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To cite this article: Yuwei Qin and Arpad Horvath 2021 *Environ. Res. Lett.* **16** 014024

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OPEN ACCESS

RECEIVED
21 August 2020

REVISED
20 October 2020

ACCEPTED FOR PUBLICATION
2 December 2020

PUBLISHED
28 December 2020

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LETTER

Contribution of food loss to greenhouse gas assessment of high-value agricultural produce: California production, U.S. consumption

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Keywords: food production, food waste, fruits, vegetables, strawberry, climate change, GHG emissions

Supplementary material for this article is available online

Abstract

Food loss (wasted and spoiled food) increases the burden on resources and environmental impacts throughout the entire food chain. This study describes and deploys a model and identifies data sources for estimation of greenhouse gas (GHG) emissions associated with food loss from farm production, delivery and refrigeration, retail sale, household consumption, and waste management in the United States using four California-grown high-value produce as case studies. The ratios of food wasted to food produced are 50%, 60%, 50%, and 64% for avocados, celery, lemons, and strawberries, respectively, and the differences are largely influenced by consumer-level and on-farm food loss. From the consumption perspective, this means, for example, that 1.8 units of strawberries are wasted for every unit consumed. The packaging material is a significant environmental offender, contributing, e.g. 52% to the total emissions (without food loss) for strawberries. End-of-life analysis of wasted food and packaging covers the common waste management practices: landfilling, composting, anaerobic digestion, incineration, and recycling. Uncertainties in the data are assessed through Monte Carlo simulation. With the consideration of food loss, the total GHG emissions from the entire life cycle of strawberries, celery, avocados, and lemons increase by 93%, 62%, 56%, and 53% to 0.26, 0.038, 0.061, and 0.058 kg CO_2 eq. per one serving size, respectively. Emissions from the annually wasted strawberries, avocados, celery, and lemons in California amount to 76, 24, 12, and 12 000 tons of CO_2 eq., respectively. Fourteen percent of the world's population could have a serving of strawberries just from the annually wasted strawberries in California. However, wasteful consumer action can be even more significant. Emissions from a typical driving scenario to a store to purchase only one produce exceeds the emissions associated with all four produce combined. Reducing food waste during consumption and the environmental impacts of packaging should be prioritized.

1. Introduction

One of the challenges of the 21st century is to meet the food demand of the increasing world population while achieving sustainability [1–3]. The world's total food production was 20 Gt in 2013 [4], or 2.8 tons per person. The world food demand will double from 2005 to 2050 due to population growth and consumption increase [5]. However, around a third of the food is lost (e.g. at the farm) or wasted (spoiled, rejected based on appearance, or otherwise inedible) every year as estimated by the Food and Agriculture Organization (FAO) of the United Nations [6]. On average, 40% of edible food ends up uneaten, equaling 181 kg of food per capita each year in the United States alone [7].

Wasting food means wasting energy and materials and creating unnecessary pollution along food supply chains. Several studies to date have evaluated the environmental impacts associated with food loss. Kummu *et al* estimated that about 1/4 of the total use of water, cropland, and fertilizers are wasted due to food losses at the global scale [8]. Hall *et al* confirmed that the production of wasted food consumed more

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than 25% of the freshwater used in the United States [9]. The FAO estimated that the annual carbon footprint from food loss was 3.3 Gt CO_2 eq., contributing 8.0% to the total anthropogenic greenhouse gas (GHG) emissions in 2007 [10]. The GHG emissions of post-harvesting food loss were estimated to be 1.4 kg CO_2. eq. per capita per day in the United States, contributing 28% to the total carbon footprint of an American's diet on average [11] GHG emissions associated with rejected food due to cosmetic imperfection is believed to amount to 22.5 Mt CO_2 eq. per year in the European Economic Area [12]. Rethink Food Waste through Economics and Data (ReFED) estimated that 9.2 billion kg of food was lost on the farm in the United States [13]. Common causes of food loss include unsatisfactory quality of the food, deterioration during transportation or storage, excessive purchasing of food for home, and excessive ordering of food at restaurants [14, 15].

As shown, while some high-level data and estimates of food loss are available, insufficient and inconsistent data on food loss rates for specific foods and regions remain major challenges of understanding the current food loss situation [16]. Case in point, most studies to date have used an average food loss ratio collected for all food items to calculate the related impacts on the environment [17–19]. For example, Moult *et al* assessed the GHG emissions of retail-level food waste for five types of food groups in the United Kingdom [20]. In addition, methodological issues have also been limiting factors in revealing the true environmental effects of food loss.

Life-cycle assessment (LCA) has been applied to several studies to evaluate the environmental impacts associated with food production, delivery, storage, and consumption. However, most LCA studies only account for emissions from a part of the supply chain and ignore food losses [15, 21–23]. For example, Cerutti *et al* evaluated the cradle-to-market environmental impacts of apples in Italy [24]. Knudsen *et al* analyzed fresh oranges and orange juice in Brazil [25]. The environmental impacts of organic and conventional avocados were compared in a cradle-to-gate LCA study [26]. Pergola *et al* performed an energy, cost, and environmental analysis for lemon and orange and found that organic farms had lower environmental impacts than conventional farms [27]. However, these environmental analyses were only performed for the cradle-to-gate or cradle-to-market cycles, and food loss was not considered.

Most of the studies that included food loss have done it via mathematical modeling, without empirical data from measuring food loss in the field. Williams and Wikström developed a method to represent the linear relationship between the reduced environmental impacts of packaging and food losses [28, 29]. A hierarchical framework for food management during each stage in the food supply chain was proposed to better understand food loss and possible prevention [30]. A qualitative approach was performed to study food loss for fruits and vegetables in primary (farm) production [31]. Corrado *et al* suggested a common methodological framework to model food loss in LCA studies [15].

