Resources, Conservation & Recycling 188 (2023) 106660

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Optimal allocation of tomato supply to minimize greenhouse gas emissions in major U.S. metropolitan markets

Eric Bell, Yuwei Qin *, Arpad Horvath

Department of Civil and Environmental Engineering, University of California, Berkeley, United States

ARTICLE INFO

Keywords:
Food
Fruit
Fresh
Urban
Consumption
Agriculture
Transportation

ABSTRACT

Our food system is very resource and emissions intensive and contributes to a broad range of environmental impacts. We have developed cradle-to-market greenhouse gas emissions estimates of supplying fresh tomatoes to 10 of the largest metropolitan areas in the United States and applied a linear optimization algorithm to determine the optimal tomato distribution scheme that will minimize tomato-related greenhouse gas emissions across all 10 areas. Monte Carlo simulation was performed to assess the uncertainties in the data. Results indicate that the current tomato distribution scheme is suboptimal. Reallocation of the fresh tomato supply across the 10 areas could decrease transportation-related emissions by 34% and overall tomato-related greenhouse gas emissions by 13%—from 277,000 metric tons of CO_2e to 242,000 metric tons of CO_2e. Production practices and geographic conditions (such as soil and climate) are more significant for GHG emissions than the supply allocation or the seasonality of supply.

1. Introduction

Our food system places high demands on natural resource use and emissions, being responsible, for example, for the emissions of approximately 2.6 metric tons of CO_2e (tonCO_2e) per person per year, or 8.4 kg CO_2e per person per day (Weber and Matthews, 2008) in the United States, or roughly 10% of overall greenhouse gas (GHG) emissions (Weber and Matthews, 2008, US EPA. Inventory of U.S 2016). It demands 140 MJ of energy per person per day—four times the global average—and 1,200 liters (330 gallons) of water per person per day (Canning, 2010, UNESCO 2014), accounting for approximately 14% of national energy consumption and half of water withdrawals.

As the global population continues to grow and the middle class expands, demand for food, and different kinds of food—in particular, high-value products such as vegetables, fruits, and meat—will increase. The United Nations estimates that global food production must increase by 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 the agricultural systems at regional, national, and global levels. (Bell and Horvath, 2020, Dorr et al., 2021)

In this study, we build a linear optimization model to estimate the cradle-to-market GHG emissions associated with fresh tomatoes supplied to 10 of the 12 most populous metropolitan areas in the United States (Table 1) based on 6 unique geographic production regions and four tomato growing practices (United States Census Bureau 2016). (The U.S. Department of Agriculture's Agricultural Marketing Service has not compiled data for Houston and Phoenix.) The 10 metropolitan statistical areas account for roughly one quarter of the U.S. population and 26% of tomato consumption.

Tomatoes were chosen as the focus of this study for a few 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 (USDA 2020). Second, tomatoes are grown using a variety of production methods, including indoors. In 2012, greenhouse tomatoes were a $400 million industry with over 1,000 acres of greenhouse tomatoes under production (USDA 2020). Tomatoes account for more than half of all greenhouse production of fruits and vegetables by area and nearly two-thirds of all greenhouse production by economic value (USDA 2020). Although indoor tomato production often requires more energy relative to conventional production, transportation distances to the consumer are typically shorter. Third, tomato production in the United States is diffuse; in 2019, 10 states reported over 1000 acres harvested (USDA 2020) .

* Corresponding author.
E-mail address: rainsmile333@gmail.com (Y. Qin).

https://doi.org/10.1016/j.resconrec.2022.106660
Received 26 February 2022; Received in revised form 25 July 2022; Accepted 9 September 2022
Available online 20 September 2022

Table 1
Top 12 metropolitan statistical areas in the United States (US Census Bureau 2020).

Rank	Metropolitan statistical area	2019 Population	Shorthand name	Abbreviation
1	New York-Newark-Jersey City	19,216,182	"New York City"	NY
2	Los Angeles-Long Beach-Anaheim	13,214,799	"Los Angeles"	LA
3	Chicago-Naperville-Elgin	9,458,539	"Chicago"	CH
4	Dallas-Fort Worth-Arlington	7,573,136	"Dallas"	DA
5	*Houston-The Woodlands-Sugar Land*	*7,066,141*	*"Houston"*	*HO*
6	Washington-Arlington-Alexandria	6,280,487	"Washington DC"	DC
7	Miami-Fort Lauderdale-West Palm Beach	6,166,488	"Miami"	MI
8	Philadelphia-Camden-Wilmington	6,102,434	"Philadelphia"	PH
9	Atlanta-Sandy Springs-Roswell	6,020,364	"Atlanta"	AT
10	*Phoenix-Mesa-Scottsdale*	*4,948,203*	*"Phoenix"*	*PO*
11	Boston-Cambridge-Newton	4,873,019	"Boston"	BO
12	San Francisco-Oakland-Hayward	4,731,803	"San Francisco"	SF

Notes: Italicised rows indicate metropolitan statistical areas that were excluded from the analysis due to lack of data. The total population for all 10 areas included in the analysis comes to 84 million, representing roughly one quarter of the U.S. population in 2019.

2. Background

Environmental assessments of tomatoes are numerous in the literature, but not for the United States. Table 2 presents 48 cradle-to-farm-gate GHG intensity values collected from 30 peer-reviewed journal articles. The values represent a variety of growing practices and geographic regions, but only four were calculated for a United States region. The data in Table 2 reflect only the farm 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.)

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. Only two consider some impacts of seasonality and logistics. Roos and Karlsson (Roos and Karlsson, 2013) found that the carbon footprint of Swedish tomato consumption was strongly impacted by seasonality since out-of-season tomatoes travel great distances or are produced in heated greenhouses. Kulak et al. (Kulak et al., 2013) estimated the GHG emissions of fresh produce sourced from an urban community farm in a London borough in contrast to conventional, open-field farming. They used linear optimization to determine the optimal community farm design to maximize environmental savings.

3. Methods

We calculate the GHG emissions associated with fresh tomatoes supplied to each of the metropolitan areas during each week of a year. Next, we implement a linear optimization algorithm to compute the optimal tomato distribution scheme for the 10 metropolitan areas that minimizes total GHG emissions. Last, we comment on whether the

Table 2
Summary of cradle-to-farm gate GHG intensities (to two significant digits) from the literature, grouped by production method and sorted by year and increasing value.

