Optimal Allocation of Tomato Supply to Minimize Greenhouse Gas Emissions in Major U.S. Metropolitan Markets

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Abstract

The United States food system requires energy, water, and land in significant proportions, releases large quantities of greenhouse gases, and contributes to other environmental concerns. Meeting future demand for fresh food will be especially challenging, requiring the adoption of holistic, systems-level thinking to maximize production and supply while limiting consequences to the climate and natural resources. We have developed a cradle-to-market life-cycle environmental model to assess the greenhouse gas 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. Monte Carlo simulation was performed to assess the uncertainties in the data. 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 transportation-related emissions by 34% and overall tomato-related greenhouse gas emissions by 13%—from 277,000 $MTCO_2e$ to 242,000 $MTCO_2e$. The substantial variability of the optimized scenario raises questions about its practical implementation. Ultimately, however, production practices and geographic conditions (such as soil and climate) are more significant with respect to environmental impact than the supply allocation or the seasonality of supply. Our analysis found a roughly six-fold difference between Philadelphia tomatoes sourced from open-field Virginian production (0.38 $kgCO_2e/kg$) compared with controlled-environment Mexican production (2.3 $kgCO_2e/kg$).

Main

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[1]. The emissions of the food system account for roughly 10% of overall U.S. greenhouse gas (GHG) emissions[1,2]. 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[3,4]. 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 [5]. 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 a linear optimization model to estimate the cradle-to-market life-cycle GHG emissions associated with fresh tomatoes supplied to ten of the twelve most populous metropolitan statistical areas in the U.S. (Table 1)—based on six unique geographic production regions and four tomato growing methods[6]. 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 1
Summary of top metropolitan statistical areas in the United States [7].

Rank	Metropolitan statistical area	2019 estimate	Shorthand name
1	New York-Newark-Jersey City	19,216,182	"New York City"
2	Los Angeles-Long Beach-Anaheim	13,214,799	"Los Angeles"
3	Chicago-Naperville-Elgin	9,458,539	"Chicago"
4	Dallas-Fort Worth-Arlington	7,573,136	"Dallas"
5	*Houston-The Woodlands-Sugar Land*	*7,066,141*	*"Houston"*
6	Washington-Arlington-Alexandria	6,280,487	"Washington DC"
7	Miami-Fort Lauderdale-West Palm Beach	6,166,488	"Miami"
8	Philadelphia-Camden-Wilmington	6,102,434	"Philadelphia"
9	Atlanta-Sandy Springs-Roswell	6,020,364	"Atlanta"
10	*Phoenix-Mesa-Scottsdale*	*4,948,203*	*"Phoenix"*
11	Boston-Cambridge-Newton	4,873,019	"Boston"
12	San Francisco-Oakland-Hayward	4,731,803	"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 84 million, representing roughly one quarter of the U.S. population in 2019.

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 4,680 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 (21 pounds) of fresh tomatoes and 30 kilograms (66 pounds) of processed tomatoes are consumed annually per person in the United States[8]. Second, tomatoes are grown using a variety of production methods, including indoor. In 2012, greenhouse tomatoes were a $400 million industry with over 1000 acres of greenhouse tomatoes in production[9]. Tomatoes account for more than half of all greenhouse production by area and nearly two-thirds of all greenhouse production by economic value[9]. 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 2019, ten states reported over 1000 acres harvested [9] .

Life-cycle assessments of tomatoes are numerous in the literature. Table 2 presents 47 cradle-to-farm gate life-cycle carbon footprints collected from 29 published journal articles. The values represent a variety of

growing practices and geographic regions. The data presented in Table 1 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 2.

Table 2
Summary of cradle-to-farm gate life-cycle carbon footprints from the literature.

Source	Value [$kgCO_2e/kg$]	Geographic scope	Description / Notes
Canaj et al., 2020[10]	0.028	Albania	Unheated greenhouse, plastics, soler energy
Zarei et al., 2019[11]	0.05	Iran	Open field
Zarei et al., 2019[11]	0.066	Iran	Heated greenhouse, natural gas heating
Ronga et al., 2019[12]	0.067	Italy	Open field, organic cropping system
Goldstein et al., 2016[13]	0.08	Northeast U.S.	Field-based, urban agriculture
Wang et al., 2020[14]	0.085	China	Unheated greenhouse, plastics
Andersson et al., 1998[15]	0.15	Mediterranean	Open field, used for production of ketchup
Martinez-Blanco et al., 2011[16]	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[17]	0.15	Spain	Unheated greenhouse, soil medium, no water recycling
Winans et al., 2020[18]	0.16	California, U.S.	Heated greenhouse
Martinez-Blanco et al., 2011[16]	0.16–0.29	Mediterranean	Open field (range based on variability in fertilizer use)
Jones et al., 2012[19]	0.19–0.27	Florida, U.S.	Open field (range based on variability in irrigation systems)
Roy et al., 2008[20]	0.19	Japan	Plastic cover
Roos and Karlsson, 2013[17]	0.21	Sweden	Hydroponic unheated greenhouse, uses recycling of drainage water
Maraseni et al., 2010[21]	0.22	Australia	Open field
Payen et al., 2015[22]	0.22	Morocco	Unheated plastic greenhouse, soil substrate