The studies that have incorporated quantitative food loss assessment have seldom considered food losses in all stages of the food supply chain, and most of them focused on the post-harvest, retail, or the consumption phases. On-farm food loss has gained attention recently, and the quantification of farm-level food loss often relies on grower interviews [31–33]. Baker *et al* collected on-farm food loss data for 20 different crops from 123 field surveys in California [34]. Research on food loss at retail and consumer stages found that economic management practices, marketing considerations, and consumer behavior are the main drivers of loss [35–40]. Parfitt *et al* reviewed the worldwide post-harvest food waste studies and found that fresh vegetables and fruits are usually the most wasted food items [14]. Buzby *et al* analyzed the retail food losses for 61 fruits and 60 vegetables using shipment data and sales data [36]. Brancoli *et al* performed an LCA study for three food categories and assessed the impacts of waste treatment practices.

Food loss should be estimated from harvest to final consumption in the food life cycle [6]. In this study, we analyze five stages—production, delivery, retail sales, consumption at home, and waste management—and describe a life-cycle method to analyze food loss using empirical data on high-value produce to demonstrate how food loss contributes to the total environmental impact. To our knowledge, this study is the first to quantify the life-cycle GHG emissions of food and food waste along the entire food supply chain from farm-to-retail operations and then to the individual consumer, and apply practical waste management options to food and packaging wastes.

2. Methods and data

Food loss is the reduction in food intended for human consumption. We have evaluated food loss at four main stages, and the categorization of food loss stages was inspired by the FLW Standard, the FAO's definition, and the FUSIONS Definitional Framework for Food Waste [10, 41, 42]. Table 1 describes the four assessed food loss stages and figure 1 shows the food loss stages and assessed processes. Although the retail-to-consumer stage is not included in the environmental assessment of food loss associated with produce because it would vary with the consumer's driving distance, vehicle type, and total food purchased per trip, we compared the estimated emissions of retail-to-consumer transportation and the total life-cycle emissions at the end of the analysis.

Table 1. Definition of the food loss stages and their coverages in the study.

Stage	Definition
On-farm	Crops not harvested and crops left in the field
Farm-to-retail	Food lost during transportation from farm to retail
Retail sales	Food lost due to bad storage and unsold food
Consumer	Food lost due to bad storage and uneaten food at home

For one unit of consumed food, the total emissions from cradle to grave are:

$$E_t = E_c + E_l \quad (1)$$

where E_c denotes the cradle-to-grave emissions without food loss for one unit of consumed food; E_l is the cradle-to-grave emissions from food loss for one unit of consumed food.

The life-cycle emissions without consideration of food loss (E_c) for one unit of consumed food can be calculated as:

$$E_c = E_{pr} + E_{pa} + E_t + E_{rt} + E_{re} + E_{rh} + E_w \quad (2)$$

where E_{pr} is the emissions of food production; E_{pa} denotes the emissions of food packaging; E_t is the emissions of food transportation; E_{rt} is the emissions of food refrigeration in truck transportation; E_{re} is the emissions of food refrigeration in retail store; E_{rh} is the emissions of food refrigeration at home; E_w is the emissions of waste management of packaging materials for consumed food. The detailed calculation steps for production, packaging, transportation, and refrigeration in the truck, retail store, and home of the consumer are included in the supplementary data (S2–S5, available online at https://stacks.iop.org/ERL/16/014024/mmedia).

The cradle-to-grave GHG emissions from food loss (E_l) can be calculated for one unit of consumed food as:

$$E_l = \sum_{i=1}^{4} r_i \left(e_i + W_i\right) \quad (3)$$

where r_i is the food loss ratio of food loss phase i ($i = 1$ is the on-farm phase; $i = 2$ is the farm-to-retail phase; $i = 3$ is the retail phase; $i = 4$ is the consumer phase); f_i denotes the emissions of food production, transportation, and refrigeration of the wasted food during phase i; and W_i is the parameter for emissions associated with food waste management at phase i. e_1 includes the emissions of food harvesting; e_2 includes the emissions from food harvest, packaging, transportation, and refrigeration in the truck; e_3 includes the emissions of food harvesting, packaging, transportation, and refrigeration in the truck and retail store, e_4 includes the emissions of food harvesting, packaging, transportation, and refrigeration in the truck, retail store, and home.

The emissions from waste management for wasted food and packaging materials for each phase can be calculated as:

$$W_i = t_i + \sum_{n=1}^{5} rf_{n,i} f_{n,i} + rp_{n,i} p_{n,i} \quad (4)$$

where t_i denotes the emissions from transporting the food and packaging wastes in the food loss phase i; n is the waste management method ($n = 1$ is incineration; $n = 2$ is landfilling; $n = 3$ is composting; $n = 4$ is anaerobic digestion; $n = 5$ is recycling); $rf_{n,i}$ is the ratio of food waste management for the waste management method n; $f_{n,i}$ is the emission factor of the food waste management method n; $rp_{n,i}$ is the ratio of packaging waste management for the waste management method n; $p_{n,i}$ is the emission factor of the packaging waste management method n.

2.1. Data

The food loss ratios were obtained from the loss-adjusted food availability (LAFA) dataset from the United States Department of Agriculture (USDA) and other literature [34, 43, 44]. The LAFA data have been used to estimate the amount and value of food loss at the retail and consumer levels in the United States, and the food loss includes the loss from inadequate climate control, pests, mold, and food waste [1, 45]. The production data were sourced from the 'cost and return studies' from the University of California, Davis [46–49]. Truck transportation was used for transporting food from farm to retail, and for transporting food and packaging wastes from the farm, retail, and home to waste management locations [50]. The emissions from refrigeration during farm-to-retail transportation, retail operations, and at the consumer's home were estimated by the volume of packaged food [41, 42, 51]. The detailed data and emission calculations for production, packaging, transportation, and refrigeration can be found in the supplementary data (S3–S5). The GHG emissions from waste management practices of wasted food and packaging materials were calculated from the U.S. Environmental Protection Agency's (EPA) waste reduction model (WARM) [52]. The material-specific emissions and energy factors used in the WARM model are based on a life-cycle perspective.