Source	Value [kgCO_2e/kg]	Geographic scope	Description / Characteristics of case studies
Andersson et al., 1998	0.15	Mediterranean	Open field, used for production of ketchup
Maraseni et al., 2010	0.22	Australia	Open field
Martínez-Blanco et al., 2011	0.16-0.29	Mediterranean	Open field (range based on variability in fertilizer use)
González et al., 2011	0.28	United States	Open field
González et al., 2011	0.37	Spain	Open field
Jones et al., 2012	0.19-0.27	Florida, U.S.	Open field (range based on variability in irrigation systems)
Page et al., 2012	0.3	Australia	Open field
Webb et al., 2013	0.3	Spain	Open field
Del Borghi et al., 2014	0.40-0.59	Italy	Open field, used for production of pureed, chopped, and peeled tomatoes (range based on different tomato products)
Goldstein et al., 2016	0.08	Northeast U.S.	Open field, urban agriculture
De Marco et al., 2018	1.4	Italy	Open field
Zarei et al., 2019	0.05	Iran	Open field
Ronga et al., 2019	0.067	Italy	Open field, organic cropping system
Roy et al., 2008	0.19	Japan	Unheated greenhouse, plastic
Martínez-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)
Boulard et al., 2011	0.51	France	Unheated greenhouse (20-yr GWP calculation)
Torrellas et al., 2012	0.25	Spain	Unheated multi-tunnel greenhouse, natural ventilation
Page et al., 2012	0.43	Australia	Unheated greenhouse, open hydroponic system (i.e., no water recycling)
Cellura et al., 2012	0.82-1.0	Italy	Unheated greenhouse, pavilion style (range based on variability in yield)
Roos and Karlsson, 2013	0.15	Spain	Unheated greenhouse, soil medium, no water recycling
Roos and Karlsson, 2013	0.21	Sweden	Unheated greenhouse, hydroponic, recycles drainage water
Payen et al., 2015	0.22	Morocco	Unheated greenhouse, plastic, soil substrate
Goldstein et al., 2016	0.26	Northeast U.S.	Unconditioned green roof
Chen et al., 2018	0.43	China	Unheated greenhouse, organic fertilizer
Canaj et al., 2020	0.028	Albania	Unheated greenhouse, plastic
Wang et al., 2020	0.085	China	Unheated greenhouse, plastic
Carlsson-Kanyama, 1998	2.7	Sweden	Heated greenhouse, fuel oil (20-y GWP)
Roy et al., 2008	0.77	Japan	Heated greenhouse
Boulard et al., 2011	1.6-2.4	France	Heated greenhouse, plastic, predominantly natural gas (20-y GWP, range based on geographic variability)
González et al., 2011	2.8	Holland	Heated greenhouse, natural gas heating

(continued on next page)

Table 2 (*continued*)

Source	Value [kgCO_2e/kg]	Geographic scope	Description / Characteristics of case studies
González et al., 2011	3.7	Sweden	Heated greenhouse, electricity and propane heating
Page et al., 2012	1.7	Australia	Heated greenhouse, coal heating, open hydroponic system (no water recycling)
Page et al., 2012	1.9	Australia	Conditioned greenhouse, coal and natural gas heating, closed hydroponic system (i.e., water is recycled)
Berners-Lee et al., 2012	5.6	United Kingdom	Heated greenhouse
Roos and Karlsson, 2013	0.28	Sweden	Climate-controlled greenhouse, hydroponic, mainly non-fossil energy, recirculation of drainage water
Roos and Karlsson, 2013	0.85	Netherlands	Hydroponic climate-controlled greenhouse, uses fossil fuels with CHP system, recirculation of drainage water
Webb et al., 2013	2.1	United Kingdom	Heated greenhouse, primarily natural gas
Sanyé-Mengual et al., 2015	0.22	Mediterranean	Rooftop greenhouse, uses residual heat and CO_2 from building, rainwater collection
Goldstein et al., 2016	1.6	Northeast U.S.	Conditioned greenhouse
Goldstein et al., 2016	2.2	Northeast U.S.	Conditioned rooftop greenhouse, rainwater capture, integrated with building energy system
Bosona and Gebresenbet, 2018	0.37	Sweden	Heated greenhouse, concrete and plastic, renewable energy
Sanjuan-Delmás et al., 2018	0.56-1.4	Spain	Rooftop greenhouse, uses residual heat and CO_2 from building, rainwater collection
Zarei et al., 2019	0.066	Iran	Heated greenhouse, natural gas heating
Hollingsworth et al., 2020	3.7	Arizona, U.S.	Heated greenhouse, electricity heating
Winans et al., 2020	0.16	California, U.S.	Heated greenhouse
Maham et al., 2020	0.24	Canada	Heated greenhouse, organic fertilizer
Maaoui et al., 2020	0.95	Tunisia	Heated greenhouse, soilless, geothermal

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.

Our cradle-to-market study is unique in that it estimates GHG emissions associated with tomato consumption for several growing regions and practices. It is also the first study of its kind to compute the optimal supply portfolio of a staple fresh food at a subnational level, in top metropolitan areas of the United States, in order to investigate the potential for reductions of GHG emissions from farm production and fresh-food distribution.

The objective of the linear optimization is to develop a mathematical model to minimize the total annual climate change impact 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 differentiating 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 model was developed based on data of production, supply, and demand in 2019. We performed the optimization model in Python. 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} = *climate change impact 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 impact function is subject to the following three constraints:

i $x_{ijk} \geq 0 \quad \forall \ i, j, k$ supply cannot be negative
ii $\sum_{i=1}^{9} x_{ijk} \ \geq d_{jk} \ \forall \ j, k$ 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 9 production pathways to supply the majority of our fresh tomatoes (representing 92% of total tomato supply in the United States). 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.

The environmental impact matrix consisting of 90 origin/destination pairs was computed (Table 4). Following the method of Bell and Horvath (Bell and Horvath, 2020), the environmental impact 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, fertilizer, various consumable 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 environmental impact matrix (c_{ij}) represents the cradle-to-market life-cycle carbon footprint between the production origin and the destination city (i.e., the environmental

Table 3
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 (U.S. Department of Commerce 2008)

Table 4
Environmental impact 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

impact 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).

