Resources, Conservation & Recycling 176 (2022) 105945

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

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

Full Length Article

What contributes more to life-cycle greenhouse gas emissions of farm produce: Production, transportation, packaging, or food loss?

Yuwei Qin [a,b,*], Arpad Horvath [a,b]

[a] Department of Civil and Environmental Engineering, University of California, Berkeley, CA 94720, United States
[b] ReNUWIt Engineering Research Center, University of California, Berkeley, CA 94720, United States

ARTICLE INFO

Keywords:
Waste
Plastics
Fruits
Vegetables
Logistics
Retail

ABSTRACT

The food production and supply systems are some of the biggest contributors to climate change, and food loss from the entire food chain aggravates the problem. We developed a model to estimate the GHG emissions from the entire food cycle (production, packaging, transportation, refrigeration, and waste management), and applied it to cherries, onions, and plums, the first time these produce have been assessed comprehensively in the United States. We pulled into the analysis 6 additional fruits and vegetables for which California accounts for more than 50% of U.S. production and which we have assessed at least partially earlier: strawberries, avocados, lemons, celery, oranges, and tomatoes. We assessed uncertainty for 34 parameters through Monte Carlo simulation. The total life-cycle food losses for one unit of cherries, onions, and plums produced are 66%, 57%, and 44%, respectively. The consumer stage contributes most of the food loss for eight of the nine produce. The results show that food loss contributes 19–61%, transportation 14–46%, packaging 11–31%, and farm production 7.7–30% to the total emissions. Alternative packaging was also explored. Polyethylene produce bags substituted with PLA bags can lower the total food-loss-inclusive emissions by only 7%, 5%, and 4% for tomatoes, oranges and onions, respectively. Forgoing retail-provided PE bags for produce that are not pre-packaged could reduce total GHG emissions by 12%, 10%, 6%, 6%, and 4% for one unit of tomatoes, onions, lemons, plums, and oranges, respectively. The GHG emissions for the 9 produce can be significantly reduced by decreasing consumer-level food loss. For tomatoes and onions, more than half of the emissions due to food loss can be offset by forgoing packaging at the retail stores.

1. Introduction

Providing sufficient food for the world's growing population while reducing the impacts on the environment is one of the major challenges of the 21st century (United Nations, 2015). Food consumption contributes a significant proportion to the world's energy use and greenhouse gas (GHG) emissions (Camilleri et al., 2019; Clune et al., 2017; Hu et al., 2016). Agricultural production accounts for 19–29% of annual global GHG emissions, generating 9,800–16,900 megatons of carbon dioxide equivalent (CO_2 eq.) (Vermeulen et al., 2012). A recent study found that food-system emissions contributed 34% to the total GHG emissions globally due to agricultural and land use activities (Crippa et al., 2021). A European analysis found that 31% of the EU-25's GHG impacts were contributed by food (Tukker et al., 2006). A recent study estimated that the U.S. food system is responsible for 985 megatons of CO_2 eq. or 3200 kg of CO_2 eq. per capita per year (Hitaj et al., 2019). Beside the energy sector, transportation, buildings, and industry, the food sector has a significant responsibility to lower its environmental footprint.

The food chain generates GHG emissions at all phases in its life cycle from the farm to processing, packaging, transportation, refrigeration, retailing, consumption, and waste management. Among the food-related emissions, food loss and packaging are thought to be significant sources of GHG emissions. A study based on U.S. diets indicates that food loss accounted for 34% of GHG emissions, 35% of energy use, and 34% of blue water use to the total food-related resource consumption (Birney et al., 2017). Packaging also accounts for a large proportion of the food carbon footprint, contributing about 20% to the emissions associated with fruits and vegetables (Heller, 2017). These are aggregate estimates. The task for industry and assisting researchers is to attribute emissions to specific food items and find ways to make food chains more environmentally friendly.

In this monumental task, life-cycle assessment (LCA) has an essential

* Corresponding author at: Department of Civil and Environmental Engineering, University of California, Berkeley, CA 94720, United States.
E-mail address: yuweiqin@berkeley.edu (Y. Qin).

https://doi.org/10.1016/j.resconrec.2021.105945
Received 24 May 2021; Received in revised form 7 August 2021; Accepted 18 September 2021
Available online 7 October 2021

role. It is a quantitative method that is performed according to the ISO 14040 and 14044 principles, focuses on all life-cycle stages of a product, process or service, documents the steps and assumptions of the analysis, catalogues the data, and interprets the findings so that decisions can be made with confidence. Many studies on food products have used LCA to identify hotspots of environmental impacts and offer directions for improvement (Canaj et al., 2020; Cellura et al., 2012; Del Borghi et al., 2014; Roy et al., 2009).