3. Case study

California is the top producer for many agricultural products in the United States, accounting for 98% of avocados, 96% of celery, 89% of strawberries, and 79% of lemons [53]. The key parameters and assumptions for the four high-value produce used in the study are presented in table 2. The transportation distances and refrigeration periods for the four produce are based on our estimates, and the uncertainties

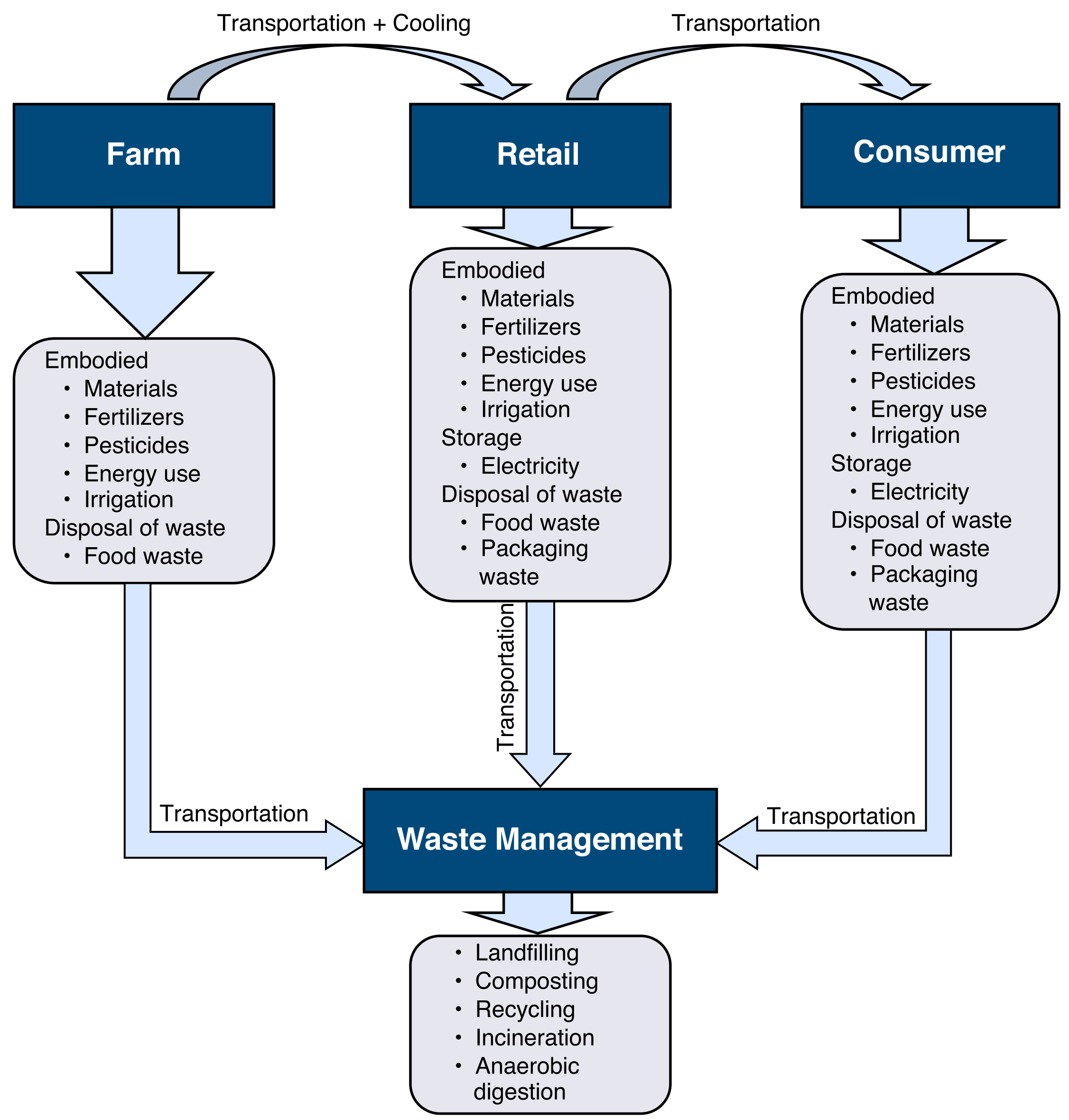

Figure 1. Flow diagram of assessed food waste stages and processes in the study.

for those parameters and other parameters are considered in the uncertainty analysis. The detailed production data and emission factors are included in the supplementary data S2 and S9.

The food loss ratios at each phase are summarized in table 3. The food loss ratio is defined as the ratio of wasted food to food available for final consumption. The on-farm food loss ratio represents the produce left on the field after harvest as a proportion to the food intended for human consumption. The farm-to-retail food loss ratio denotes the ratio of food lost before retail to the food sold at the farm. The retail-level food loss ratio represents the rate of unsold food to total food for sale. The consumer-level food loss ratio is the percentage of uneaten food to purchased food.

The on-farm food loss ratios for strawberries and celery were estimated from in-field surveys and interviews in California in 2017 [34]. The on-farm food loss ratios for avocados and lemons were estimated based on interviews with Californian growers in 2017 [44]. The food loss ratios at the farm-to-retail, retail, and consumer phases were extracted from the LAFA dataset [43].

The total food losses for one unit of *produced* avocados, celery, lemons, and strawberries are 50%, 60%, 50%, and 64%, respectively (table 3). For example, 2.5% avocados will be lost on farm when 1 kg was produced. Therefore, 0.975 kg leaves the farm. Then 6.0% will be lost during the transportation from farm to retail, followed by an additional loss of 19% in retail and 33% in the consumer's home. Therefore, of the original 1 kg of avocados produced, only 50% will be eaten.

On-farm food loss ratios vary significantly across the different produce, while the consumer-level loss

Table 2. Key parameters and assumptions used in the study [41, 42, 50, 51, 54, 55].

