LETTER

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

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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 exceed 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...
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, Moul 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:

\[ E_l = E_c + E_l \]

(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:

\[ E_c = E_{pr} + E_{pa} + E_1 + E_{rt} + E_{re} + E_{rh} + E_w \]

(2)

where \( E_{pr} \) is the emissions of food production; \( E_{pa} \) denotes the emissions of food packaging; \( E_1 \) 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:

\[ E_l = \sum_{i=1}^{4} r_i (e_i + W_i) \]

(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:

\[ W_i = t_i + \sum_{n=1}^{5} r_{n,i} f_{n,i} + r_{p,n,i} p_{n,i} \]

(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); \( r_{n,i} \) 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 \( n \); \( r_{p,n,i} \) 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 (LFAA) dataset from the United States Department of Agriculture (USDA) and other literature [34, 43, 44]. The LFAA 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...
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 CO₂ eq. kg⁻¹ km⁻¹ | 0.00036 | 0.00036 | 0.00036 | 0.00036 |
| Emission factor of passenger car [54]         | kg CO₂ eq. km⁻¹ | 0.61    | 0.61   | 0.61  | 0.61       |
| Transportation refrigeration [41]              | kg CO₂ eq. m⁻³ km⁻¹ | 0.0025  | 0.0025 | 0.0025 | 0.0025    |
| Retail refrigeration [42, 51]                  | kg CO₂ eq. m⁻² d⁻¹ | 2.0     | 2.0    | 2.0   | 2.0        |
| Home refrigeration [55]                       | kg CO₂ eq. m⁻² 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
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,
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.
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, and retail to consumer; and the total emissions from cradle to grave with food loss. The emissions from production and packaging include the emissions from production; the emissions from retail to consumer include the emissions from production, and packaging; and emissions from cradle to grave

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**Table 5.** GHG emissions (in kg CO$_2$ eq.), $E_i$, 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              | 0.00010  | 0.000077| 0.000082| 0.00047    |
| Consumer          | Packaging waste management        | 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.), $E_i$, 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              | 0.00041  | 0.00018 | 0.00018 | 0.00091    |
|                   | Waste transportation              | 0.00014  | 0.00016 | 0.00015 | 0.00056    |
|                   | Retail food and packaging waste management | −0.0040 | −0.0045 | −0.0043 | −0.015     |
| 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  | 0.0015  | 0.017      |
|                   | Retail refrigeration              | 0.00058  | 0.00075 | 0.0015  | 0.0019     |
|                   | Consumer refrigeration            | 0.00058  | 0.00075 | 0.0015  | 0.0019     |
|                   | 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       |
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 CO₂ eq., respectively. If we assume that the avocados and lemons are
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, celeries, lemons, and strawberries in California are 24, 12, 12, and 76 000 tons of CO₂ 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 CO₂ 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 CO₂ 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 cardboard 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).