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 2020). These national-level data were scaled down proportionally to account for the fact that the 10 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 (US Census Bureau 2020, USDA 2020).

Detailed supply portfolios under the baseline and the optimized scenarios for the 10 metropolitan areas can be found in the Supplementary Material (section S7).

3.1. 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, electricity, fuels, packaging materials, and transportation. Most of the ranges of the parameters were based on the existing literature. The probability distribution functions of the parameters are provided in the Supplementary Material (section S5). We ran 10,000 iterations for each city, and the error bars show 90% uncertainty intervals of simulated results.

4. Results

Under the current (i.e., baseline) scenario, supplying the 10 metropolitan areas with fresh tomatoes releases roughly 277,000 $tonCO_2e$ per year. Fig. 1 was created by summing the environmental impact of fresh tomatoes across all 10 destination cities. Optimization can save roughly 35,000 $tonCO_2e$ per year—a 13% improvement. Our model assumes fixed supply and demand, thus the only opportunity for improvement is in reducing transportation-related emissions by varying the supply portfolios of the 10 destination cities. By our calculations, transportation represents 33% of the total environmental impact of fresh tomatoes delivered to these 10 areas. This limits the potential for improvement. However, optimization can reduce transportation-related emissions by 34%.

Fig. 2 plots the GHG emissions associated with fresh tomatoes delivered to market in the 10 metropolitan areas in the current (baseline) scenario. The environmental impact can vary a little to quite a lot throughout the year and city by city, e.g., approximately one-third to one-half higher in the worst-performing city (Boston, followed closely by New York City) than in the best-performing city (Dallas). Boston's (and New York's) imports are mostly fairly GHG-intensive, adapted-environment tomatoes from far-away Mexico and less-GHG-intensive, open-field tomatoes from closer-in Florida outside of the summer months (Figure S11 in the Supporting Material), and in this Boston (and New York City) does not differ much in environmental impact from several other cities. However, in summertime, the Floridian open-field tomatoes get replaced by far-away Californian open-field tomatoes (overall more GHG intensive than Floridian tomatoes because of the transportation distance) and, significantly, by very GHG-intensive Californian greenhouse-grown tomatoes, boosting the carbon footprint

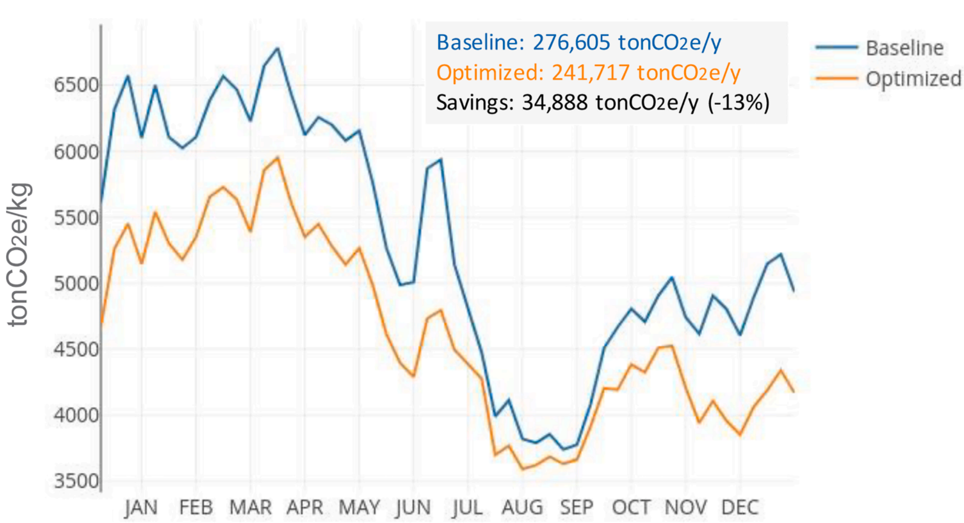

Fig. 1. Greenhouse gas intensity of fresh tomato supply to 10 major U.S. metropolitan areas (baseline vs. optimized scenario).

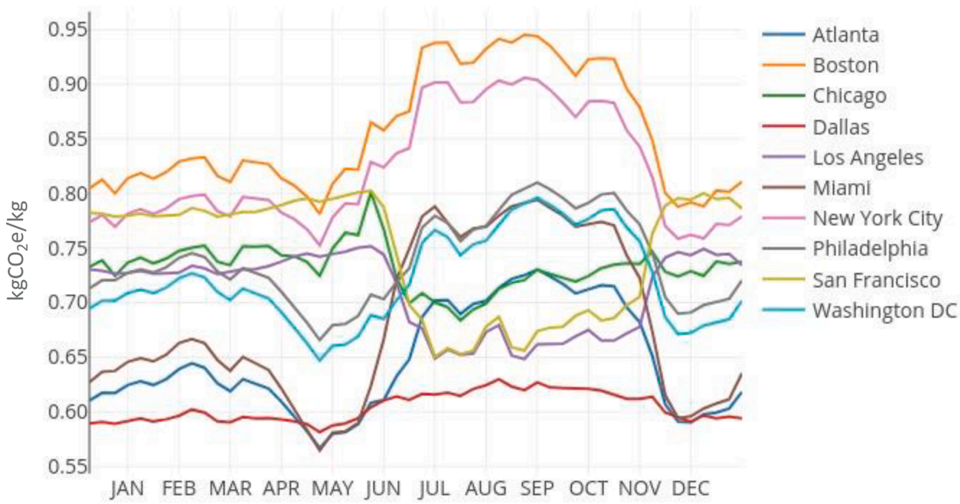

Fig. 2. Greenhouse gas intensity of fresh tomatoes delivered to market in 10 U.S. metropolitan areas (baseline).

of both metropolitan areas far above the other 8. Incidentally, this same occurrence, i.e., that Californian tomatoes become abundantly available in the summer, works very well in favor of Los Angeles and San Francisco: transportation distances drop, and the GHG intensity of fresh tomatoes decreases. Dallas is in its own category and exhibits the lowest overall carbon footprint without noticeable variability throughout the year, primarily due to its proximity to Mexico's abundant supply throughout the year and no noticeable differences in GHG intensities of tomato supply.

There are several cities in the middle of the pack for which the supply portfolio may change throughout the year, but without much change in the GHG intensity of consumed fresh tomatoes.