Parameter	Unit	Avocado	Celery	Lemon	Strawberry
Transportation distance from farm to retail	km	300	300	300	300
Transportation distance from retail to consumer	km	2	2	2	2
Transportation distance of waste	km	30	30	30	30
Refrigeration period in retail	d	0	7	0	3
Refrigeration period at home	d	0	4	0	2
Emission factor of truck transportation [50]	kg CO_2 eq. kg^{-1} km^{-1}	0.00036	0.00036	0.00036	0.00036
Emission factor of passenger car [54]	kg CO_2 eq. km^{-1}	0.61	0.61	0.61	0.61
Transportation refrigeration [41]	kg CO_2 eq. m^{-3} km^{-1}	0.0025	0.0025	0.0025	0.0025
Retail refrigeration [42, 51]	kg CO_2 eq. m^{-3} d^{-1}	2.0	2.0	2.0	2.0
Home refrigeration [55]	kg CO_2 eq. m^{-3} d^{-1}	0.80	0.80	0.80	0.80

Table 3. Food loss ratios for avocados, celery, lemons, and strawberries [34, 43, 44].

	Avocado	Celery	Lemon	Strawberry
On-farm loss [34, 45]	2.5%	23%	2.0%	31%
Farm-to-retail loss [44]	6.0%	7.0%	4.0%	8.0%
Retail-level loss [44]	19%	8.5%	5.1%	14%
Consumer-level loss [44]	33%	39%	44%	35%

Table 4. Waste management ratios for food and packaging wastes.

	Incineration	Landfilling	Composting	Anaerobic Digestion	Recycling
On-farm food waste	0%	50%	50%	0%	0%
Farm-to-retail food waste [56]	50%	0%	25%	25%	0%
Retail-level food waste [56]	50%	0%	25%	25%	0%
Consumer-level food waste [56]	33%	51%	8.0%	8.0%	0%
Plastic packaging waste [57]	17%	70%	0%	0%	13%
Paperboard packaging waste [57]	5.0%	22%	0%	0%	73%

ratios are similar. Consumer-level food loss is the top contributor to total food losses of three of four produce, contributing about four-fifths for lemons and one-half for avocados and celery, respectively. On-farm losses for strawberries and celery contribute about a half and a third to the total, respectively.

The end-of-life analysis in the study considers all the common waste management practices, including landfilling, composting, anaerobic digestion, incineration, and recycling. The waste management ratios for food and packaging wastes are presented in table 4. The food waste ratios at the farm-to-retail, retail, and consumer levels were based on a study of waste management at different post-harvest phases [56]. Due to lack of data, on-farm food waste management ratios are based on our estimates. Because the produce left in the field is usually tilled back into the soil [44], we assumed half of the on-farm food waste was landfilled and half was composted. The packaging waste management ratios were collected from the EPA's container- and packaging product-specific data [57].

3.1. Uncertainty assessment

Monte Carlo simulation was performed to explore the uncertainties in the 32 parameters used in our model. The uncertainty sources included food loss ratios, transportation distances, refrigeration times, and emission factors for materials, electricity, fuels, refrigeration, and waste management covering the four food supply phases. The ranges of on-farm food loss ratios were based on the existing literature [32, 34]. We assumed uncertainty ranges of 20% for the emission factors of materials, electricity, fuels, refrigeration, and transportation, and uncertainty ranges of 50% for the emission factors of food and packaging waste management and refrigeration time. The probability distribution functions of the

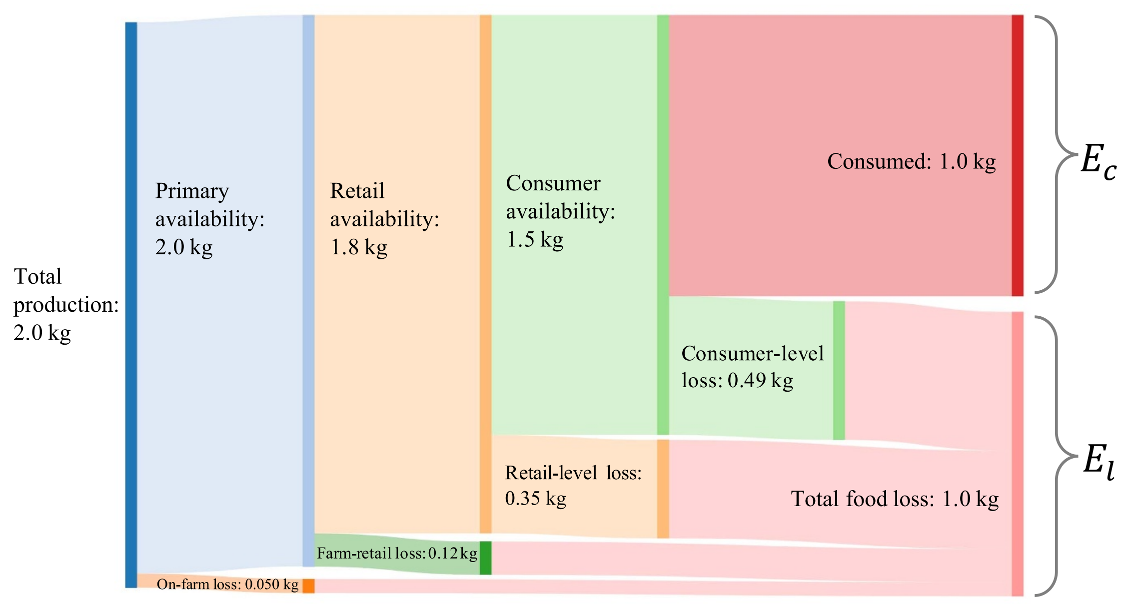

Figure 2. Sankey diagram for the production and food loss of 1 kg of avocado consumption. E_c covers the life-cycle emissions for consumed food from production, packaging, transportation, and refrigeration in the truck, retail store, and consumer's home. E_l covers the cradle-to-grave emissions from total food loss.

