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Modeling the carbon footprint of fresh produce: effects of transportation, localness, and seasonality on US orange markets

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Abstract

Agriculture is one of the most impactful ways that we interact with the environment. Food demand 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 production and supply. We present a conceptual framework for estimating the cradle-to-market life-cycle seasonal 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, Los Angeles, Chicago, and Atlanta 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 US cities can vary by more than a factor of two, depending on the production origin (e.g. 0.3 kgCO$_2$e/kg for Californian oranges delivered to New York City versus 0.7 kgCO$_2$e/kg for Mexican oranges delivered to New York City). The 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. Seasonality had a moderate impact on the results and varied depending on the destination city; based on our cradle-to-market analysis, the average carbon footprint of 'out-of-season' oranges relative to 'in-season' oranges increased by 51%, 46%, 14%, and 24% for Atlanta, Chicago, Los Angeles, and New York City, respectively. This study highlights the value of regionally-specific carbon footprinting for fresh produce and the need for a consistent and standardized data reporting framework for agricultural systems.

1. Introduction

Agriculture imposes significant demands on the world's natural resources while releasing large quantities of pollutants. Agriculture—as defined by both crop and livestock production—accounts for 70% of all global water withdrawals, occupies roughly half of the Earth's habitable land area, and is responsible for at least one quarter of global greenhouse gas (GHG) emissions [1–3]. Our global food system is responsible for roughly one third of energy consumption and a multitude of other resource and environmental impacts including conventional air pollution, eutrophication, groundwater contamination, habitat destruction, and species extinction [1]. Ensuring the sustainable growth of agricultural systems 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 [4]. 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 [5]. As a result of these trends, food production must increase by an estimated 70% by 2050 to meet demand [4]. 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 [6].

In this paper, we characterize the environmental impact of fresh produce (i.e. fresh fruits and vegetables) supply. Our analysis 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 the production, post-harvest processing, packaging, and transportation stages. Using oranges as a case study, we illustrate the variability in the carbon footprint of fresh fruit delivered to wholesale markets in three of the largest metropolitan areas: New York City, Los Angeles, and Chicago. Atlanta was chosen as the fourth metropolitan area due to its proximity to major orange growing regions in Florida. We calculate unique life-cycle carbon footprints for oranges produced in Australia, California, Florida, Texas, and South Africa, contributing to the existing body of literature that is largely dominated by European markets. The results are disaggregated by transportation mode, production region, and season. We discuss how this conceptual framework 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 for particular cities.

Past cradle-to-farm gate life cycle assessments (LCAs) of citrus production report life-cycle carbon footprints ranging from 0.07 to 0.64 kgCO_2e per kilogram of citrus produced with a median value of 0.29 [7–23]. While these studies represent a variety of geographic regions, only two are specific to the United States. The life-cycle carbon footprint per unit of land ranged from 1500 to 28 700 kgCO_2e per hectare with a median value of 6540. These data reflect production only; post-harvest processing, packaging, and transportation are not included. The range of values can be attributed to variations in the quantity of agricultural inputs, methodologies across LCAs, and output yields. One recent publication conducted a literature review of over 350 LCA studies of various food crops and growing regions, encompassing over 1700 carbon footprints [24]. 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 in the United States at all, let alone at the state or county level. A summary of the literature is provided in section 1 of the supporting information (SI), available online at stacks.iop.org/ERL/15/034040/mmedia. The results presented herein are unique in their application of a conceptual framework to regionally-specific carbon footprints and temporal variations in an average city-wide carbon footprint.

There are several examples in the literature of similar supply chain analyses being applied to fresh food products [25–35]. Most of them are specific to European markets and do not include oranges. Many assess the relative environmental impacts of local and mainstream supply chains, but do not address the importance of transportation mode or seasonality of supply and demand. One study applies a similar method to ours to assess the energy use and emissions associated with imported apples, bananas, and oranges [26]. Our analysis expands upon this previous study by considering the entire cradle-to-market supply chain, including the production stage and transportation all the way to the wholesale market.