The results can be roughly grouped by geography. The northeastern (Boston, New York City, Philadelphia, and Washington, DC), the southeastern (Atlanta, Miami), and the western cities (Los Angeles, San Francisco) all share similar seasonal GHG emissions profiles.

Fig. 3 plots the GHG emissions associated with fresh tomatoes delivered to market in the 10 metropolitan areas under the optimized scenario. The optimized results exhibit much less order and uniformity. While most cities display a lower overall environmental impact, fluctuations are frequent and significant. For example, the environmental impact per kg of fresh tomatoes delivered to the Philadelphia market remains low at 0.38 $kgCO_2e$ in the summer, but spikes to 0.86 $kgCO_2e$ during the months when tomatoes are supplied by Mexican agriculture. This "spikiness" is characteristic of most of the 10 markets. Tomatoes in Boston are still the most GHG intensive of all 10 cities in the summer and optimization could not change that, but New York City's GHG intensity (previously second highest) drops somewhat. The GHG intensity of tomatoes supplied to Dallas are still about the same throughout the year, but optimization could not lower it because most of the supply comes from the nearby Mexican fields under both scenarios. Philadelphia and Los Angeles now get lower-GHG-intensive tomatoes than Dallas in the summer (LA because local tomato season kicks in, Philadelphia for the reasons discussed in detail below), displaying the positive effect of optimization.

Complete results for Philadelphia (middle of the pack in Figs. 2 and 3) are displayed in Figs. 4 to 6 for illustrative purposes. Complete results for the remaining 9 metropolitan areas are included in the Supplementary Material (sections S6-S8, Figures S1-S27). Figure 4 shows the average GHG emissions for fresh tomatoes sourced from 9 growing regions and practices. For the 10 cities, growing locations and practices make the decisive differences. The emissions for tomatoes grown in greenhouses or controlled environment are higher than for open-field tomatoes. Transportation distances make some difference.

The top panel of Fig. 5 shows Philadelphia's current (baseline) tomato supply breakdown on a weekly basis. As illustrated by the figure, Philadelphia currently receives tomato shipments from 7 out of 9 major growing regions and practices. Under the optimized scenario (bottom

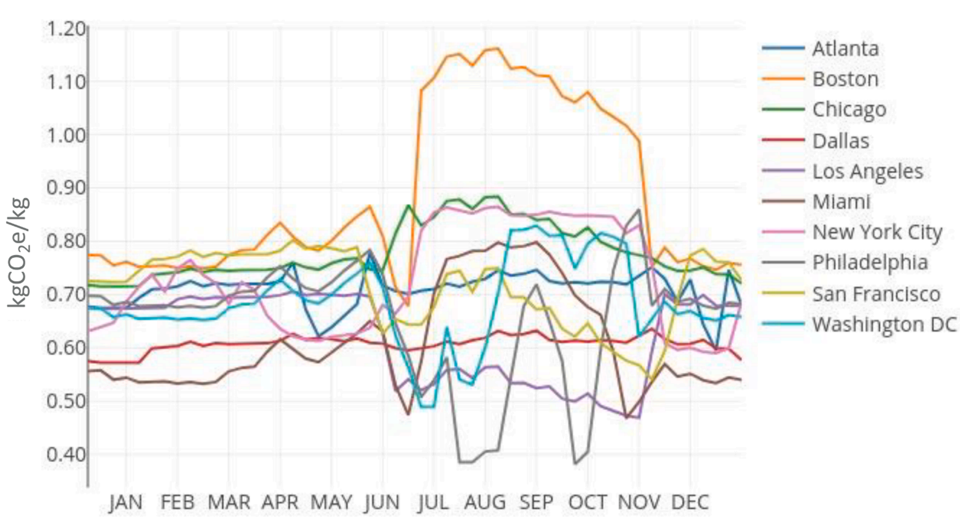

Fig. 3. Greenhouse gas intensity of fresh tomatoes delivered to market in 10 U.S. metropolitan areas (optimized scenario).

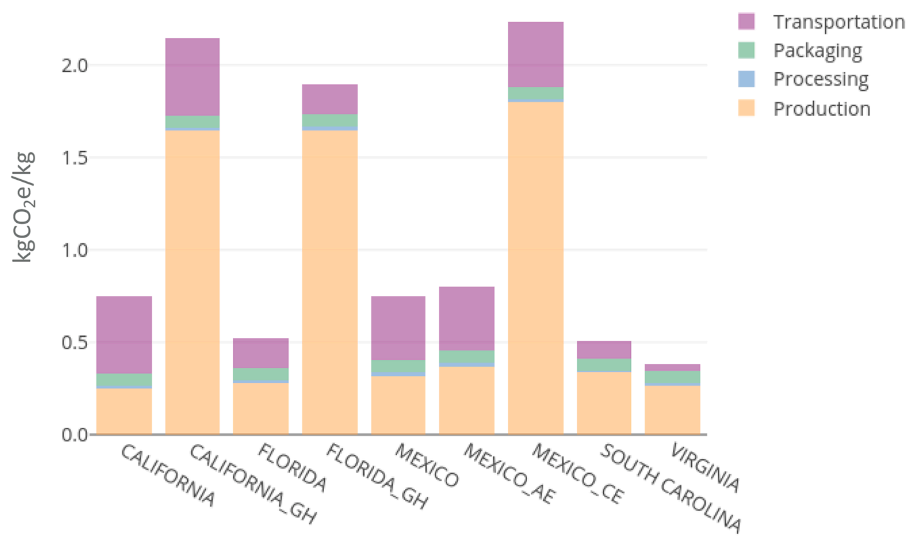

Fig. 4. Cradle-to-market GHG emissions for Philadelphia's fresh tomato supply. Errors bars represent 90% uncertainty ranges obtained from Monte Carlo simulations.
Key: AE = adapted environment, CE = controlled environment, GH = greenhouse