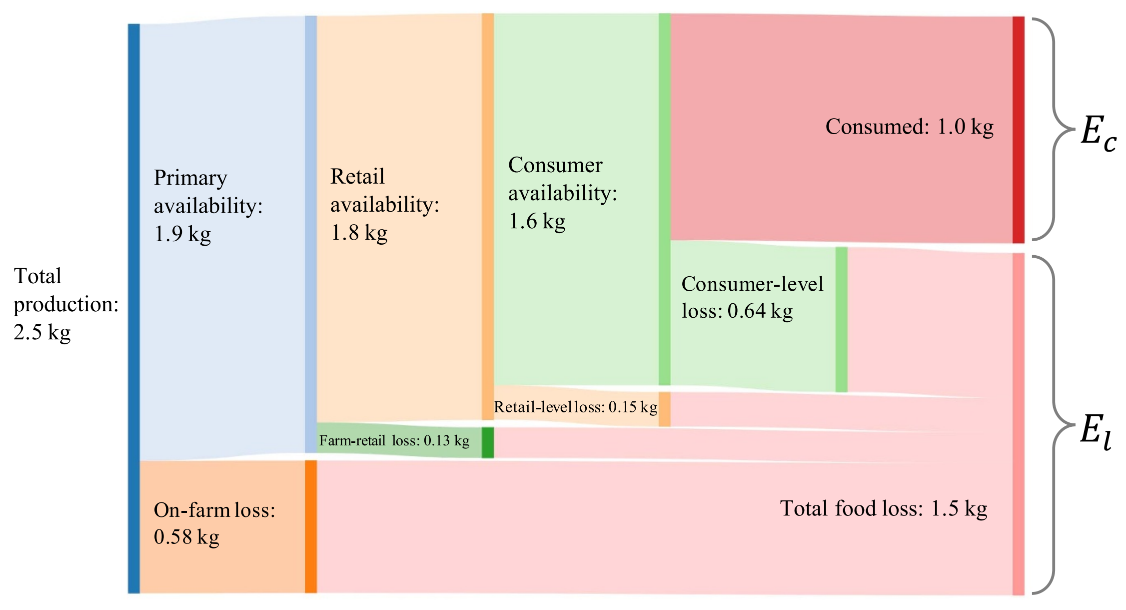

Figure 3. Sankey diagram for the production and food loss of 1 kg of celery consumption.

parameters for the four produce are presented in the supplementary data (tables S9.1–S9.4). We conducted 10 000 iterations for each produce. The ranges which contain 95% uncertainty intervals of the simulated results are presented as error bars in figures 7 and 8.

4. Results

From the consumption perspective, 1.0, 1.5, 1.0, and 1.8 units of produce are wasted for every unit of avocados, celery, lemons, and strawberries consumed, respectively. Figures 2–5 are Sankey diagrams for the four stages of the food availability and food loss phases for 1 kg of avocados, celery, lemons, and strawberries *consumed*. For example, in order to consume 1 kg of strawberries, 2.8 kg of strawberries need to be grown on the farm; 0.85 kg will be wasted on the field; 0.16 kg will be spoiled during the transportation from farm to retail; 0.25 kg will be thrown away at retail stores, and 0.54 kg will be forgone at home.

We have calculated the GHG emissions for one serving size of consumed food without food loss, E_c, which included production, packaging, transportation, refrigeration during transportation,

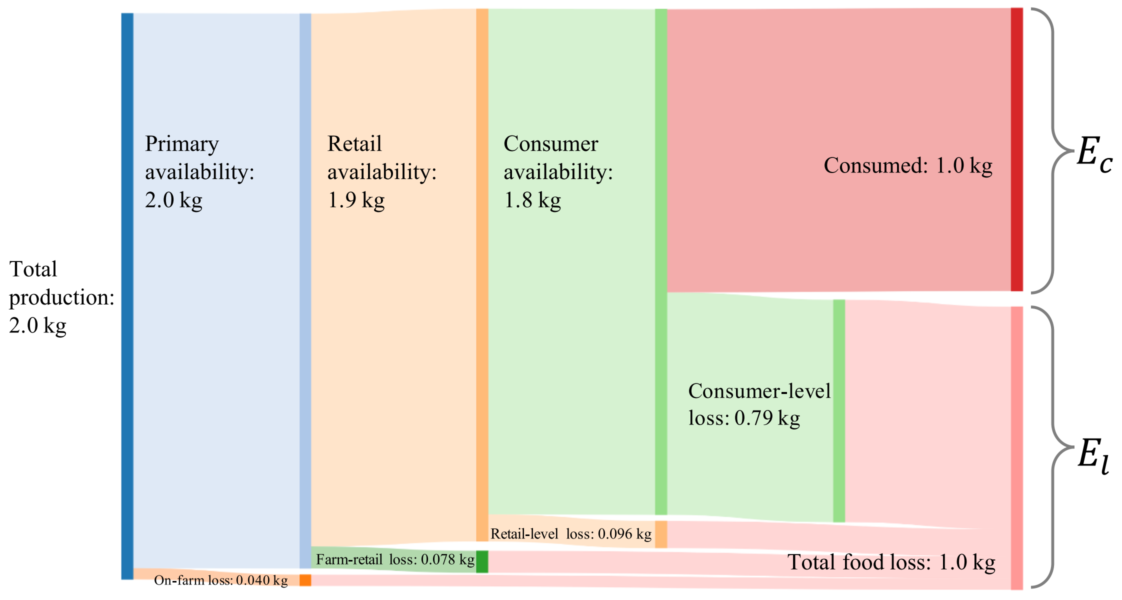

Figure 4. Sankey diagram for the production and food loss of 1 kg of lemon consumption.