This conceptual framework focuses specifically on the demand for fresh produce in the United States. The US food system as a whole is responsible for the emissions of approximately 2.6 tCO_2e per person per year [35]. By our calculations, this accounts for roughly 10% of overall US GHG emissions [35, 36]. Fresh produce accounts for roughly one-tenth of food-related GHG emissions, or approximately 1% of overall US GHG emissions [35]. While 1% of US GHG emissions may not seem like much, the United States emits roughly 20% of the world's greenhouse gases, despite having only 5% of the world's population. With global population growth and increasing preference for the consumer patterns of wealthier nations, food-related emissions—in particular, emissions associated with specialty commodities such as fresh produce—are likely to increase.

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 that of those produced in California [37]. 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 [38]. Second, transportation is of greater importance for fruits and vegetables than for most commodities. Although transportation accounts for only 11% of the carbon footprint of all US food on average, it accounts for 28% of the carbon footprint of fruits and vegetables [35]. This fact allows for the possibility of mitigating the carbon footprint of certain fresh produce commodities by redesigning supply networks or integrating emerging transportation technologies. Third, many fruits and vegetables

are highly perishable, resulting in higher rates of food loss[3] (roughly 30% in North America) relative to other food groups such as meat (~10%) and grains (~10%) [39]. The relatively short shelf life of certain perishable fresh food commodities also eliminates the possibility of long-term storage for many fresh fruits and vegetables, simplifying the logistical model. 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 production and supply chain would be economically viable. In addition, demand for such specialty crops will only increase with the growth of the global middle class. We currently have the opportunity to plan for the expansion of the fresh produce market in a manner that is deliberate and sustainable.

2. Methods

The carbon intensity (CI) of a given agricultural commodity delivered to a given US city—measured in kilograms of CO_2e per kilogram of produce—can be expressed for each production region (i) by equation (1):

$$CI_i = PD_i + \frac{PS_i}{(1 - l_{PS})} + \frac{PK}{(1 - l_{PK})} + \frac{TR_{AVGi}}{(1 - l_{TR})},$$ (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 US city.

l_{PS}, l_{PK}, l_{TR} = food loss during the processing, packaging, and transportation stages, respectively.

Figure 1 further breaks down the individual processes included in the analysis. A detailed explanation of each stage follows.

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. Since the environmental impact of a particular crop can vary geographically, we calculated

unique life-cycle carbon footprints for the majority of production regions considered in this analysis based on enterprise budget reports collected from each of the production regions. Data were not available for orange production in Mexico or Chile. For Mexico, data from Texas orange production were used as proxy. For Chile, the literature average was applied. Additional information regarding this approach is included in section 2.7 below and section 2 of the SI.

The framework used herein estimates the production-related GHG emissions for each production region by dividing the regionally-specific GHG emissions impact per unit area of farmland by the regionally-specific annual yield, per equation (2):

$$PD_i = \frac{PD_i^*}{Y_i}$$ (2)

where:

PD_i = GHG emissions associated with crop production, by production region, per unit mass produced ($kgCO_2e/kg$)

PD_i^* = GHG emissions impact associated with crop production, by production region, per unit area of farmland ($kgCO_2e/ha$).

Y_i = average annual net harvested yield[4], by production region (kg ha^{-1}).

Domestic yields were determined at the state level from the US Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) Quick