Source	Value [$kgCO_2e/kg$]	Geographic scope	Description / Notes
Sanye-Mengual et al., 2015[23]	0.22	Mediterranean	Rooftop greenhouse, uses residual heat and CO_2 from building, rainwater collection
Maham et al., 2020[24]	0.24	Canada	Heated greenhouse, organic fertilizer
Torrellas et al., 2012[25]	0.25	Spain	Multi-tunnel greenhouse, unheated, natural ventilation
Goldstein et al., 2016[13]	0.26	Northeast U.S.	Unconditioned green roof
Gonzalez et al., 2011[26]	0.28	United States	Open field
Roos and Karlsson, 2013[17]	0.28	Sweden	Hydroponic climate-controlled greenhouse, mainly non-fossil energy, recirculation of drainage water
Page et al., 2012[27]	0.3	Australia	Open field
Webb et al., 2013[28]	0.3	Spain	Open field
Bosona and Gebresenbet, 2018[29]	0.37	Sweden	Heated greenhouse, concrete, plastics, renewable energy
Gonzalez et al., 2011[26]	0.37	Spain	Open field
Del Borghi et al., 2014[30]	0.40–0.59	Italy	Open field, used for production pureed, chopped, and peeled tomatoes (range based on different tomato products)
Page et al., 2012[27]	0.43	Australia	Unheated greenhouse, open hydroponic system (i.e., no water recycling)
Chen et al., 2018[31]	0.43	China	Unheated greenhouse, organic fertilizer
Boulard et al., 2011[32]	0.51	France	Unheated greenhouse (20-y GWP)
Sanjuan-Delmás, et al., 2018[33]	0.56–1.4	Spain	Rooftop greenhouse, uses residual heat and CO2 from building, rainwater collection
Roy et al., 2008[20]	0.77	Japan	Heated greenhouse

Source	Value [$kgCO_2e/kg$]	Geographic scope	Description / Notes
Cellura et al., 2012[34]	0.82-1.0	Italy	Unheated greenhouse, pavilion style (range based on variability in yield)
Roos and Karlsson, 2013[17]	0.85	Netherlands	Hydroponic climate-controlled greenhouse, uses fossil fuels with CHP system, recirculation of drainage water
Maaoui et al., 2020[35]	0.95	Tunisia	Heated greenhouse, soilless, geothermal
De Marco et al., 2018[36]	1.4	Italy	Open field
Boulard et al., 2011[32]	1.6–2.4	France	Heated greenhouse, plastic, predominantly natural gas (20-y GWP, range based on geographic variability)
Goldstein et al., 2016[13]	1.6	Northeast U.S.	Conditioned greenhouse
Page et al., 2012[27]	1.7	Australia	Heated greenhouse, coal heating, open hydroponic system (no water recycling)
Boulard et al., 2011[32]	1.8–2.1	France	Heated greenhouse, glass, predominantly natural gas (20-y GWP, range based on geographic variability)
Page et al., 2012[27]	1.9	Australia	Conditioned greenhouse, coal and natural gas heating, closed hydroponic system (i.e., water is recycled)
Webb et al., 2013[28]	2.1	United Kingdom	Heated greenhouse, primarily natural gas
Goldstein et al., 2016[13]	2.2	Northeast U.S.	Conditioned rooftop greenhouse, rainwater capture, integrated with building energy system
Carlsson-Kanyama, 1998[37]	2.7	Sweden	Heated greenhouse, fuel oil (20-y GWP)
Gonzalez et al., 2011[26]	2.8	Holland	Heated greenhouse, natural gas heating
Gonzalez et al., 2011[26]	3.7	Sweden	Heated greenhouse, electricity and propane heating
Berners-Lee et al., 2012[38]	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[17] 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.[39], 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. The model was applied to ten of the largest metropolitan statistical areas in the United States to investigate the potential reduction of environmental impacts from food production and distribution.

Results

Under the current (i.e., baseline) scenario, supplying the ten metropolitan statistical areas with fresh tomatoes releases roughly 277,000 metric tons of CO_2e per year. Figure 1 was created by summing the environmental impact of fresh tomatoes across all ten destination cities. The optimization scenario saves roughly 35,000 $MTCO_2$e per year—a 13% 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 34%.