The number of papers across the vast range of food items is impossible to cite, but to date, the most comprehensive summary of the field has been provided in Clune et al.'s (2017) study, which evaluated 369 LCA studies that covered 168 food types and 1718 values of GHG emissions. A trend that has emerged from the Clune et al. (2017) paper is that although the applications of LCA techniques to food studies have increased, there are relatively few analyses available for fruits and vegetables, considered high-value, specialty, fresh, and perishable produce that we should be consuming more of in a healthy diet.

In this article, for the first time in the United States, we estimate the GHG emissions of three fruits and vegetables: cherries, plums, and onions. Table 1 lists the available LCA studies over the past decade. The life-cycle GHG emissions of one kilogram of cherries range from 0.26 to 0.88 kg CO_2 eq., and the emissions for one kilogram of onions range from 0.21 to 0.42 kg CO_2 eq. One kilogram of plum production emits 0.88 kg CO_2 eq. emissions. However, several of these studies did not consider comprehensively the emissions due to food loss, and packaging was omitted. The growing regions may not be significant (e.g., Norway), representative, or specific. The United States, on the other hand, is the world's second largest producer of cherries (FAOSTAT, 2019a), third for plums (FAOSTAT, 2019b), and fourth for onions (FAOSTAT, 2019b).

Even beyond the articles shown in Table 1, most of the limited number of LCA studies on high-value produce only focus on the cradle-to-farm-gate phase, and do not consider food loss anywhere in the food cycle, packaging, or waste management of food waste and packaging (Astier et al., 2014; Cerutti et al., 2014; Khoshnevisan et al., 2013; Knudsen et al., 2011; Pergola et al., 2013). To our knowledge, the question of whether food loss or packaging contributes more to the total GHG emissions of food cycles has also not been addressed yet.

2. Methods and data

To help fill the gap in food environmental assessment studies, we have developed a model to estimate the GHG emissions from the entire life cycle of fruits and vegetables (from farm to consumers and waste management), and considered the food loss in each life-cycle stage. We have also evaluated the emission differences in switching from typical customer packaging to alternative packaging. The functional unit in the study is one packaging size of produce. We also included the detailed food loss results per serving size of produce.

The life cycle of produce covered in our study consists of the following stages (Fig. 1): farm production, packaging, farm-to-retail transportation and refrigeration, retail refrigeration and sales, consumption, and end of life (waste management). We evaluated food loss at four main stages, and the categorization of food loss stages was inspired by the FLW Standard, the UN Food and Agricultural Organization's definition, and the FUSIONS Definitional Framework for Food Waste (FAO, 2013; Hanson et al., 2016; Östergren et al., 2014). Table S1 in the *Supplementary Material* presents the glossary of terms used in the study. Note that the retail-to-consumer stage is not included in the environmental assessment of produce because it varies with the consumer's choices to carry home the produce.

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

$$E_t = E_c + E_l \tag{1}$$

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:

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

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 a 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 and data used to assess emissions associated with production, on-farm and customer packaging, transportation, refrigeration in the truck, refrigeration in the retail store, consumption at home, and waste management are included in the *Supplementary Material* (Section S5-S8).

The production data were sourced from the "cost and return studies" of the University of California, Davis, and they are representative of the newest data (2016-2017) for Californian growing practices (Bolda et al., 2016; Day et al., 2016; Grant et al., 2017; O'Connell et al., 2015a, 2015b; Takele et al., 2013, 2011; Turini et al., 2018; Wilson et al., 2016). The state produces 95% of U.S. plums (UCDavis, 2021), the most onions (Lazicki et al., 2016), and is second in cherry growing (Shahbandeh, 2020). Detailed data of production inputs and yields are provided in the *Supplementary Material* (Table S2).

The packaging of agricultural produce consists of two stages: (1) packaging on the farm, usually in large boxes, and (2) packaging for retail sale, which can be in plastic boxes and produce bags or pouches. In some stores, produce is available for purchasing in bulk, without individual packaging.

Fig. 2 illustrates the food packaging assessed. Big carton boxes are used in bulk delivery of produce from the farm to the point of retail sale (Fig. 2 (a)). We also considered the packaging in retail stores, which includes default packaging for the produce in retail stores and alternative packaging that customers can use to carry the produce home (Fig. 2 (b)). For example, cherries are typically packaged in polyethylene (PE) pouches. Onions and plums are most often displayed in bulk in the stores, and customers can choose to use the provided PE produce bags or forgo packaging and carry the produce home in their own shopping bags, commingled with other purchased goods. We estimated the emissions associated with the amount of typical packaging for 1 kg of the produce. Detailed information on packaging methods and materials can be found in the *Supplementary Material* (Tables S7 and S8).