'food waste.' Considered collectively, over 50% of fruits and vegetables are lost or wasted in North America [39].
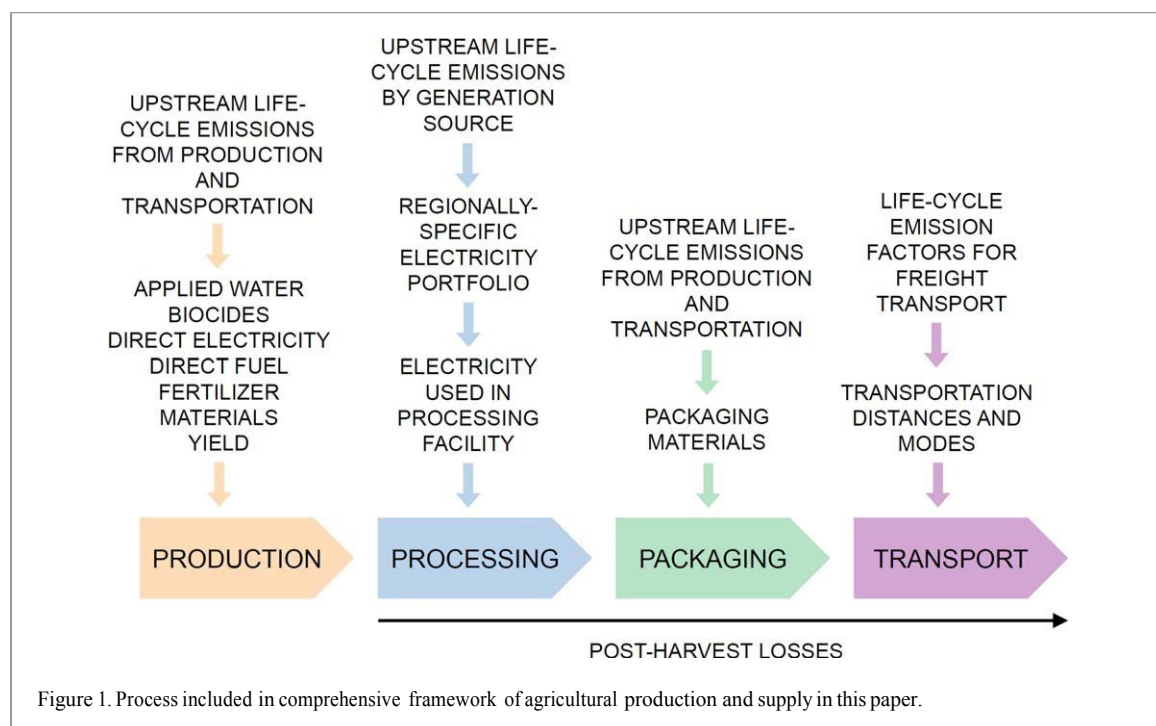
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[3] While the exact definition of 'food loss' is not universal, it refers herein to the decrease in the edible food mass throughout the production, post-harvest, processing, and transportation-to-market stages of the food supply chain. Food loss does not include losses at the retailer or consumer stages, which are generally categorized as

Stats Database based on a 20 year average from 1998 to 2017 [41]. International yields were determined at the national level from the Food and Agriculture Organi- zation of the United Nations [42].

2.2. Processing

The post-harvest processing stage may include elec- tricity 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 [43]. 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 US Environmental Protection Agency's (EPA's) Emis- sions & Generation Resource Integrated Database (eGRID) [45]. International electricity mixes were determined at the national level from The World Bank Group [46]. Life-cycle GHG emission factors by electricity generation type were determined from the literature [47].

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[4] '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' [40].

Figure 1. Process included in comprehensive framework of agricultural production and supply in this paper.

2.3. Packaging

This analysis 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 [44].

2.4. Transportation

The GHG emissions associated with transporting fresh produce from farm gate to wholesale market are a function of the mode-specific freight emission factors (truck, rail, containership) and the transportation distances between the origin (i.e. production-weighted centroid of each region) and destination (i.e. wholesale market). The life-cycle freight emission factors used in this analysis are 86 gCO_2e/tkm for truck, 13 gCO_2e/tkm for rail, and 4.6 gCO_2e/tkm for containership [48]. Transport by rail and containership is multimodal (i.e. trucking is still required for 'first-mile' and 'last-mile' deliveries); the 'mode,' therefore, references the primary mode of transportation. The average transportation emissions from each production region to the destination market, weighted by transportation mode, can be described by equation (3):

$$TR_{AVGi} = \sum_{n=1}^{N} [SM_{ij} . * TR_{ij}] \text{ '' } m, \qquad (3)$$

where:

SM_{ij} = matrix describing the proportion of food delivered by each transportation mode (j) for each production region (i).

TR_{ij} = matrix describing transportation-related GHG emissions by production region (i) and trans- portation 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) [49]. 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 [50, 51]. Destinations were defined as the largest wholesale produce market in the destination city. Trucking transportation distances were determined via Google Maps. Rail transportation distances were determined from GIS datasets of intermodal rail hubs and US Department of Transportation (USDOT) railroad lines [52, 53]. 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 USDOT 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 trucking route from the destination hub to the wholesale market. Containership transportation distances were determined based on tables of nautical shipping distances between major ports [54]. 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 [49]. Lastly, Google Maps was again used to determine the shortest trucking route between the destination port and the wholesale market.