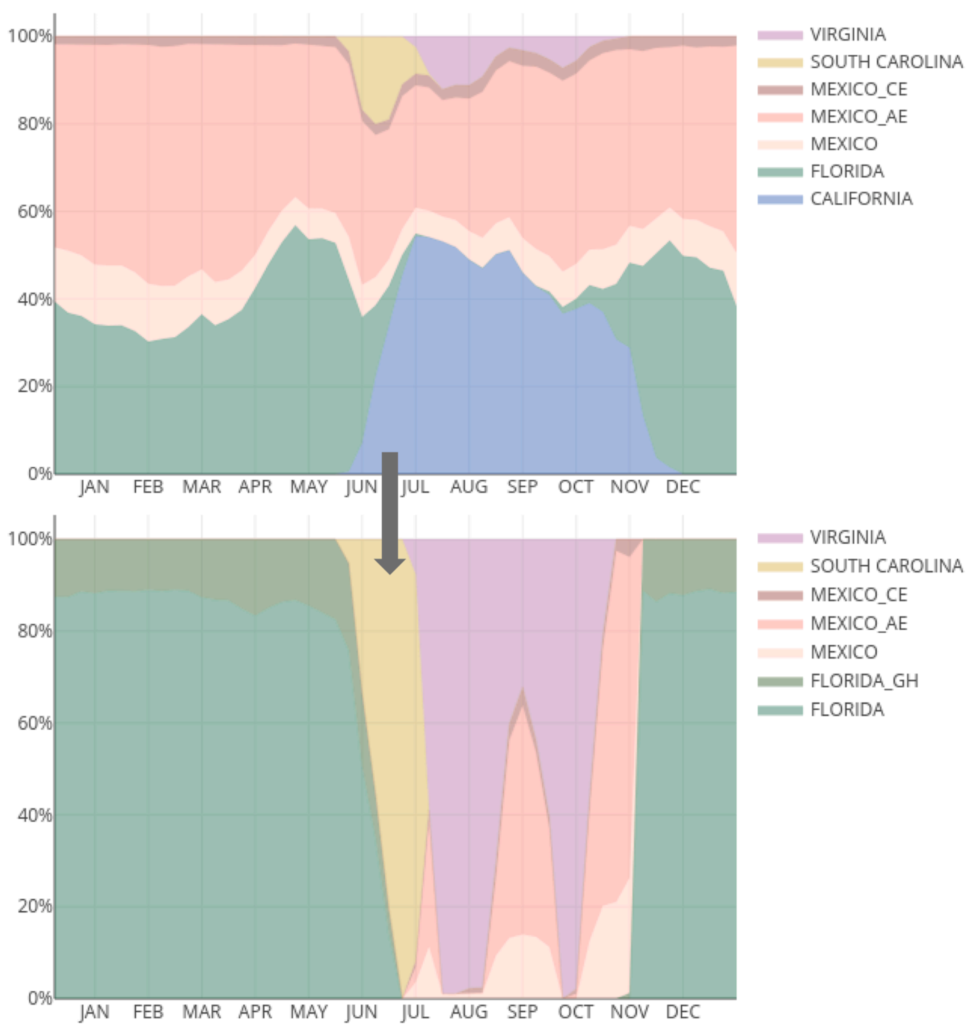

Fig. 5. Tomato supply portfolio of the Philadelphia market under the baseline (top) and the optimized scenario (bottom).
Key: AE = adapted environment, CE = controlled environment, GH = greenhouse

panel), the majority of Philadelphia's tomato supply would shift to one region dominating the supply each week. It would be receiving a larger proportion of tomatoes from nearby regions (Florida, South Carolina, Virginia) than from distant regions (California and Mexico). These general conclusions are consistent across all 10 metropolitan areas.

The top panel of Fig. 6 illustrates the current cradle-to-market GHG emissions profile of Philadelphia's tomato supply on a weekly basis. Considering the temporal variation in tomato supply shown in the top panel of Fig. 2, the emissions profile is surprisingly consistent, remaining around 0.73 $kgCO_2e$ per kg throughout the year. Under the optimized scenario (bottom panel), the GHG emissions drop to roughly 0.60 $kgCO_2e$ per kg for the majority of the year. However, the GHG footprint under the optimized scenario experiences distinct spikes in July, September, and November. These spikes can be attributed to an increase in shipments of Mexican tomatoes during these months. Once again, these conclusions are consistent across all 10 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 below.

5. Discussion

Out of 10 major metropolitan statistical areas in the United States, Dallas has the lowest-impact tomatoes—0.61 $kgCO_2e$ per kg on average—due to its relatively close proximity to Mexican agriculture. Boston has the highest impact at 0.87 $kgCO_2e$ per kg on average, an increase of roughly 40%. More significant is the tomato production origin: open-field tomatoes supplied to Philadelphia from Virginia were found to have emissions of 0.38 $kgCO_2e$ per kg, whereas controlled-environment tomatoes supplied to Philadelphia from Mexico were associated with 2.3 $kgCO_2e$ per kg, a sixfold difference. The impact of seasonality was minimal; winter, spring, summer, and fall tomatoes for the Philadelphia market were found to have emissions of 0.72, 0.72, 0.75, and 0.77 $kgCO_2e$ per kg, respectively. However, other seasonal differences than just the origin and destination combinations may exist. For example, with *cij* being static with respect to time of year for specific origin-destination combinations, the study could not account for changes in cultivation management (e.g., seasonal differences in greenhouse heating demand) and differences over time in the electricity mix at a given location.

Our analysis indicates that the current national tomato distribution scheme is suboptimal. Urban markets source tomatoes from several