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References
[1] Kantor L S, Lipton K, Manchester A and Oliveira V 1997 Estimating and addressing America’s food losses Food Rev. 20 2–12
[2] Lipinski B, Hanson C, Lomax J, Kitinoja L, Waite R and Searchinger T 2013 Reducing food loss and waste World Resour. Inst. Work. Paper pp 1–40 (https://www.academia.edu/download/34564759/WRI-UNEP_Reducing_Food_Loss_and_Waste.pdf)
[3] Oelofse S H and Nahman A 2013 Estimating the magnitude of food wasted generated in South Africa Waste Manag. Res. 31 86–88
[4] FAO 2017 FAOSTAT statistics database (FAO) (available at: http://faostat.fao.org/)
[5] Tilmann D, Balzer C, Hill J and Beforet B L 2011 Global food demand and the sustainable intensification of agriculture Proc. Natl Acad. Sci. 108 20260–4
[6] Gustavsson J, Cederberg C, Sonesson U, Van Otterdijk R and Meybeck A 2011 Global food losses and food waste—extent, causes and prevention (Rome: FAO) (available: https://www.fao.org/3/a-j597e.pdf)
[7] Gunders D and Bloom J 2017 Wasted: how America is losing up to 40 percent of its food from farm to fork to landfill (Natural Resources Defense Council New York) (available at: https://www.nrdc.org/sites/default/files/wasted-food-1p.pdf)
[8] Kummu M, De Moel H, Porkka M, Siebert S, Varis O and Ward P J 2013 Lost food, wasted resources: global food supply chain losses and their impacts on freshwater, cropland, and fertilizer use Sci. Total Environ. 438 477–89
[9] Hall K D, Guo J, Dore M and Chow C C 2009 The progressive increase of food waste in America and its environmental impact PloS One 4 e7940
[10] FAO 2013 Food Waste Footprint: Impacts on Natural Resources (FAO)
[11] Heller M C and Keoleian G A 2015 Greenhouse gas emission estimates of US dietary choices and food loss J. Ind. Ecol. 19 391–401
[12] Porter S D, Reay D S, Bomberg E and Higgins P 2018 Avoidable food losses and associated production-phase greenhouse gas emissions arising from application of cosmetic standards to fresh fruit and vegetables in Europe and the UK J. Clean. Prod. 201 869–78
[13] ReFED 2016 A roadmap to reduce US food waste by 20 percent Rethink Food Waste through Economics and Data (available at: https://www.refed.com/downloads/ReFED_Report_2016.pdf)
[14] Parfitt J, Barthel M and Macnaughton S 2010 Food waste within food supply chains: quantification and potential for change to 2050 Philos. Trans. R. Soc. B 365 3065–81
[15] Corrado S, Ardente F, Sala S and Saouter E 2017 Modelling of food loss within life cycle assessment: from current practice towards a systematisation J. Clean. Prod. 140 847–59
[16] Shafiee-Jood M and Cai X 2016 Reducing food loss and waste to enhance food security and environmental sustainability Environ. Sci. Technol. 50 8432–43
[17] Wang K and Nakakubo T 2020 Comparative assessment of waste disposal systems and technologies with regard to
greenhouse gas emissions: a case study of municipal solid waste treatment options in China. J. Clean. Prod. 260 120827
[18] Ribeiro A R, Rok J, Harmsen R, Carreón J R and Worrell E 2019 Food waste in an alternative food network—a case-study Resour. Conserv. Recycl. 149 210–9
[19] Djekić I, Milošadovíc Z, Djekić S and Tomasevic I 2019 Household food waste in Serbia—attitudes, quantities and global warming potential J. Clean. Prod. 229 44–52
[20] Moutj J A, Allan S R, Hewitt C N and Berners-Lee M 2018 Greenhouse gas emissions of food waste disposal options for UK retailers Food Policy 77 50–58
[21] Cerutti A K, Beccaro G L, Bruun S, Bosco S, Donno D, Notarnicola B and Boussou G 2014 Life cycle assessment application in the fruit sector: state of the art and recommendations for environmental declarations of fruit products J. Clean. Prod. 73 125–35
[22] Maraseni T N, Coulfield G, Maroulis J and Chen G 2010 An assessment of greenhouse gas emissions from the Australian vegetables industry J. Environ. Sci. Health. B 45 578–88
[23] Khoshnevisan B, Raffie S and Mousazadeh H 2013 Environmental impact assessment of open field and greenhouse strawberry production Eur. J. Agron. 50 29–37
[24] Cerutti A K, Galizia D, Bruun S, Mellano G M, Beccaro G L and Boussou G 2014 Life cycle assessment of different apple supply chains in Northern Italy Towards Life Cycle Sustainability Management (Berlin: Springer) pp 341–8
[25] Knudsen M T, de Almeida G F, Langer V, de Abreu L S and Halberg N 2011 Environmental assessment of organic juice imported to Denmark: a case study on oranges (Citrus sinensis) from Brazil Org. Agric. 1 167
[26] Astier M, Merlin-Uribe Y, Villamil-Echeverri L, Garciaareal A, Gavito M E and Masera O R 2014 Energy balance and greenhouse gas emissions in organic and conventional avocado orchards in Mexico Ecol. Indic. 43 281–7
[27] Pergola M, D’Amico M, Celano G, Palese A, Scuderi A, Di Vita G, Pappalardo G and Inglese P 2013 Sustainability evaluation of Sicily’s lemon and orange production: an energy, economic and environmental analysis J. Environ. Manage. 128 674–82
[28] Williams H and Wikström F 2011 Environmental impact of packaging and food losses in a life cycle perspective: a comparative analysis of five food items J. Clean. Prod. 19 43–48