Figure 2 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 3 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 Philadelphia market remains low at 0.38 $kgCO_2$e per kg in the summer, but spikes to 0.86 $kgCO_2$e per kg—a double increase—during those periods when tomatoes are supplied by Mexican. This “spikiness” is characteristic of most of the ten destination cities.

Results for Philadelphia are displayed in Figs. 4–6 for illustrative purposes. Complete results for the remaining nine cities are included in the Supporting Data (S6-S8). As an example, Fig. 4 shows the average life-cycle GHG emissions for fresh tomatoes sourced from nine production origins for Philadelphia. Production

locations and practices make the decisive difference. The emissions for tomatoes grown in greenhouses or controlled environment are higher than for open-field tomatoes. Transportation distances make some difference. The results for the remaining nine metropolitan statistical areas are shown in the Supporting Data (S6).

The top panel of Fig. 5 shows Philadelphia's current (i.e., baseline) tomato supply on a weekly basis. As illustrated by the figure, Philadelphia currently receives tomato shipments from seven out of the nine major production origins. Under an optimized scenario (bottom panel), Philadelphia's tomato supply would shift to less diverse production regions that the supply of one region dominates the total supply each week. In addition, the optimized scenario suggests that Philadelphia should receive a larger proportion of its tomatoes from nearby regions (e.g., Florida, South Carolina, Virginia) and a lesser proportion from distant regions (e.g., California, Mexico). These general conclusions are consistent across all ten destination cities.

The top panel of Fig. 6 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 Fig. 2, the carbon footprint of Philadelphia tomatoes is surprisingly consistent, remaining around 0.73 kgCO_2e per kg throughout the year. Under the optimized scenario (bottom panel), the carbon footprint drops to roughly 0.60 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 the Discussion and Conclusions section.

Discussion

Out of ten major metropolitan statistical areas in the United States, Dallas proves to have the lowest-impact tomatoes—0.61 kgCO_2e per kg on average—due to its relatively close proximity to Mexican production. Boston has the highest impact at 0.87 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 2.3 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 0.72, 0.72, 0.75, and 0.77 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 34% and overall cradle-to-market life-cycle GHG emissions by 13%. 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, 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.

The tomato distribution systems generated by our model might be also optimized for cost. Comparing with the cost data of tomato shipments from the USDA AMS database[40], the environmental impacts share similar trends with the costs of tomatoes: (1) The environmental impacts and costs of tomatoes from protected environment production are higher than those from open-field cultivation. (2) The GHG emissions and costs of tomatoes with longer transportation distances are higher than those with shorter distances (e.g., the cost of California tomatoes is higher if shipped to Boston than to San Francisco).

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 Philadelphia, this variability is as much as a factor of two. 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.

The uncertainty analysis showed that the environmental impacts of protected-environment systems have larger variation than the open-field cultivation system due to geographic conditions and production techniques. As demonstrated by the literature review in Table 1, there is significant variability within these sub-classifications of protected cultivation. 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. Another suggestion from the uncertainty analysis is to improve the results by high-resolution transportation data. Since the USDA movement reports used in the model 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.

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 footprint of agricultural commodities, and would lay the groundwork for optimal decision-making at the nexus of food, energy, and water.

Methods

The objective of the 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. Since we find no support for a difference between the quality of tomatoes from open-field and protected cultivation, we assume that tomatoes grown under field and protected conditions are interchangeable in the market. The problem formulation is as follows:

$$\min_{x_{ijk}} \sum_{i=1}^{9} \sum_{j=1}^{10} \sum_{k=1}^{52} c_{ij} x_{ijk}$$

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

ii. $\sum_{i=1}^{9} x_{ijk} \geq d_{jk} \quad \forall \quad j, k$ tomato demand must be met for each city in each week

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

The United States primarily relies on 9 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, Florida, and Mexico have protected production. Mexico’s protected tomato production can be further subdivided into adapted environment and controlled environment. Table 3 summarizes the various classifications of protected agriculture used in this analysis.

Table 3
Classification of protected tomato production.

Adapted environment (AE)	Includes such strategies as mulching, row covers, high tunnel, and shade cloth [41]
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 [41]
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 [42]