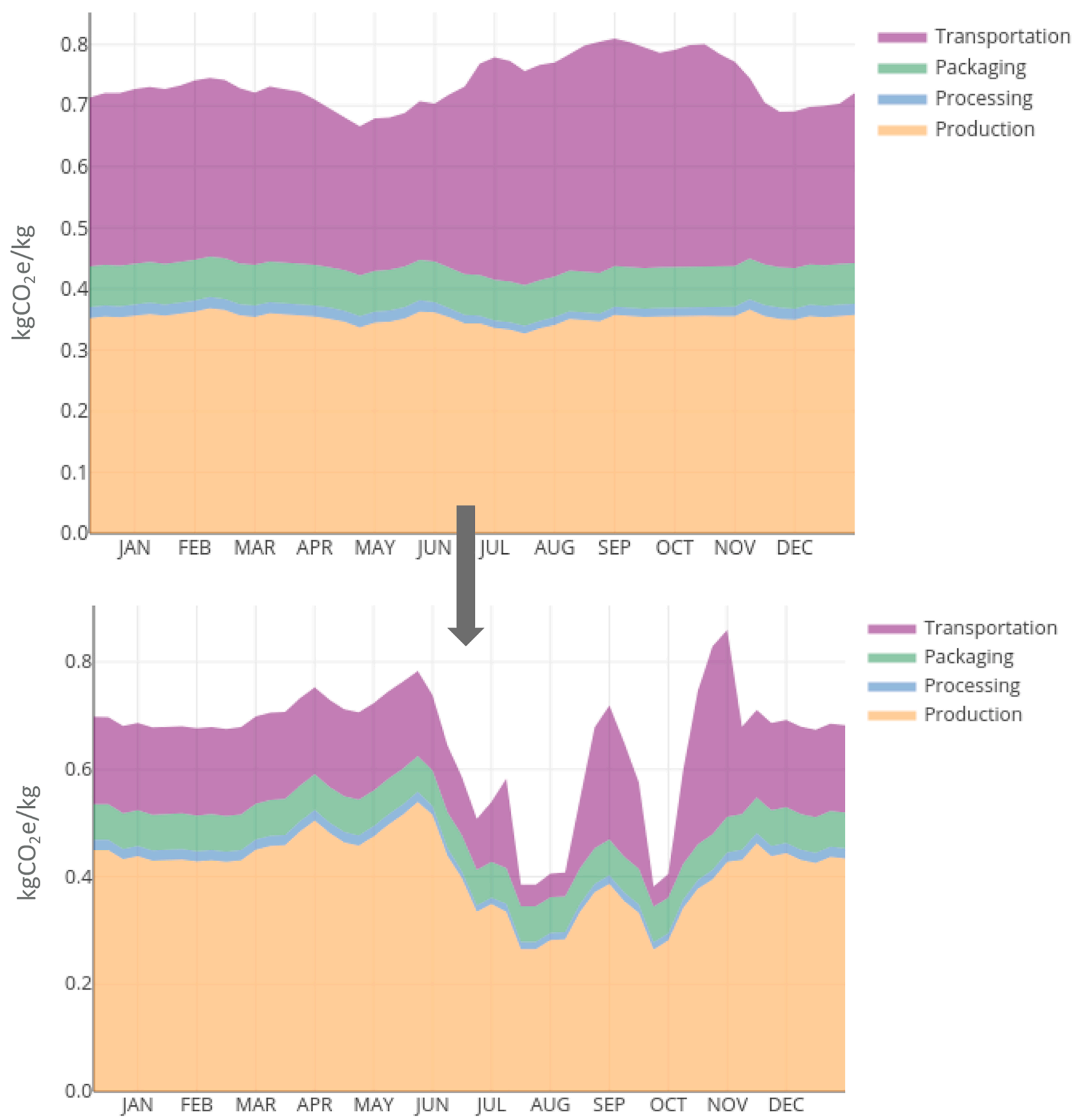

Fig. 6. Greenhouse gas emissions associated with fresh tomatoes supplied to the Philadelphia market under the baseline (top) and the optimized scenario (bottom).

production regions, some of which are located far away. Under an optimal scenario (one an agricultural "social planner" could try to implement), each city would source tomatoes from a select subset of production origins, giving preference to local production (Bell et al., 2018). Such a scheme could reduce transportation-related GHG emissions by 34% and overall cradle-to-market 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 10 cities. This is consistent with the conclusion of Weber and Matthews (Weber and Matthews, 2008) 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 GHG emissions of fresh tomatoes than the supply portfolio.

The tomato distribution systems generated by our model might be also optimized for economic cost. Comparing with the cost data of tomato shipments from the USDA AMS database (USDA 2020), the environmental impacts share similar trends with the costs of tomatoes: (1) The environmental impacts as well as costs of tomatoes from protected environment production are higher than those from open-field cultivation, and (2) the GHG emissions and costs of tomatoes with longer transportation distances are higher than those from closer by locations (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 (recognizing that the scenario may not be Pareto optimal (Lidicker et al., 2013), 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 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. In addition, the study did not consider the food processing facilities outside of the metropolitan centers and the improvements to transportation emissions (Nahlik et al., 2015) such as the use of biofuels (Taptich et al., 2018) and electrification (Tong et al., 2021), which would affect the optimization results.

Uncertainty analysis showed that the environmental impacts of protected-environment systems have larger variation than the open-field cultivation systems due to geographic conditions and production techniques. As demonstrated by the literature review in Table 2, there is significant variability within these subclassifications 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. More geographically relevant and recent data about tomato production would be desirable, especially with respect to US production.

Reallocating tomato supplies of cities could decrease the associated GHG emissions. However, the results also suggest that geography and production practices may play a more significant role in mitigating the environmental impact of fresh fruits and vegetables than the supply portfolio or the seasonality of supply.

The accuracy of these results, as well as the applicability of systems-level approaches to other commodities and regions, could be greatly improved by the adoption of a universal framework (Falchetta, 2021, Chester and Allenby, 2022, Memarzadeh et al., 2020) for agricultural data collection and reporting, as well as the availability of locally specific and relevant models (Cicas et al., 2007) and data of relevance to agricultural products' life cycle, such as energy (Grubert et al., 2020), water (Qin and Horvath, 2020, Stokes-Draut et al., 2017) and wastewater (Gursel et al., 2020, Kavvada et al., 2016), wastewater harvesting for nutrients (Kavvada et al., 2017), waste (Qin and Horvath, 2021, Qin and Horvath, 2022), and waste management (Vergara et al., 2011), recognizing that such data may change over time (Peer and Chini, 2021). Such a comprehensive framework and data sets would allow for the development of regionally and temporally specific environmental assessments of agricultural commodities and would lay the groundwork for optimal decision-making in the food system.

Supplementary material

See the attached separate file.

CRediT authorship contribution statement

Eric Bell: Methodology, Data curation, Formal analysis, Software, Writing – original draft. **Yuwei Qin:** Investigation, Validation, Visualization, Writing – review & editing. **Arpad Horvath:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

This material is based upon work supported by the National Science Foundation under Grant No. 1739676. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106660.