2.5. Food loss

Food losses were determined from USDA's Loss-Adjusted Food Availability (LAFA) Dataset [55], which reports the total percentage of specific fruits and vegetables in the US that are lost between post-harvest and delivery to market. Due to a lack of detailed data, the analysis used herein assumes that losses are distributed equally across the processing, packaging, and transportation stages. Only 3% of oranges is lost from post-harvest through delivery [55]. As a result, our assumption that 1% is lost at each of the three stages minimally impacted the accuracy of the results. Since the yield data used in this analysis represent net harvested yield, food loss at the production stage is already accounted for.

2.6. Weekly weighted-average environmental impact

By determining the proportion of market 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 commodity and illustrate how this carbon footprint varies seasonally. The weighted-average carbon footprint of a given agricultural commodity delivered to a given destination market in a particular week (k) can be described by equation (4):

$$CI_{AVGk} = SW_{ki} * CI_i, \qquad (4)$$

where:

$SW_{ki} = $ matrix describing the proportional food supply by week (k) and production region (i).

$CI_i = $ vector describing the carbon intensity of a given agricultural commodity delivered to a given US 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 [49, 56]. 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 US's 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 US cities on a weekly basis. National-level statistics were modified for each city based on unique records of each city's market suppliers throughout the year. Additional information regarding this approach is available in section 6 of the SI.

2.7. Case studies: oranges supplied to Atlanta, Chicago, Los Angeles, and New York City
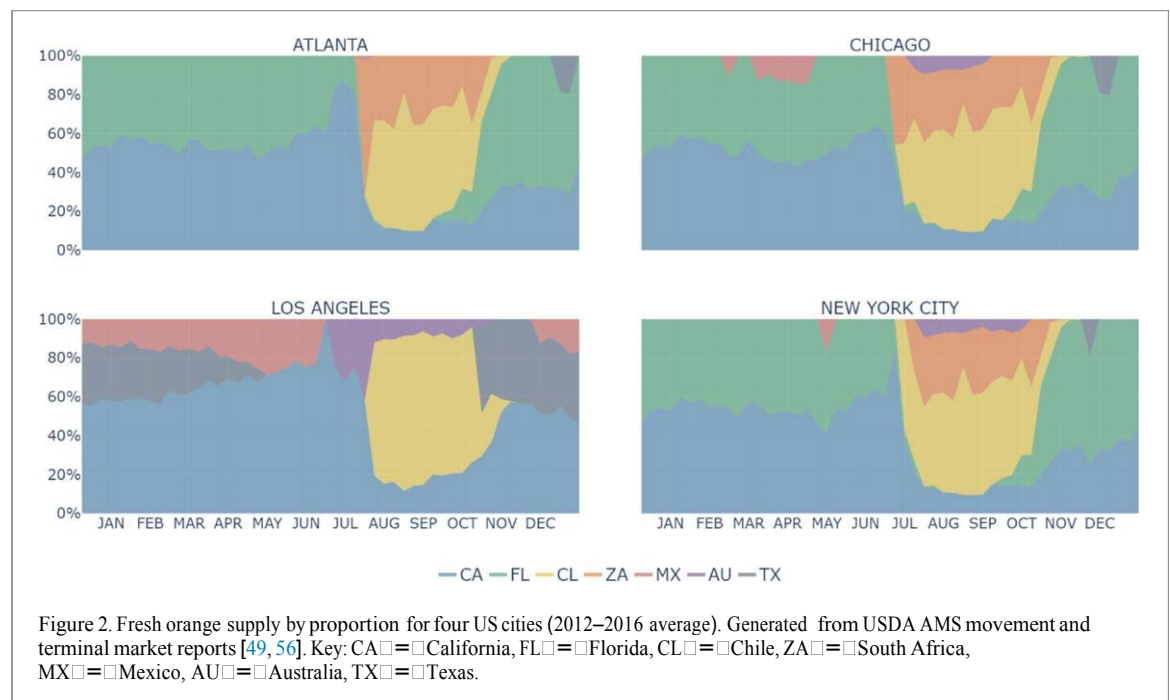
The orange markets for Atlanta, Chicago, Los Angeles, and New York City were selected as case studies for several reasons. First, oranges are one of the most popular fresh produce items in the United States. Roughly 5 kg of fresh oranges are consumed per capita in the US annually[5], ranking fourth on the list of most popular fresh fruits—behind bananas, melons, and apples [55]. Atlanta, Chicago, Los Angeles, and New York City represent four of the largest US markets and comprise four distinct geographic regions. 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. Second, the seasonal variability in orange supply makes for an interesting case study. Fresh oranges consumed in the US 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 is met with imports from Chile, South America, and/or Australia (figure 2). A small quantity of oranges is also supplied by Texas and Mexico. Lastly, the relative uniformity of fresh orange packaging simplifies the analysis.