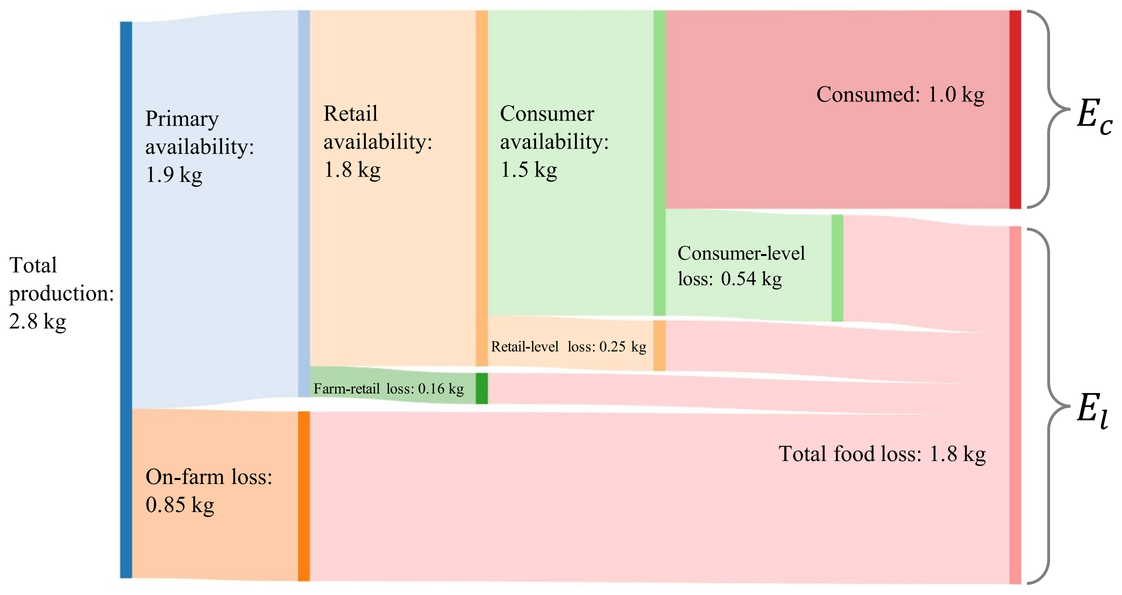

Figure 5. Sankey diagram for the production and food loss of 1 kg of strawberry consumption.

retail operations, and home refrigeration. The U.S. serving sizes for strawberry and celery are 144 g (1 cup) and 51 g (1/2 cup), respectively [58]. Due to unavailable guidance, we used 1 lemon and 1/2 avocado as serving sizes.

The results in table 5 show that, without the consideration of food loss, the life-cycle emissions for one serving size of avocados, celery, lemons, and strawberries are 0.039, 0.023, 0.038, 0.13 kg CO_2 eq., respectively. The emissions for 1 kg of food consumption can be found in the supporting data (table S6). Packaging contributes 52% of the total emissions for strawberries without the consideration of food loss. For strawberries and celery, refrigeration is needed for storage during retail and at home. For avocados and lemons, refrigeration is not required but is often practiced, thus we calculated the emissions under both scenarios of refrigeration.

We also estimated the GHG emissions associated with food loss, E_l, for avocados, celery, lemons, and strawberries through equation (1). The results of the GHG emissions for one serving size are presented in table 6. (Results for 1 kg can be found in the supplementary data.) The food harvesting process contributes a large portion of emissions associated with food loss among all the processes in the food life

Table 5. GHG emissions (in kg CO_2 eq.), E_c, associated with one serving size of consumed avocados, celery, lemons, and strawberries without considering food loss. Color bars denote the magnitudes of the numbers.

Phase	Process	Avocado	Celery	Lemon	Strawberry
On-farm	Food harvesting	0.021	0.0052	0.016	0.035
	Packaging manufacturing	0.010	0.0045	0.0057	0.070
Farm-to-retail	Farm-to-retail transportation	0.011	0.011	0.018	0.031
	Farm-to-retail refrigeration	0.00038	0.00035	0.00060	0.0010
Retail	Retail refrigeration	0	0.0032	0	0.0038
Consumer	Consumer refrigeration	0	0.00074	0	0.0010
	Packaging waste transportation	0.00010	0.000077	0.000082	0.00047
	Packaging waste management	−0.0033	−0.0018	−0.0028	−0.0078
Total		0.039	0.023	0.038	0.13

Table 6. GHG emissions (in kg CO_2 eq.), E_l, associated with food loss of one serving size of consumed avocados, celery, lemons, and strawberries. Color bars denote the magnitudes of the numbers. Note that the emissions of the transportation between retail and consumer were not included in the result below, but the emissions from driving were compared with the total emissions (without driving) in the latter part of the results section.

Phase	Process	Avocado	Celery	Lemon	Strawberry
On-farm	Food harvesting	0.0010	0.0030	0.00064	0.030
	Waste transportation	0.000054	0.00064	0.000073	0.0027
	On-farm food waste management	0.00023	0.0027	0.00030	0.011
Farm-to-retail	Food harvesting	0.0024	0.00070	0.0013	0.0055
	Packaging manufacturing	0.0012	0.00061	0.00044	0.011
	Farm-retail transportation + refrigeration	0.0013	0.0015	0.0015	0.0050
	Waste transportation	0.00014	0.00016	0.00015	0.00056
	Farm-to-retail food and packaging waste management	−0.0040	−0.0045	−0.0043	−0.015
Retail	Food harvesting	0.0073	0.00079	0.0015	0.0090
	Packaging manufacturing	0.0036	0.00069	0.00054	0.018
	Farm-retail transportation + refrigeration	0.0039	0.0017	0.0018	0.0082
	Retail refrigeration	0	0.00048	0	0.00096
	Waste transportation	0.00041	0.00018	0.00018	0.00091
	Retail food and packaging waste management	−0.012	−0.0051	−0.0052	−0.025
Consumer	Food harvesting	0.010	0.0033	0.013	0.019
	Packaging manufacturing	0.0050	0.0029	0.0045	0.038
	Farm-retail transportation + refrigeration	0.0055	0.0073	0.015	0.017
	Retail refrigeration	0	0.0020	0	0.0020
	Consumer refrigeration	0	0.00047	0	0.00055
	Waste transportation	0.00058	0.00075	0.0015	0.0019
	Consumer food and packaging waste management	−0.0053	−0.0060	−0.012	−0.016
Total		0.022	0.014	0.020	0.13

cycle, contributing 51% emissions to the total emissions from lost strawberries. Because the food loss ratios at the consumer level are the highest among the food loss phases for avocados, celery, and lemons, the emissions at the consumer level contribute the largest portion of the total emissions. The consumer level is also the last phase, which means it cumulates all the emissions from the previous phases. Thus, the consumer phase is the phase that contributes the most to the total emissions for one serving size of avocados (74%), celery (74%), and lemons (95%). Waste management can lead to negative GHG emissions because incineration can generate energy, composting (if the compost is then applied to soil) can store more carbon than it emits to the atmosphere, and recycling of wastes can avoid emissions from raw material production.