The environmental cost matrix consisting of 90 origin/destination pairs was computed (Table 4). Following the method of Bell and Horvath (2020), the environmental cost matrix includes GHG emissions associated with the production, post-harvest processing, packaging, and transportation stages. The emissions from the production stage include the life-cycle emissions associated with the uses of electricity, direct fuel, fertilize, various materials, pesticides, and water. The processing stage includes electricity use for short-term cold storage. The packaging stage covers the emissions from the manufacturing of cardboard for packaging tomatoes. The emissions from the transportation stage are the life-cycle emissions from shipping tomatoes by truck. The transportation distances were determined by Google Maps. The detailed method and data sources can be found in the Supporting Data (S1-S4). 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 4
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	0.73	0.37	0.62	0.55	0.71	0.74	0.72	0.66	0.75	0.34
	California_GH	2.18	1.82	2.08	2.01	2.17	2.19	2.18	2.11	2.21	1.80
	Florida	0.53	0.72	0.53	0.52	0.49	0.38	0.51	0.43	0.55	0.76
	Florida_GH	1.96	2.15	1.97	1.96	1.93	1.81	1.94	1.87	1.99	2.20
	Mexico	0.74	0.62	0.66	0.53	0.71	0.68	0.73	0.62	0.77	0.67
	Mexico_AE	0.86	0.73	0.77	0.64	0.82	0.79	0.84	0.74	0.88	0.78
	Mexico_CE	2.29	2.16	2.20	2.07	2.25	2.22	2.27	2.17	2.31	2.21
	South Carolina	0.51	0.75	0.53	0.55	0.48	0.49	0.50	0.45	0.54	0.79
	Virginia	0.39	0.71	0.46	0.53	0.36	0.48	0.38	0.42	0.42	0.75

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[40]. These national-level data were scaled down proportionally to account for the fact that the ten metropolitan statistical areas comprise only 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 in 2019[7,8].

Uncertainty assessment

Monte Carlo simulation was performed to assess the uncertainties in the data. The sources of uncertainty included electricity use for storage, material use for packaging, transportation distance, and emission factors of production practices, electricy, fuels, packaging materials, and transportation. Most of the ranges of the parameters were based on existing literature. The probability distribution functions of the parameters are provided in the Supplementary Data (S5). We ran 10,000 iterations for each city, and the error bars show 90% uncertainty intervals of simulated results.