As illustrated by figure 2, seven regions supply oranges to the four US cities studied. The annual average orange yields for these seven regions range from 13 000 kg ha^{-1} (Mexico) to 33 000 kg ha^{-1} (South Africa). Unique life-cycle production footprints for five of the seven regions were calculated, ranging from 0.20 kgCO$_2$e/kg (California, Texas) to 0.33 kgCO$_2$e/kg (South Africa). These life-cycle footprints were calculated using a methodology described in Bell et al [38], based on data from a combination of enterprise budget reports and the literature [13, 57–60]. Data were not available for orange production in Mexico or Chile. For Mexico, data from Texas orange production were used as proxy. For Chile, a value of 6300 kgCO$_2$e/ha was applied, representing the literature average. Additional information regarding this approach is provided in section 2 of the SI. A Monte Carlo simulation was conducted to assess—among other things—the uncertainties in crop yield and life-cycle GHG emissions per hectare.

Post-harvest processing included washing, waxing, drying, sorting, grading, packing, and short-term

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[5] This does not include the additional 20 kg of oranges consumed per capita annually in the form of juice (roughly 12 litres per person per year) [55].

Figure 2. Fresh orange supply by proportion for four US cities (2012–2016 average). Generated from USDA AMS movement and terminal market reports [49, 56]. Key: CA☐=☐California, FL☐=☐Florida, CL☐=☐Chile, ZA☐=☐South Africa, MX☐=☐Mexico, AU☐=☐Australia, TX☐=☐Texas.

cold storage for a total of 39 kWh/ton of oranges processed [43]. Life-cycle GHG emissions for post-harvest processing ranged from 12 gCO_2e/kg of oranges processed (California) 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 [44]. The resulting life-cycle GHG emissions impact of packaging was estimated to be 9 gCO_2e/kg of oranges packaged, based on an estimated mass of 170 g of cardboard per carton. This value was assumed to be independent of the production region.

Throughout the course of the year, Atlanta, Chicago, Los Angeles, and New York City receive oranges by truck (Florida, Mexico, Texas), rail (California, Florida (negligible quantity[6])), and containership (Australia, Chile, South Africa). The largest wholesale produce market in each city was chosen as the shipping destination. Figure 3 illustrates the origin and destination nodes for Hunt's Point Cooperative Market in New York City, as well as the transportation routes for each production region.

3. Results

Figure 4 illustrates the life-cycle GHG emissions associated with transporting fresh oranges from each of the seven production regions to each of the four destination cities. When comparing across transportation modes, there is roughly an order of magnitude difference between the life-cycle freight emission

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[6] Roughly 0.1% of Florida oranges are transported by rail annually versus 99.9% by truck.

factors for truck, rail, and containership (86, 13, and 4.6 gCO_2e/tkm, respectively) [48]. 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 (e.g. containership) [61, 62]. The error bars represent the 10/90 uncertainty bounds and were calculated via Monte Carlo simulation. Additional information regarding uncertainty is provided in section 10 of the SI.

Figure 5 summarizes the total life-cycle carbon footprint of oranges by production region and life-cycle stage for each of the four US cities. The carbon footprint is dominated by the production and transportation stages; processing and packaging collectively account for only 4%–9% of the total. Transportation impacts range from 4% to 54% of the total (California oranges delivered to Los Angeles by rail and Texas oranges delivered to New York City by truck, respectively).

In the case of all four cities, California oranges have the lowest carbon footprint (0.3, 0.3, 0.2, and 0.3 $kgCO_2e$/kg for Atlanta, Chicago, Los Angeles, and New York City, respectively). The carbon footprint of oranges from Mexico is more than double that of California in the case of all four cities (0.6, 0.6, 0.6, and 0.7 $kgCO_2e$/kg for Atlanta, Chicago, Los Angeles, and New York City, respectively).