References

Weber, C.L., Matthews, H.S., 2008. Food-miles and the relative climate impacts of food choices in the United States. Environ. Sci. Techn.
US EPA. Inventory of U.S. Greenhouse gas emissions and sinks. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks (2016).
Canning, P.N., 2010. Energy use in the US Food System. Diane Publishing.
UNESCO, 2014. The United Nations world water development report 2014. Water and Energy 1. http://unesdoc.unesco.org/images/0022/002257/225741E.pdf.
United Nations. World population prospects, the 2010 Revision. (2011).
United States Census Bureau. Metropolitan and micropolitan: glossary. https://www.census.gov/programs-surveys/metro-micro/about/glossary.html (2016).

US Census Bureau. Metropolitan and micropolitan statistical areas totals: 2010-2019. https://www.census.gov/data/tables/time-series/demo/popest/2010s-total-metro-and-micro-statistical-areas.html (2020).
USDA. Food availability (Per Capita) data system. https://www.ers.usda.gov/data-products/food-availability-per-capita-data-system/food-availability-per-capita-data-system/#Food%20Availability (2020).
USDA. Quick stats tools. https://www.nass.usda.gov/Quick_Stats/index.php (2020).
Canaj, K., Mehmeti, A., Cantore, V., Todorović, M., 2020. LCA of tomato greenhouse production using spatially differentiated life cycle impact assessment indicators: an Albanian case study. Environ. Sci. Pollut. Res. 27, 6960–6970.
Zarei, M.J., Kazemi, N., Marzban, A, 2019. Life cycle environmental impacts of cucumber and tomato production in open-field and greenhouse. J. Saudi Soc. Agric. Sci. 18, 249–255.
Ronga, D., et al., 2019. Carbon footprint and energetic analysis of tomato production in the organic vs the conventional cropping systems in Southern Italy. J. Clean. Prod. 220, 836–845.
Goldstein, B., Hauschild, M., Fernandez, J., Birkved, M, 2016. Testing the environmental performance of urban agriculture as a food supply in northern climates. J. Clean. Prod. 135, 984–994.
Wang, X., et al., 2020. Integrated systematic approach increase greenhouse tomato yield and reduce environmental losses. J. Environ. Manage. 266, 110569.
Andersson, K., Ohlsson, T., Olsson, P., 1998. Screening life cycle assessment (LCA) of tomato ketchup: a case study. J. Clean. Prod. 6, 277–288.
Martínez-Blanco, J., Muñoz, P., Antón, A., Rieradevall, J., 2011. Assessment of tomato Mediterranean production in open-field and standard multi-tunnel greenhouse, with compost or mineral fertilizers, from an agricultural and environmental standpoint. J. Clean. Prod. 19, 985–997.
Roos, E., Karlsson, H, 2013. Effect of eating seasonal on the carbon footprint of Swedish vegetable consumption. J. Clean. Prod. 59, 63–72.
Winans, K., Brodt, S., Kendall, A., 2020. Life cycle assessment of California processing tomato: an evaluation of the effects of evolving practices and technologies over a 10-year (2005–2015) timeframe. Int. J. Life Cycle Assess. 25, 538–547.
Jones, C.D., Fraisse, C.W., Ozores-Hampton, M., 2012. Quantification of greenhouse gas emissions from open field-grown Florida tomato production. Agric. Syst. 113, 64–72.
Roy, P., et al., 2008. Life cycle inventory analysis of fresh tomato distribution systems in Japan considering the quality aspect. J. Food Eng. 86, 225–233.
Maraseni, T.N., Cockfield, G., Maroulis, J., Chen, G, 2010. An assessment of greenhouse gas emissions from the Australian vegetables industry. J. Environ. Sci. Health Part B 45, 578–588.
Payen, S., Basset-Mens, C., Perret, S., 2015. LCA of local and imported tomato: an energy and water trade-off. J. Clean. Prod. 87, 139–148.
Sanyé-Mengual, E., Oliver-Solà, J., Montero, J.I., Rieradevall, J., 2015. An environmental and economic life cycle assessment of rooftop greenhouse (RTG) implementation in Barcelona, Spain. Assessing new forms of urban agriculture from the greenhouse structure to the final product level. Int. J. Life Cycle Assess. 20, 350–366.
Maham, S.G., Rahimi, A., Subramanian, S., Smith, D.L., 2020. The environmental impacts of organic greenhouse tomato production based on the nitrogen-fixing plant (Azolla). J. Clean. Prod. 245, 118679.
Torrellas, M., et al., 2012. LCA of a tomato crop in a multi-tunnel greenhouse in Almeria. Int. J. Life Cycle Assess. 17, 863–875.
González, A.D., Frostell, B., Carlsson-Kanyama, A., 2011. Protein efficiency per unit energy and per unit greenhouse gas emissions: potential contribution of diet choices to climate change mitigation. Food Policy 36, 562–570.
Page, G., Ridoutt, B., Bellotti, B, 2012. Carbon and water footprint tradeoffs in fresh tomato production. J. Clean. Prod. 32, 219–226.
Webb, J., Williams, A.G., Hope, E., Evans, D., Moorhouse, E, 2013. Do foods imported into the UK have a greater environmental impact than the same foods produced within the UK? Int. J. Life Cycle Assess. 18, 1325–1343.
Bosona, T., Gebresenbet, G, 2018. Life cycle analysis of organic tomato production and supply in Sweden. J. Clean. Prod. 196, 635–643.
Del Borghi, A., Gallo, M., Strazza, C., Del Borghi, M, 2014. An evaluation of environmental sustainability in the food industry through Life Cycle Assessment: the case study of tomato products supply chain. J. Clean. Prod. 78, 121–130.
Chen, H., et al., 2018. Aeration of different irrigation levels affects net global warming potential and carbon footprint for greenhouse tomato systems. Sci. Hortic. 242, 10–19.
Boulard, T., et al., 2011. Environmental impact of greenhouse tomato production in France. Agron. Sustain. Dev. 31, 757.
Sanjuan-Delmás, D., et al., 2018. Environmental assessment of an integrated rooftop greenhouse for food production in cities. J. Clean. Prod. 177, 326–337.
Cellura, M., Ardente, F., Longo, S., 2012. From the LCA of food products to the environmental assessment of protected crops districts: a case-study in the south of Italy. J. Environ. Manage. 93, 194–208.