[29] Wikström F and Williams H 2010 Potential environmental gains from reducing food losses through development of new packaging—a life cycle model Packag. Technol. Sci. 23 403–11
[30] Papargyropoulou E, Lozano B, Steinberger J K, Wright N and Bin Ujang Z 2014 The food waste hierarchy as a framework for the management of food surplus and food waste J. Clean. Prod. 76 106–15
[31] Beausang C, Hall C and Toma L 2017 Food waste and losses in primary production: qualitative insights from horticultural production in Italy Hortic. Res. 4 1–6
[32] Johnson L K, Dunning R D, Bloom J D, Gunter C C, Boyette M D and Crean-on-farm 2018 Estimating on-farm food loss at the field level: a methodology and applied case study on a North Carolina farm Resour. Conserv. Recycl. 137 243–50
[33] Gillman A, Campbell D C and Spang E S 2019 Does on-farm food loss prevent waste? insights from California produce growers Resour. Conserv. Recycl. 150 104408
[34] Baker G A, Gray L C, Harwood M J, Osland T J and Tooley J B 2019 On-farm food loss in northern and central California: results of field survey measurements Resour. Conserv. Recycl. 149 241–51
[35] Buzby J C and Hyman J 2012 Total and per capita value of food loss in the United States Food Policy 37 561–70
[36] Buzby J C, Wells H F, Axtman B and Mickey J 2009 Supermarket loss estimates for fresh fruit, vegetables, meat, poultry, and seafood and their use in the ERS loss-adjusted food availability data (USDA) (available at: https://www.ers.usda.gov/publications/pub-details/?pubid=44309)
[37] Buzby J C, Hyman J, Stewart H and Wells H F 2011 The value of retail- and consumer-level fruit and vegetable losses in the United States J. Consum. Aff. 45 492–515
[38] Kader A A 2004 Increasing food availability by reducing postharvest losses of fresh produce V Int. Postharvest Symp. vol 682 pp 2169–79
[39] Branco R, Almeia B and Bolton K 2017 Life cycle assessment of supermarket food waste Resour. Conserv. Recycl. 118 39–46
[40] Moreno I C, Tran T and Potts M D 2020 Consider a broccoli stalk: how the concept of edibility influences quantification of household food waste J. Environ. Manage. 256 109977
[41] Hanson C, Lipinska B, Robertson K, Dias D, Gavilan I, Greverath P, Ritter S, Fonseca J, VanOtterdijk R and Timmermans T 2016 Food Loss and Waste Accounting and Reporting Standard (World Resources Institute)
[42] Östergren K, Gustavsson J, Bos-Brouwers H, Timmermans T, Hansen O-J, Möller H, Anderson G, O’Conner C, Soeholdt H and Quested T 2014 FUSIONS definitional framework for food waste Europäische Union (available at: https://www.eu-fusions.org/phocadownload/Publications/FUSIONS%20Definitional%20Framework%20Food%20Waste%202014.pdf)
[43] USDA Economic Research Service 2019 Loss-adjusted food availability (LAFA) data system (USDA) (available at: https://www.ers.usda.gov/data-products/food-availability-per-capita-data-system/loss-adjusted-food-availability-documentation/)
[44] Campbell D and Munden-Dixon K 2018 On-farm food loss: farmer perspectives on food waste J. Extension 56 3
[45] Kantor L S 1998 A Dietary Assessment of the US Food Supply: Comparing per Capita Food Consumption with Food Guide Pyramid Serving Recommendations. (US Department of Agriculture, Economic Research Service) (https://doi.org/10.2204/ag.econ.34079)
[46] Bolda M P, Tourte L, Murdock J and Summer D A 2016 Sample costs to produce and harvest strawberries: central Coast Region, Santa Cruz and Monterey Counties Univ. Calif. Agric. Nat. Resour. (available at: https://coststudyfiles.ucdavis.edu/uploads/cs_public/a1/39/a39af56-5c70-48ec-8367-bc53c31eb5/lemons-vs-strawberry2016-final-2-5-1-2017.pdf)
[47] O’Connell N V, Kalbien C E, Klonsky K M and Tumber K P 2015 Sample costs to establish an orchard and produce lemons Univ. Calif. Agric. Nat. Resour. (available at: https://coststudyfiles.ucdavis.edu/uploads/cs_public/a1/39/a39af56-5c70-48ec-8367-bc53c31eb5/lemons-vs-strawberry2015.pdf)
[48] Takele E, Bender G and Vue M 2012 Avocado sample establishment and production costs and profitability analysis for San Diego and Riverside Counties Univ. Calif. Agric. Nat. Resour. (available at: https://coststudyfiles.ucdavis.edu/uploads/cs_public/53/39/5339fd8f5757-4ae6-8482-b3162d71a8fd/avocadosdororganic_reports2011.pdf)
[49] Takele E, Daugovish O and Vue M 2013 Costs and profitability analysis for celery production in the Oxnard Plain, Ventura County, 2012-2013 Univ. Calif. Agric. Nat. Resour. (available at: https://coststudyfiles.ucdavis.edu/uploads/cs_public/3c/da/3ca41bc970-4882-b2c3-f97b8758ac3d/costs-and-profitability-analysis-for-celery-production-in-the-oxnard-plain-ventura-county-2012-13.pdf)
[50] Taptich M N and Horvath A 2014 Bias of averages in life-cycle footprinting of infrastructure: truck and bus case studies Environ. Sci. Technol. 48 13045–52
[51] Fricka B and Becker B 2010 Energy use of doored and open vertical refrigerated display cases Int. Refrigeration and Air Conditioning Conf. (available at: http://docs.lib.purdue.edu/iracc/1154)
[52] U.S. Environmental Protection Agency 2016 Documentation for greenhouse gas emission and energy factors used in the waste reduction model (WARM) (Washington, DC: EPA)
Office of Resource Conservation and Recovery) (available at: https://www.epa.gov/warm/documentation-waste-reduction-model-warm)