The error bars represent 10/90 uncertainty bounds 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 well as the lack of production data for
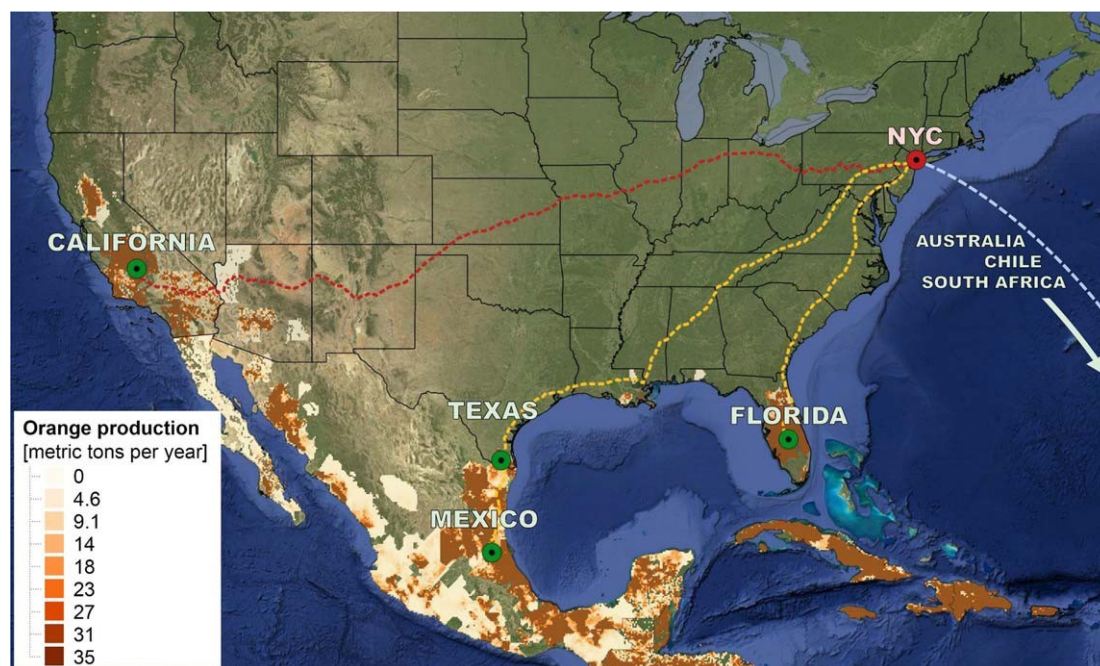
Figure 3. Production regions and transportation routes for New York City's fresh orange market. Notes: the green circles indicate production origins, as defined by the production-weighted centroid of each production region. The red circle indicates the wholesale market destination (in this case Hunts 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 [50, 51].

Figure 4. Carbon footprint associated with transportation of fresh oranges to four US cities by transportation mode (kgCO$_2$e/kg of oranges). Key: AU = Australia, CA = California, CL = Chile, FL(T) = Florida by truck, FL(R) = Florida by rail, MX = Mexico, ZA = South Africa, TX = Texas. 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 10/90 uncertainty interval.
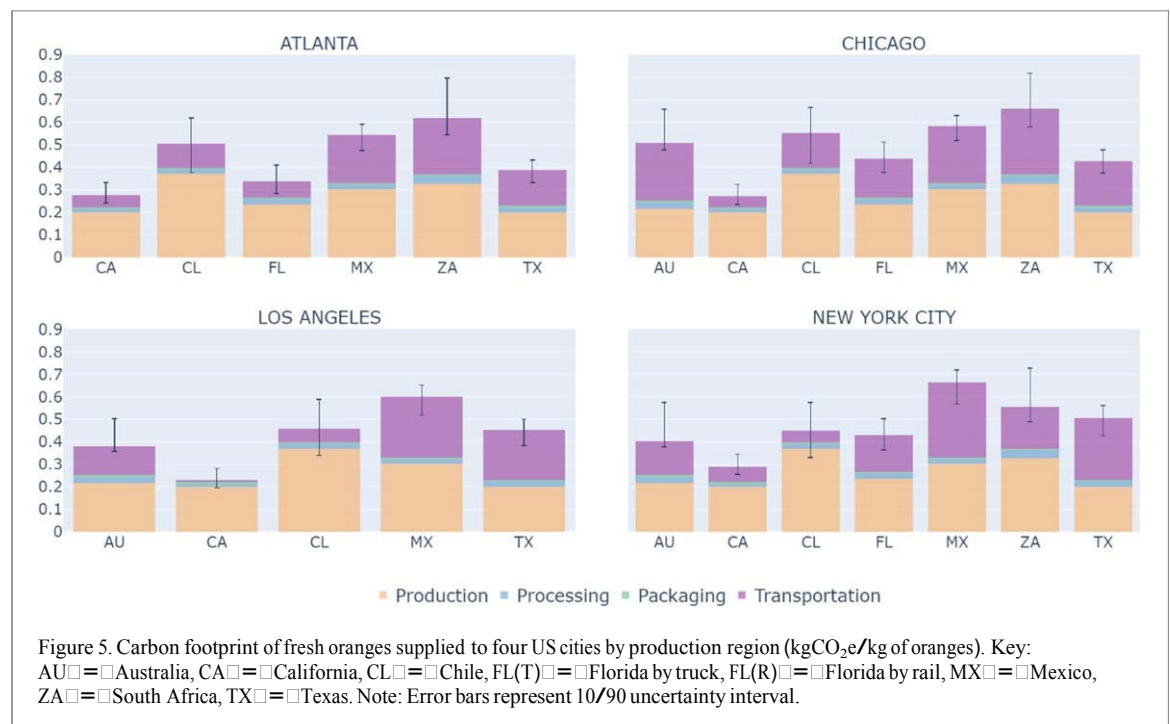
Mexico and Chile. Additional details are provided in section 10 of the SI.