Maaoui, M., Boukchina, R., Hajjaji, N., 2020. Environmental life cycle assessment of Mediterranean tomato: case study of a Tunisian soilless geothermal multi-tunnel greenhouse. Environ. Dev. Sustain. 1–22.
De Marco, I., Riemma, S., Iannone, R., 2018. Uncertainty of input parameters and sensitivity analysis in life cycle assessment: An Italian processed tomato product. J. Clean. Prod. 177, 315–325.
Carlsson-Kanyama, A., 1998. Climate change and dietary choices—how can emissions of greenhouse gases from food consumption be reduced? Food Policy 23, 277–293.
Hollingsworth, J.A., Ravishankar, E., O'Connor, B., Johnson, J.X., DeCarolis, J.F, 2020. Environmental and economic impacts of solar-powered integrated greenhouses. J. Ind. Ecol. 24, 234–247.
Berners-Lee, M., Hoolohan, C., Cammack, H., Hewitt, C.N., 2012. The relative greenhouse gas impacts of realistic dietary choices. Energy Policy 43, 184–190.
Kulak, M., Graves, A., Chatterton, J., 2013. Reducing greenhouse gas emissions with urban agriculture: a life cycle assessment perspective. Landsc. Urban Plan. 111, 68–78.
Jensen, M.H., Malter, A.J., 1995. Protected Agriculture: a Global Review, 253. World Bank Publications.
U.S. Department of Commerce. Suspension of antidumping investigation: fresh tomatoes from Mexico. https://www.federalregister.gov/documents/2013/03/08/2013-05483/fresh-tomatoes-from-mexico-suspension-of-antidumping-investigation (2008).
Bell, E., Horvath, A., 2020. Modeling the carbon footprint of fresh produce: effects of transportation, localness, and seasonality on US orange markets. Environ. Res. Letters. 15 (3), 034040.
USDA. Specialty crops movement reports. https://marketnews.usda.gov/mnp/fv-report-config-step1?type=movement (2020).
Dorr, E., Goldstein, B.P., Horvath, A., Aubry, C., Gabrielle, B., 2021. Environmental impacts and resource use of urban agriculture: a systematic review and meta-analysis. Environ. Res. Lett. 16 (9), 093002.
Nahlik, M.J., Kaehr, A., Chester, M.V., Taptich, M., Horvath, A, 2015. Goods movement life-cycle assessment for greenhouse gas reduction goals. J. Ind. Ecol. 20 (2), 317–328.
Taptich, M., Scown, C., Piscopo, K., Horvath, A., 2018. Drop-in biofuels offer strategies for meeting California's 2030 climate mandate. Environ. Res. Letters. 13 (9), 094018.
Tong, F., Wolfson, D., Jenn, A., Scown, C.D., Auffhammer, M., 2021. Energy consumption and charging load profiles from long-haul truck electrification in the United States. Environ. Res.: Infrastruct. Sustain. 1 (2), 025007.
Falchetta, G., 2021. Energy access investment, agricultural profitability, and rural development: Time for an integrated approach. Environ. Res.: Infrastruct. Sustain. 1 (3), 033002.
Chester, M.V., Allenby, B., 2022. Infrastructure autopoiesis: Requisite variety to engage complexity. Environ. Res.: Infrastruct. Sustain. 2 (1), 012001.
Memarzadeh, M., Moura, S., Horvath, A., 2020. Multi-agent management of integrated food-energy-water systems using stochastic games: From Nash equilibrium to the social optimum. Environ. Res. Letters. 15 (9), 0940a4.
Cicas, G., Hendrickson, C.T., Horvath, A., Matthews, H.S, 2007. A regional version of a U.S. economic input-output life-cycle assessment model. Int. J. Life Cycle Assessment. 12 (6), 365–372.
Grubert, E., Stokes-Draut, J., Horvath, A., Eisenstein, W., 2020. Utility-specific projections of electricity sector greenhouse gas emissions: A committed emissions model-based case study of California through 2050. Environ. Res. Lett. 15 (10), 1040a4.
Qin, Y., Horvath, A., 2020. Use of alternative water sources in irrigation: potential scales, costs, and environmental impacts in California. Environ. Res. Commun. 2 (5), 055003.
Stokes-Draut, J., Taptich, M., Kavvada, O., Horvath, A., 2017. Evaluating the electricity intensity of evolving water supply mixes: The case of California's water network. Environ. Res. Lett. 12 (11), 114005.
Gursel, A.P, Chaudron, C., Kavvada, I., Horvath, A., 2020. Reduction in urban water use leads to less wastewater and fewer emissions: Analysis of three representative U.S. cities. Environ. Res. Lett. 15 (8), 084024.
Kavvada, O., Tarpeh, W.A., Horvath, A., Nelson, K.L, 2017. Life-cycle cost and environmental assessment of decentralized nitrogen recovery using ion exchange from source-separated urine through spatial modeling. Environ. Sci. Techn. 51 (21), 12061–12071.
Qin, Y., Horvath, A., 2021. Contribution of food loss to greenhouse gas assessment of high-value agricultural produce: California production, U.S. consumption. Environ. Res. Lett. 16 (1), 014024.
Qin, Y., Horvath, A., 2022. What contributes more to life-cycle greenhouse gas emissions of farm produce: production, transportation, packaging, or food loss? Res. Conserv. Recycl. 176, 105945.
Vergara, S., Damgaard, A., Horvath, A., 2011. Boundaries matter: greenhouse gas emission reductions from alternative waste treatment strategies for California's municipal solid waste. Res. Conserv. Recycl. 57, 87–97.
Peer, R.A.M., Chini, C.M., 2021. Historical values of water and carbon intensity of global electricity production. Environ. Res.: Infrastruct. Sustain. 1 (2), 025001.
Lidicker, J., Sathaye, N., Madanat, S., Horvath, A, 2013. Pavement resurfacing policy for minimization of life-cycle costs and greenhouse gas emissions. J. Infra. Syst. 19 (2), 129–137.
Bell, E.M., Stokes-Draut, J.R., Horvath, A., 2018. Environmental evaluation of high-value agricultural produce with diverse water sources: case study from Southern California. Environ. Res. Lett. 13, 025007.
Kavvada, O., Horvath, A., Stokes-Draut, J.R., Hendrickson, T.P., Eisenstein, W.E., Nelson, K.L, 2016. Assessing location and scale of urban nonpotable water reuse systems for life-cycle energy consumption and greenhouse gas emissions. Environ. Sci. Techn. 50 (24), 13184–13194.