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

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

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 consumption 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

Table 1
LCA studies on cherries, plums, and onions.

Source	Produce	Region	Emissions (kg CO_2/kg)
Svanes and Johnsen (2019)	Cherries	Norway	0.64
Rana et al. (2019)	Cherries	Italy	0.58
Clune et al. (2017)	Cherries	World average	0.26–0.88
Tassielli et al. (2018)	Cherries	Italy	0.44
Svanes and Johnsen (2019)	Plums	Norway	0.88
Maraseni et al. (2010)	Onions	Australia	0.21
Wiltshire et al. (2009)	Onions	UK	0.42

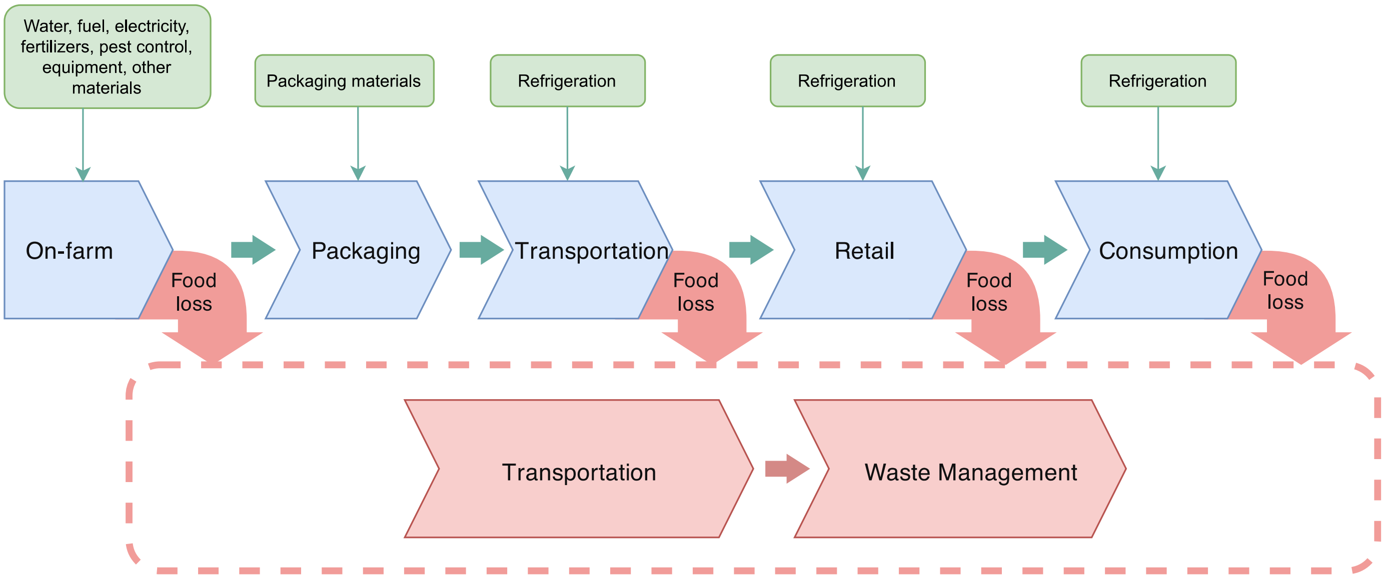

Fig. 1. Flow diagram of assessed food cycle and food loss stages and processes in the study.