Figure 6 is the result of applying the data from figure 5 to a matrix of values representing the proportion of each city's orange supply met by each production region in each week of the year. Relative to 'in-season' oranges, the average carbon footprint of 'out-of-season' oranges—as defined by a 15 week period from mid-July through mid-October—increased by approximately 51%, 46%, 14%, and 24% for Atlanta, Chicago, Los Angeles, and New York City, respectively.

4. Discussion

The results highlight the significance of the various life-cycle stages. For transportation mode, there is

Figure 5. Carbon footprint of fresh oranges supplied to four US cities by production region (kgCO$_2$e/kg of oranges). Key: AU = Australia, CA = California, CL = Chile, FL(T) = Florida by truck, FL(R) = Florida by rail, MX = Mexico, ZA = South Africa, TX = Texas. Note: Error bars represent 10/90 uncertainty interval.
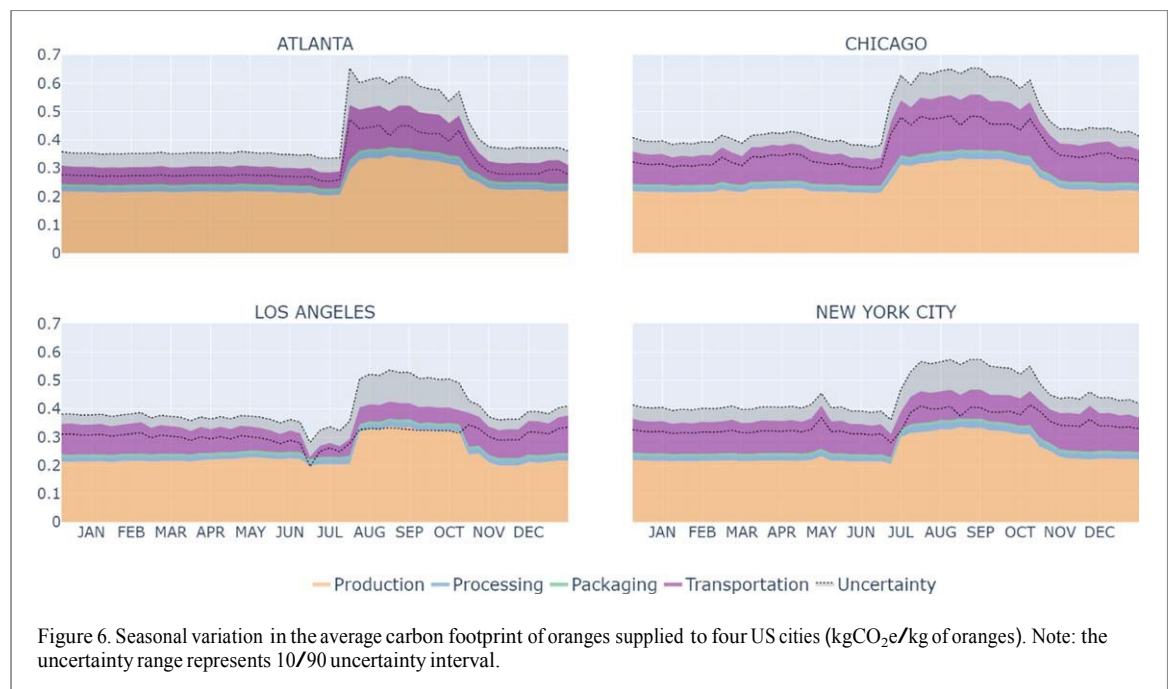
roughly an order of magnitude difference in the life-cycle freight emission factors for truck, rail, and containership. As a result, mode switching may prove an effective strategy for mitigating the environmental impact of fresh produce. For example, the GHG emissions associated with transporting fresh oranges by rail from Florida to New York City are roughly five times lower per kilogram of oranges than by truck. However, there may be practical limitations to increasing the proportion of Florida oranges supplied by rail, including railroad network constraints and the additional time required for loading and unloading. An assessment of the infrastructure network was outside the scope of this paper, but merits future consideration.