Figure 6 shows the total emissions associated with one serving size of consumed food under four scenarios: production, production and packaging, cradle to grave without food loss, and cradle to grave with food loss. The emissions from production and packaging include the emissions from production; the emissions from cradle to grave without food loss include the emissions from production and packaging; and emissions from cradle to grave

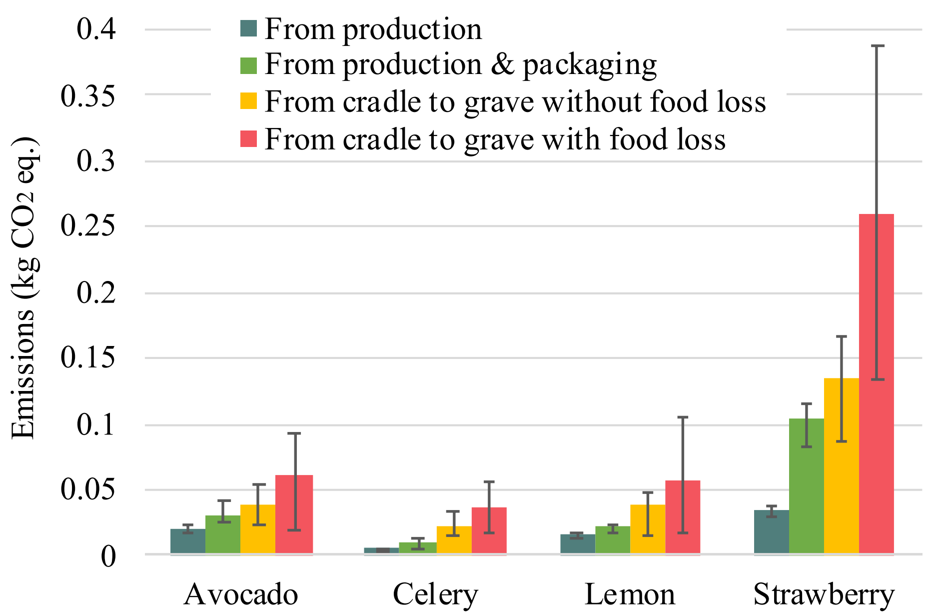

Figure 6. GHG emissions of one serving size of avocados, celery, lemons, and strawberries under four emission scenarios. 'Production' represents the emissions from on-farm production; 'production and packaging' represents the emissions from on-farm production and packaging materials; 'cradle to grave without food loss' represents the emissions from on-farm production, packaging materials, transportation, and refrigeration; 'cradle to grave with food loss' represents the emissions from on-farm production, packaging materials, transportation, refrigeration, food and packaging waste management, and food loss. Error bars represent 95% uncertainty ranges from Monte Carlo simulations.

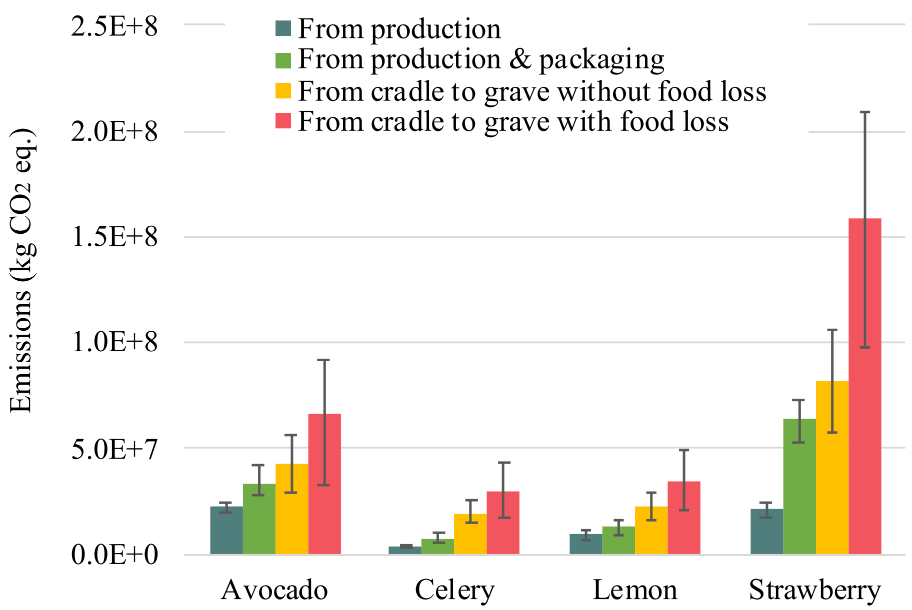

Figure 7. GHG emissions of avocados, celery, lemons, and strawberries were based on California's consumption in 2017 under four emissions scenarios. 'Production' represents the emissions from on-farm production; 'production and packaging' represents the emissions from on-farm production and packaging materials; 'cradle to grave without food loss' represents the emissions from on-farm production, packaging materials, transportation, and refrigeration; 'cradle to grave with food loss' represents the emissions from on-farm production, packaging materials, transportation, refrigeration, food and packaging waste management, and food loss. Error bars represent 95% uncertainty ranges from Monte Carlo simulations.

with food loss include the emissions from cradle to grave without food loss. The results of the 95% uncertainty interval from the Monte Carlo simulation are presented in the error bars in the figure. The result of energy consumption and the uncertainty values are included the supplementary data (S7–S9). The emissions from food loss increase the cradle-to-grave emissions by 93%, 62%, 56%, and 53% for strawberries, celery, avocados, and lemons, respectively. With the consideration of food loss, the total emissions of avocados, celery, lemons, and strawberries for one serving size were found to be 0.061, 0.038, 0.058, and 0.26 kg CO_2 eq., respectively. If we assume that the avocados and lemons are