[53] California Department of Food and Agriculture 2018 California Agricultural Statistics Review 2017–2018 State of California (available at: https://www.cdfa.ca.gov/statistics/PDFs/2017-18AgReport.pdf)

[54] Nahlik M J, Kaehr A T, Chester M V, Horvath A and Taptich M N 2016 Goods movement life cycle assessment for greenhouse gas reduction goals J. Ind. Ecol. 20 317–28

[55] Energy Star 2020 Certified residential refrigerators US Environmental Protection Agency and US Department of Energy (available at: https://www.energystar.gov/productfinder/product/certified-residential-refrigerators/results)

[56] Tonini D, Albizzati P F and Astrup T F 2018 Environmental impacts of food waste: learnings and challenges from a case study on UK Waste Manage. 76 744–66

[57] U.S. Environmental Protection Agency 2019 Advancing sustainable materials management: 2017 fact sheet EPA (available at: https://www.epa.gov/sites/production/files/2019-11/documents/2017_facts_and_figures_fact_sheet_final.pdf)

[58] U.S. Department of Agriculture, Agricultural Research Service 2019 FoodData Central (USDA) (available at: https://fdc.nal.usda.gov)

[59] Bell E M and Horvath A 2020 Modeling the carbon footprint of fresh produce: effects of transportation, localness, and seasonality on US orange markets Environ. Res. Lett. 15 034040

[60] Taptich M and Horvath A 2015 Freight on a low-carbon diet: accessibility, freightsheds, and commodities Environ. Sci. Technol. 49 11321–8

[61] Facanha C and Horvath A 2005 Environmental assessment of logistics outsourcing J. Manage. Eng. 21 27–37

[62] Stokes-Draut J, Taptich M, Kavvada O and Horvath A 2017 Evaluating the electricity intensity of evolving water supply mixes: the case of California’s water network Environ. Res. Lett. 12 114005

[63] Cicas G, Hendrickson C T, Horvath A and Matthews H S 2007 A regional version of a U.S. economic input-output life-cycle assessment model Int. J. Life Cycle Assess. 12 365–72

[64] Vergara S, Damgaard A and Horvath A 2011 Boundaries matter: greenhouse gas emission reductions from alternative waste treatment strategies for California’s municipal solid waste Resour. Conserv. Recycl. 57 87–97

[65] Bell E M, Stokes-Draut J R and Horvath A 2018 Environmental evaluation of high-value agricultural produce with diverse water sources: case study from Southern California Environ. Res. Lett. 13 025007

[66] Qin Y and Horvath A 2020 Use of alternative water sources in irrigation: potential scales, costs, and environmental impacts in California Environ. Res. Commun. 2 055003

[67] de Hooge I E, van Dulm E and van Trijp H C 2018 Cosmetic specifications in the food waste issue: supply chain considerations and practices concerning suboptimal food products J. Clean. Prod. 183 698–709