Declarations

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Figures

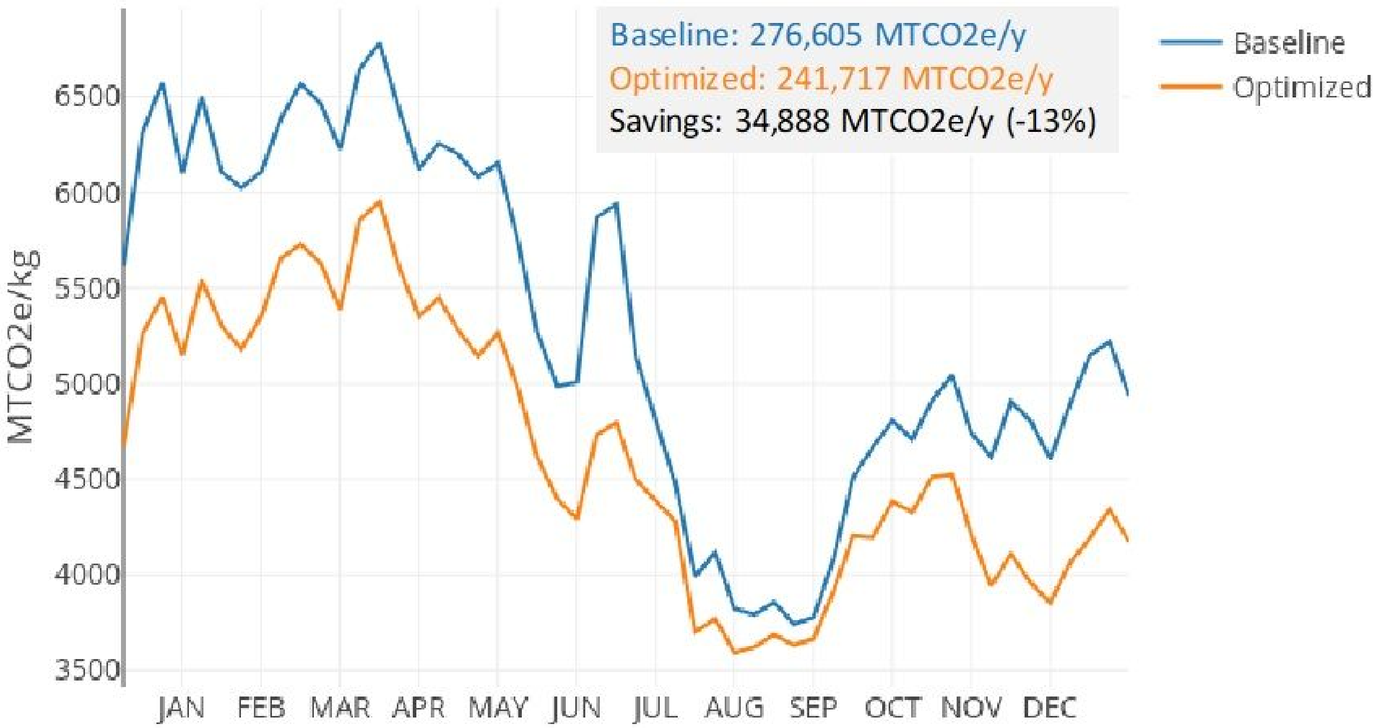

Figure 1

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

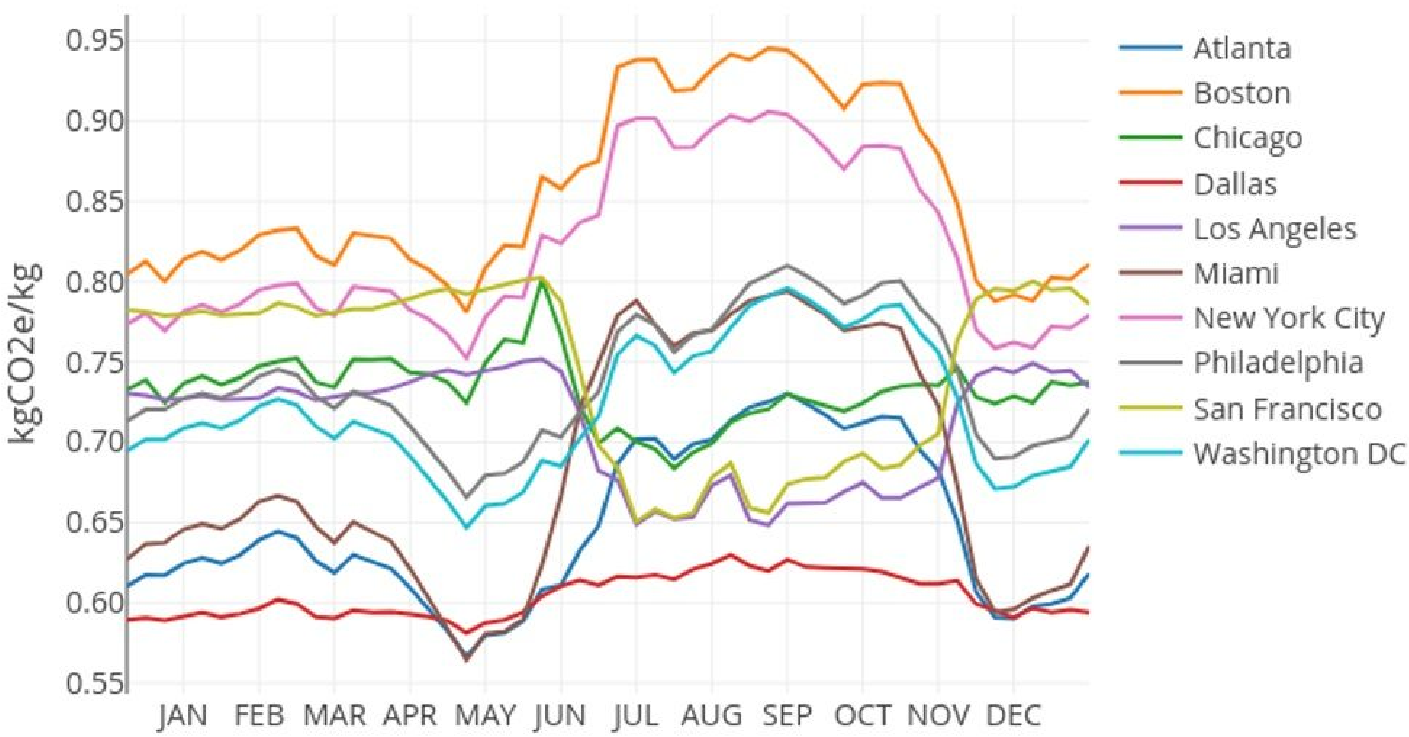

Figure 2

