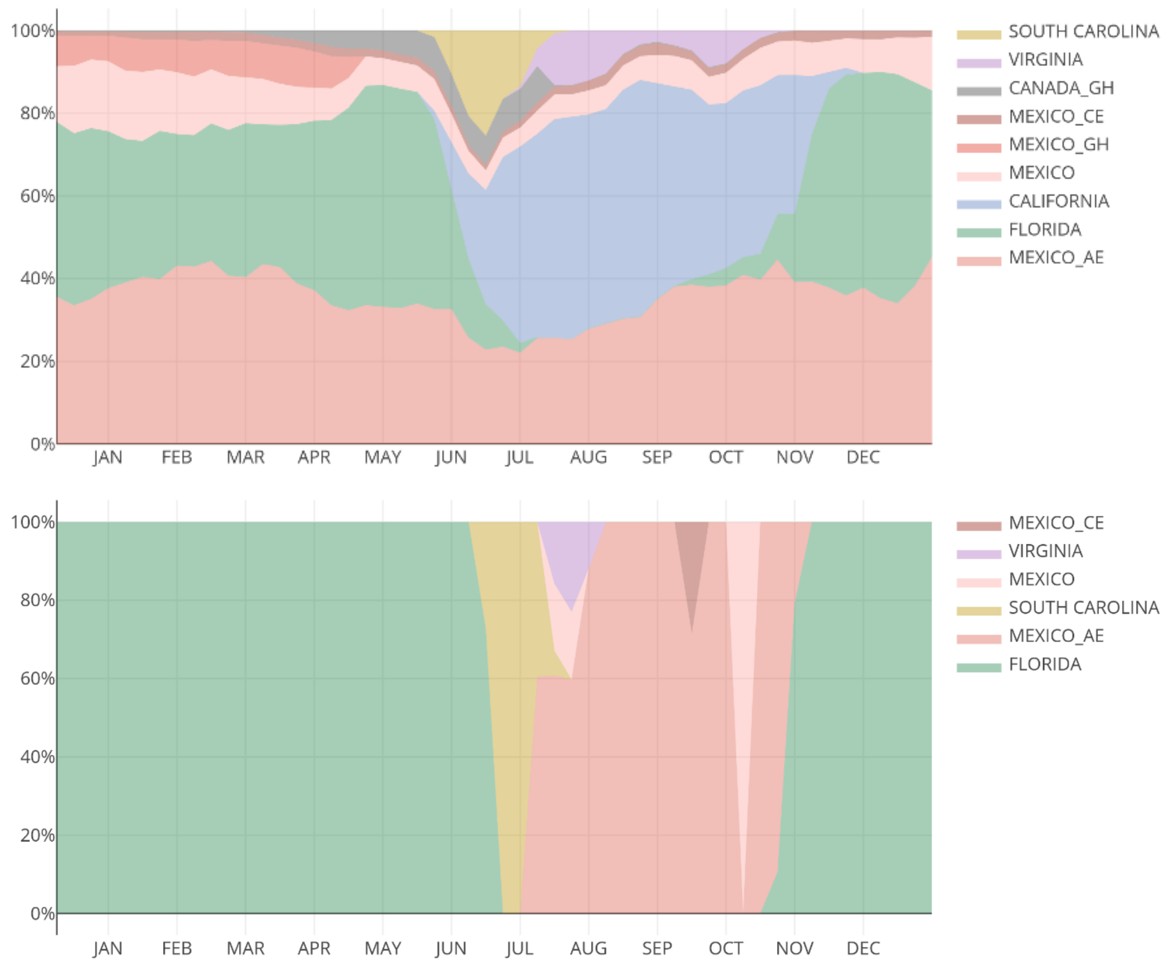


Figure C26: Tomato supply portfolio for Washington DC market under baseline (top) and optimized scenario (bottom)