From a greenhouse gas emissions 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) and possibly from more efficient growing practices. Furthermore, food losses for oranges were found to be only 3% from post-harvest through delivery [55]. In the case of New York City, Chile is the production region with the lowest transportation-related GHG emissions[7], in spite of the fact that Chilean orange production is over 8000 km away by containership from New York City. Since Chilean orange production is close 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 results of this paper indicate that oranges supplied to New York City from California have a lower cradle-to-market carbon footprint than from 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), possibly increasing net emissions at the national level. It is therefore necessary to provide incentives and options for producers and transporters to reduce their environmental impact.

The results show a moderate seasonal variation in the carbon footprint of oranges. Specifically, 'out-of-season' oranges were found to have a carbon footprint approximately 51%, 46%, 14%, and 24% higher than 'in season' oranges for Atlanta, Chicago, Los Angeles, and New York City, respectively. This fact can be attributed primarily to variations in the carbon footprint of the production stage, 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). Other common fresh produce items, including apples and bananas, do not display the seasonal variability in supply that is characteristic of

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

Figure 6. Seasonal variation in the average carbon footprint of oranges supplied to four US cities (kgCO$_2$e/kg of oranges). Note: the uncertainty range represents 10/90 uncertainty interval.

oranges—based on a similar, yet unpublished analysis conducted by the authors—and are, therefore, likely to exhibit a relatively constant carbon footprint throughout the seasons.

There are several sources of uncertainty in this assessment, which were addressed with an uncertainty analysis using Monte Carlo simulation and incorporated into the presentation of the results in figures 4–6. Additional details regarding uncertainty are included in section 10 of the SI. Most significant are crop yields, which can vary significantly 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—particularly for Mexico and Chile—as well as limited shipping data. While our results represent national-level and state-level averages, it must be acknowledged that crop yields can also vary significantly at the subregional level. While our analysis addresses these uncertainties by varying inputs and assumptions, they highlight the need for regionally- and subregionally-specific carbon footprinting [38, 63, 64] and a consistent and reliable worldwide system of reporting agricultural production methods and data.

5. Conclusions

This analysis presents a conceptual framework for estimating the cradle-to-market carbon footprint of fresh produce, including the production, post-harvest processing, packaging, and transportation stages. We demonstrate that varying the transportation mode of oranges delivered to Atlanta, Chicago, Los Angeles, and New York City has greater potential for reducing the carbon footprint of oranges than eating 'locally' or

'seasonally.' This is largely attributable to the fact that produce shipped from greater distances is more likely to travel via a relatively efficient mode (e.g. containership) than a relatively inefficient mode (e.g. truck).

Future work might include expanding this conceptual framework to assess other relevant metrics (e.g. economic costs, energy and water use, eutrophication potential, ozone depletion potential) and other fresh produce commodities. The adoption of a universal method 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 framework. Such a system would allow for the development of regionally- and temporally-specific carbon footprinting of agricultural commodities, efficiency benchmarking in agricultural production and supply, and perhaps the incorporation of a performance-based ecolabel for resource-efficient crops.

Data availability

Any data that support the findings of this study are included in the supplementary information.

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