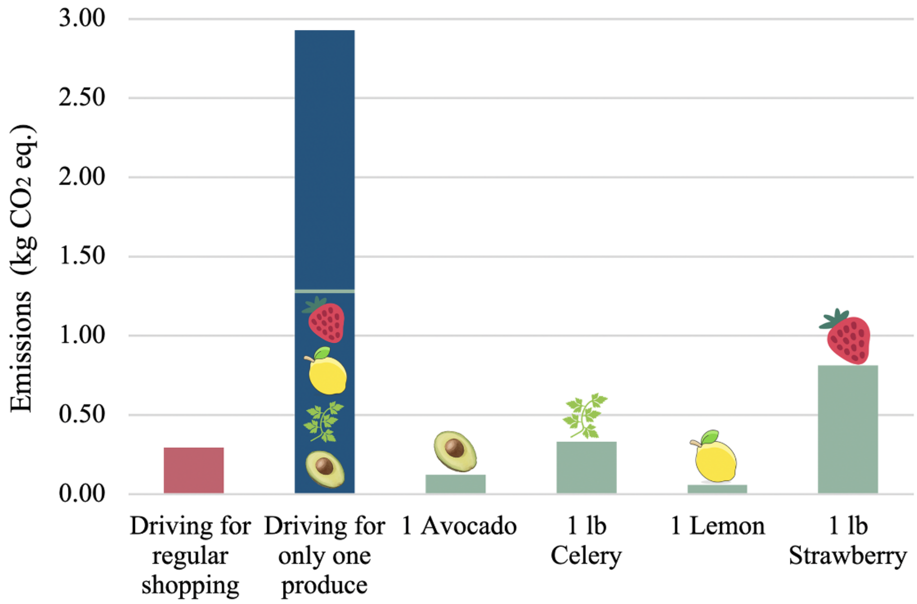

Figure 8. Comparison between the emissions of driving for shopping and cradle-to-grave emissions of one package size of avocado, celery, lemon, and strawberry consumption, including food loss consideration.

refrigerated during storage at retail stores and homes, the total emissions from cradle to grave with food loss consideration will increase by 5.8% and 8.7%, respectively.

Figure 7 shows the GHG emissions from the consumptions of the four produce in California. Considering California's total population and per capita consumption of the four produce [43], 158 000 tons of strawberries go to waste to fulfill the consumption needs for strawberries just in California in a year, equaling 1.1 billion serving sizes of strawberries. 1.2 billion serving sizes of celeries, 1.1 billion serving sizes of avocados, and 590 million serving sizes of lemons. Indeed, 14% of the world's population could have a serving of strawberries just from the annually wasted strawberries in California. The emissions from the annual food loss of avocados, celery, lemons, and strawberries in California are 24, 12, 12, and 76 000 tons of CO_2 eq., respectively.

In our calculation of cradle-to-grave emissions of food consumption, emissions associated with driving from retail to home were not included. To compare the total calculated emissions for the produce with the emissions from driving to purchase them, we allocated 10% of the emissions from driving to each food item. We also calculated the emissions from driving when only one produce is purchased.

Figure 8 shows the emissions from driving associated with a regular shopping trip when multiple items are purchased, driving only for one produce, and the cradle-to-grave emissions of one package size of the four produce, including food loss consideration. (The driving distance from home to the store and back was assumed to be 4.8 km each way, and we used the life-cycle emission factor of a light-duty truck to represent the emissions of a typical passenger vehicle in the United States [54]). The GHG emissions for one package of produce from a regular grocery shopping trip were 0.29 kg CO_2 eq., which is about the total emissions associated with two avocados. If the entire driving is for purchasing only one produce, the emissions from driving amount to about 2.9 kg CO_2 eq., which exceeds the total emissions associated with all four produce combined.

5. Discussions and conclusions

This study focused on the environmental impacts of produce in California, including food loss, but the results are applicable to other states in the United States because the food loss ratios at farm-to-retail, retail, and consumer levels represent U.S. averages, and the waste management data are also based on a national model. A few factors would need to be adjusted in an analysis for another state, including the transportation distances between farms and retail points [59–61], the on-farm food loss ratios, and the emissions associated with growing [62], harvesting, refrigeration [63] and waste management [64].

The food loss ratios vary from 50% to 64% for the four high-value produce, and the differences are largely influenced by the on-farm food loss ratios as the consumer-level losses are similar. However, data about on-farm food loss ratios are quite limited, and only a few crops have on-farm food loss ratios due to the difficulties of tracking and measuring food losses in the field. Studies for all agricultural products and a database focusing on on-farm food loss would be necessary to understand comprehensively the environmental impacts associated with food loss.

Our analysis extended the previous research on the environmental impacts of high-value produce including the farm-to-retail, retail, and consumer phases and food loss consideration. Compared with a previous study by Bell *et al* which focused on the environmental impacts from the production of the four produce [65], our study has found that the total GHG emissions of avocados, celery, lemons, and strawberries using conventional water were increased by 180%, 630%, 290%, and 190%, respectively. Compared with the study by Qin and Horvath [66] which included impacts of production with newer data and packaging materials, the emissions estimates in this study were increased by 96%, 290%, 170%, and 150% for avocados, celery, lemons, and strawberries, respectively. Clearly, food loss contributes to a staggering proportion of environmental impacts.

When food is wasted after harvesting, packaging materials waste also increases. For example, GHG emissions associated with packaging contribute 52% to the cradle-to-grave emissions (with the food loss consideration) for strawberries. Although the recycling rate of plastic containers has increased in recent years, the recycling rate of plastic containers (13% in the United States) is still very low compared with paperboard containers' recycling rate (73%) [57]. Strategies to reduce packaging emissions can play an important role in improving the overall sustainability of food consumption. Such strategies include using less environmentally burdensome packaging materials or simply less of them where feasible.

Several solutions can help reduce food loss and mitigate emissions. Selection of fresh produce based on quality, not on the appearance of fresh fruits and vegetables, by the retailers and the consumers could reduce shunned food. A recent study found that about 20% of the harvest products are rejected at the farm due to imperfect 'cosmetic' appearance [67]. Approaches to reducing the food loss due to imperfect appearance include discounting cosmetically imperfect produce and secondary processing those imperfect produce into juice or other processed food items or ingredients. Rational purchasing—only purchasing the amount of food needed—is another way to reduce food loss and save money. Future studies should also explore how different packaging techniques and transportation distances influence food loss.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Acknowledgments

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. The authors are thankful to Meghna Thomas for her help in data collection.

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