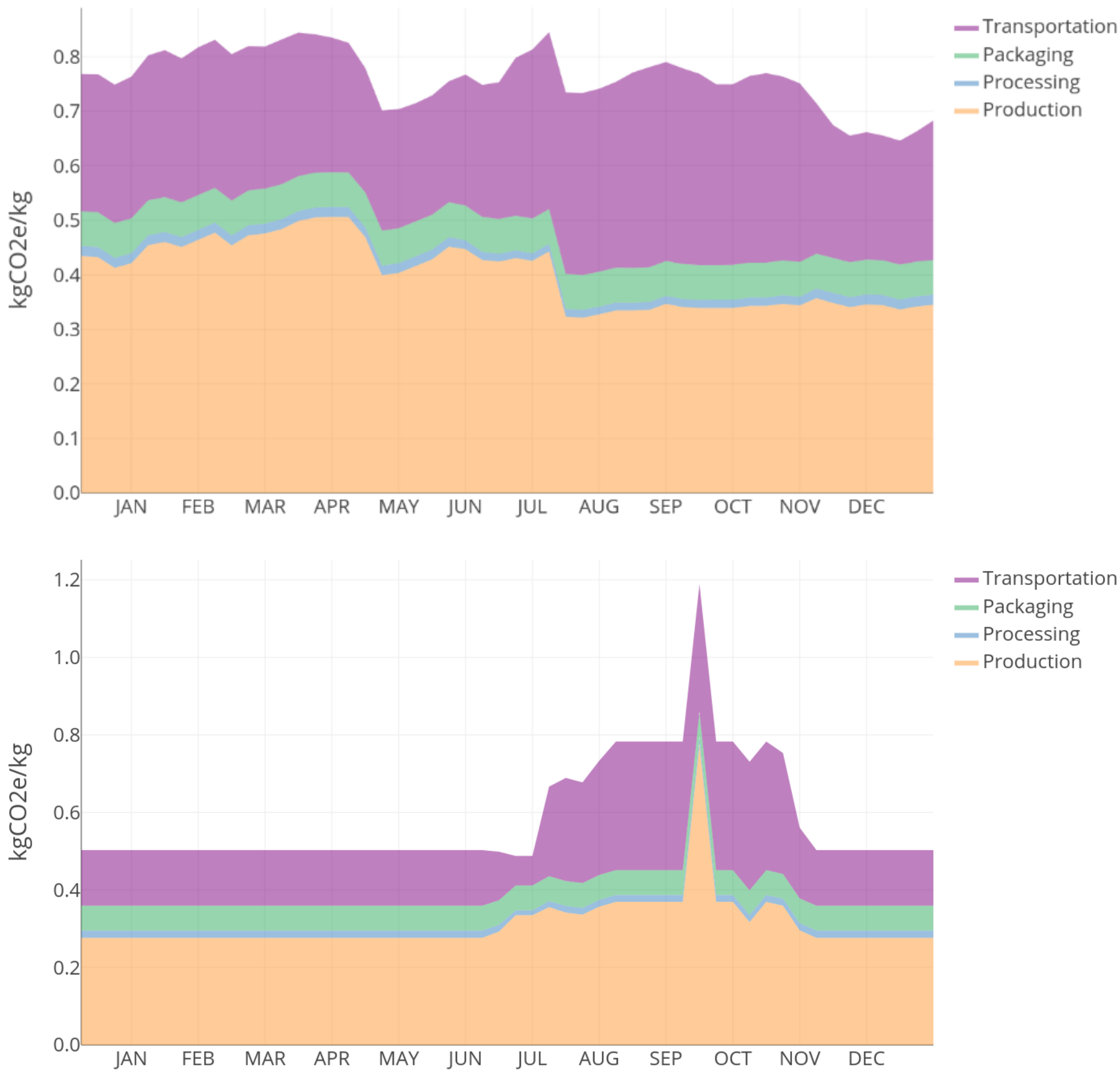


Figure C27: Environmental impact of fresh tomatoes delivered to Washington DC market under baseline (top) and optimized scenario (bottom)