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

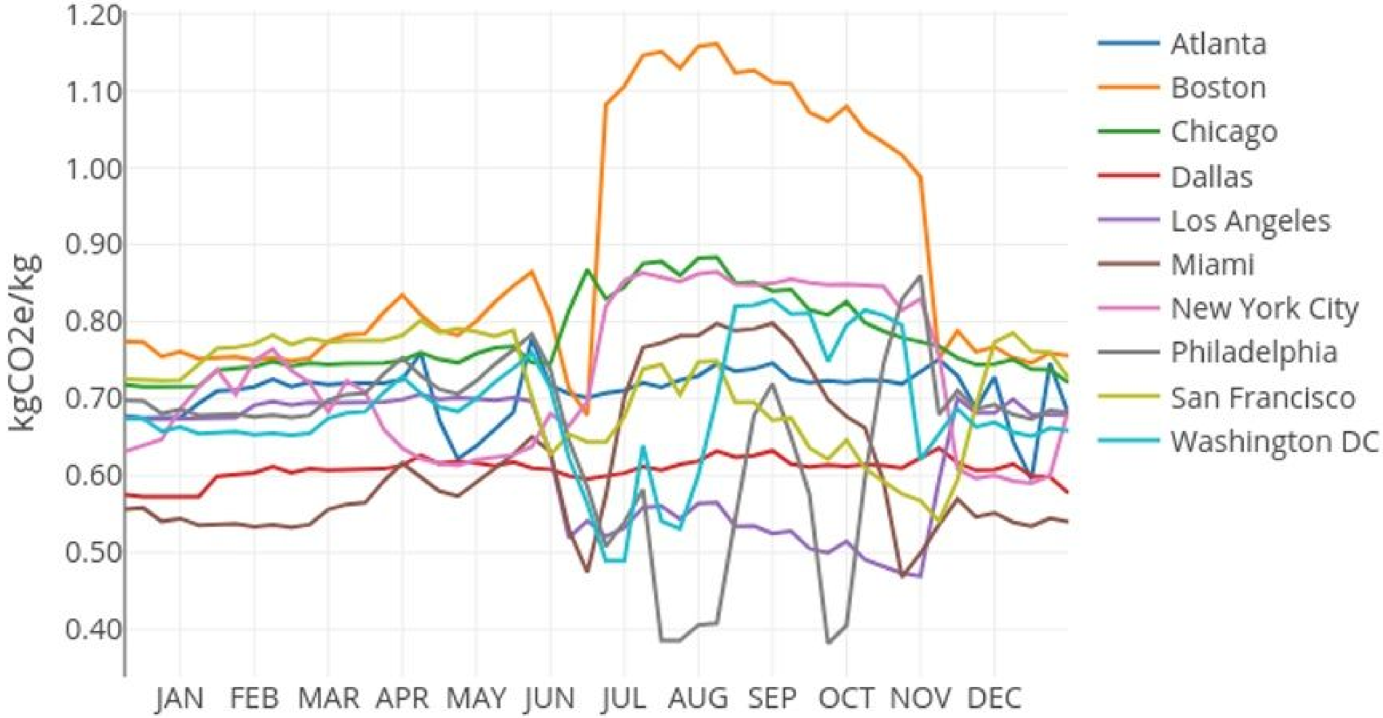

Figure 3

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

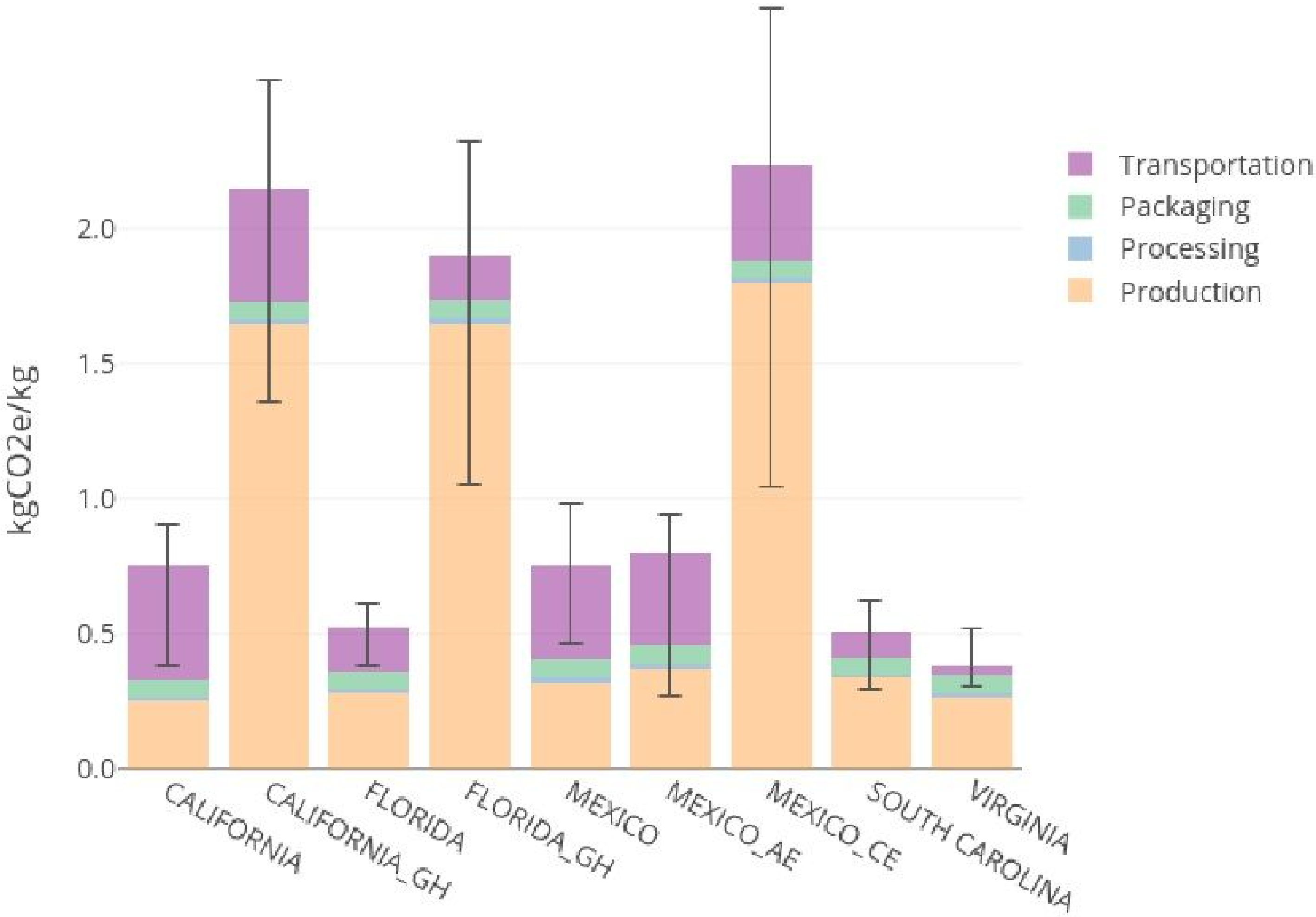

Figure 4

Cradle-to-market life-cycle GHG emissions for Philadelphia's fresh tomato supply. Errors bars represent 90% uncertainty ranges obtained from Monte Carlo simulations. Key: AE = adapted environment, CE = controlled environment, GH = greenhouse

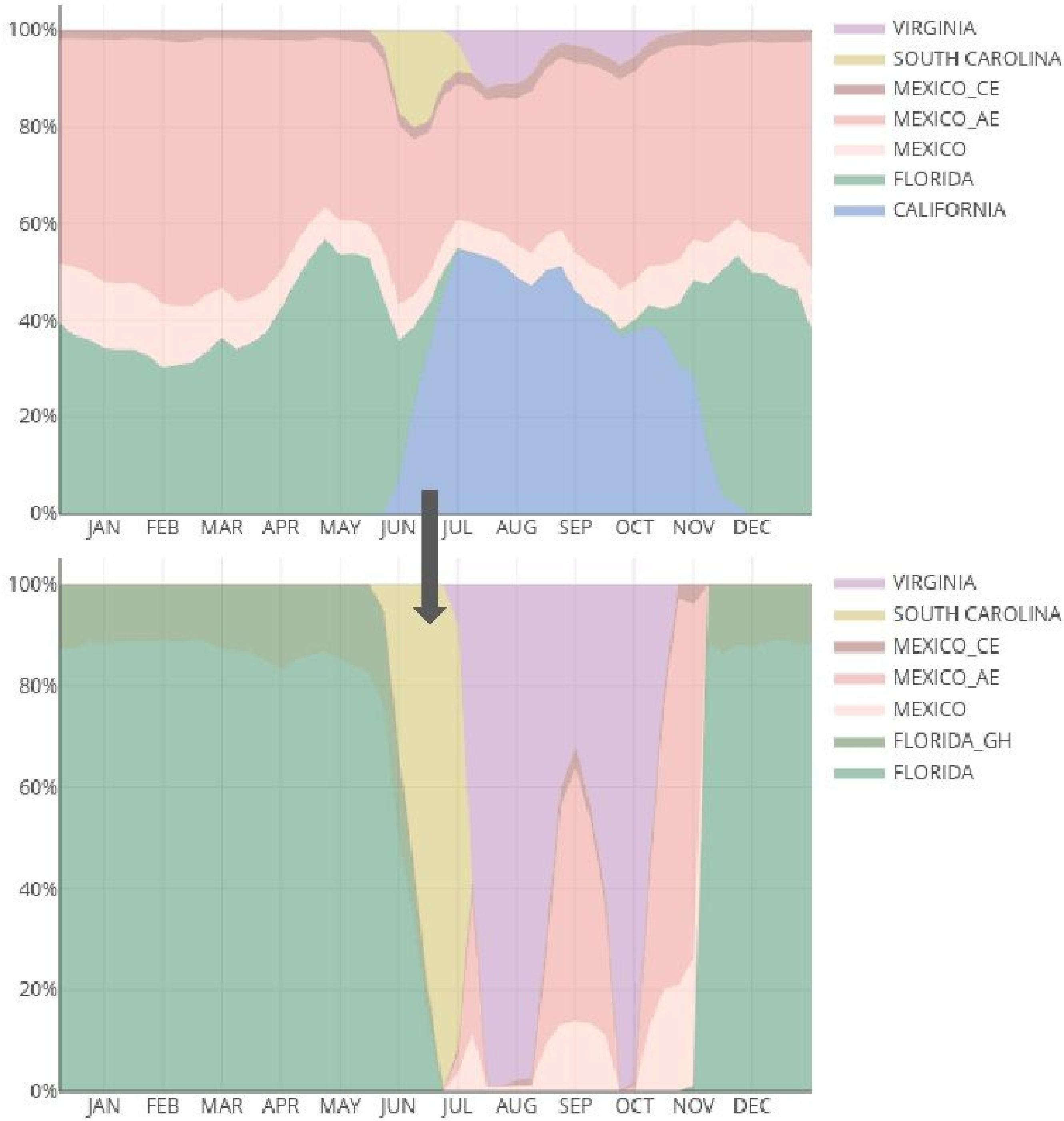

Figure 5

Tomato supply portfolio for Philadelphia market under baseline (top) and optimized scenario (bottom) Key: AE = adapted environment, CE = controlled environment, GH = greenhouse

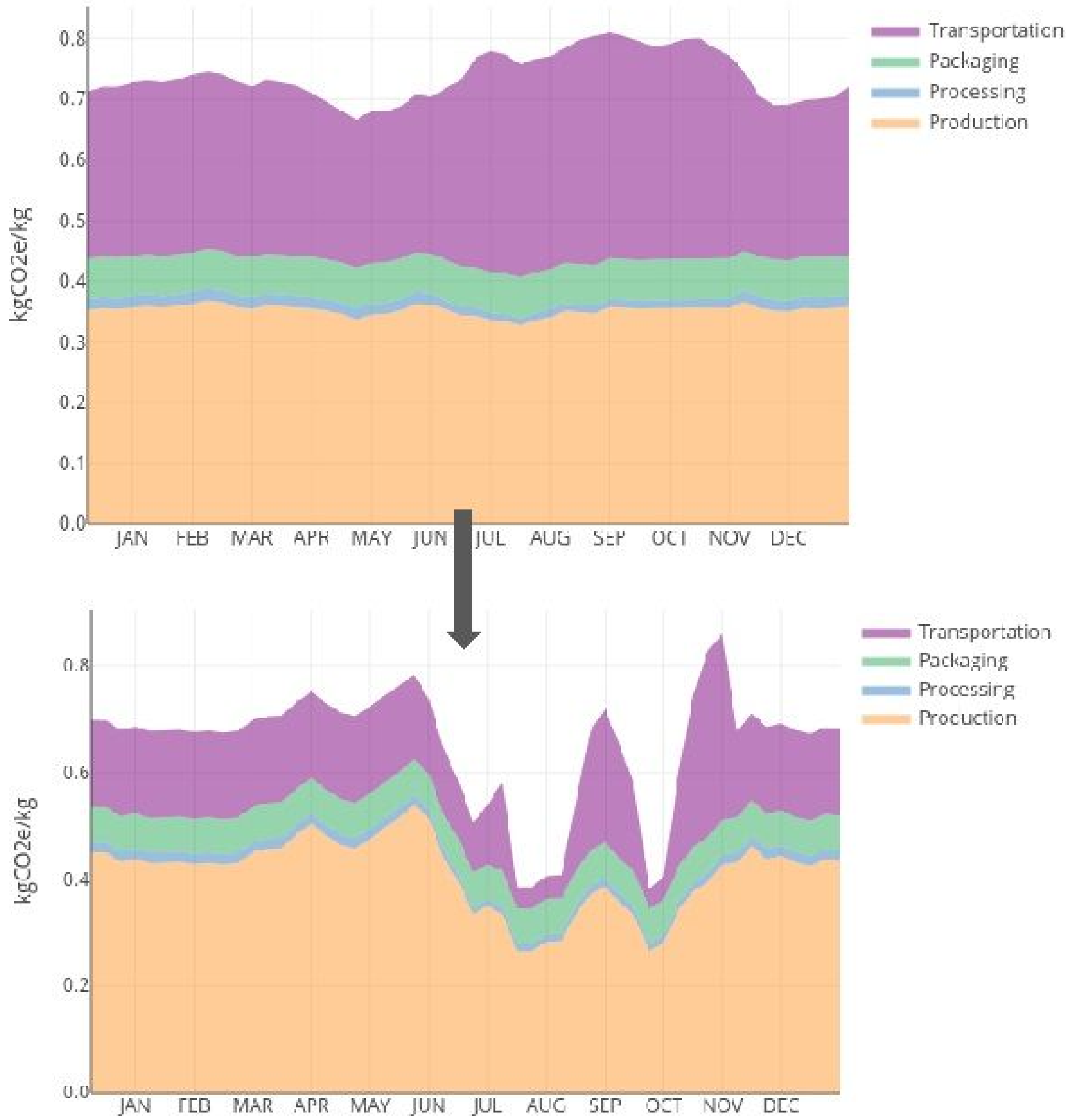

Figure 6

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

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