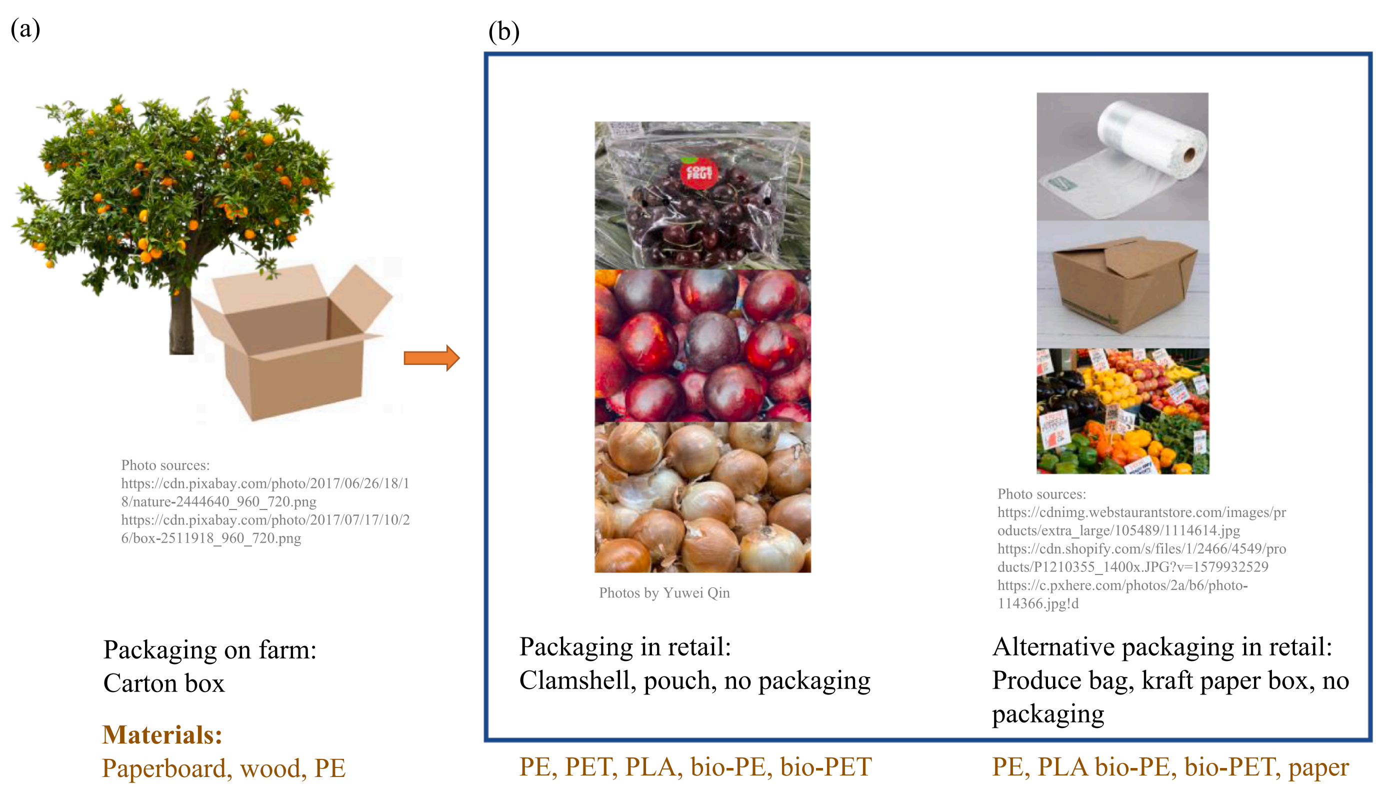

Fig. 2. Diagram of food packaging considered in the food supply chain. Typical packaging types and sizes are analyzed in the study.

the emissions from food harvest, on-farm packaging, transportation, and refrigeration in the truck; e_3 includes the emissions of food harvesting, on-farm packaging, transportation, and refrigeration in the truck and retail store, e_4 includes the emissions of food harvesting, on-farm packaging, transportation, and refrigeration in the truck and retail store, customer packaging and home refrigeration storage.

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

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

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.

Table 2 shows the food loss ratios, the rate 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 of the food

Table 2
Food loss rates for cherries, onions, and plums.

	Cherry	Onion	Plum
On-farm (Baker et al., 2019; Campbell and Munden-Dixon, 2018; Franke et al., 2016; McKenzie et al., 2017; Svanes and Johnsen, 2019)	15%	15%	13%
Farm-to-retail (USDA Economic Research Service, 2019)	8.0%	6.0%	5.0%
Retail (USDA Economic Research Service, 2019)	10%	6.5%	5.5%
Consumer (USDA Economic Research Service, 2019)	51%	43%	27%

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 data came from field studies (Baker et al., 2019; Campbell and Munden-Dixon, 2018; Franke et al., 2016; McKenzie et al., 2017; Svanes and Johnsen, 2019). The food loss ratios at the farm-to-retail, retail, and consumer phases were extracted from the LAFA dataset (USDA Economic Research Service, 2019) .

The life-cycle food losses for one unit of *produced* cherries, onions, and plums are 66%, 57%, and 44%, respectively. That means, for example, that 15% of cherries will be lost on the farm after 1 kg was produced (thus 0.85 kg leaves the farm). Then 8% of the remaining cherries will be lost during transportation from farm to retail, followed by an additional loss of 10% in retail and about 50% in the consumer's home. Therefore, of the original 1 kg of cherries produced, only about 34% will be eaten. From the consumption perspective, the Sankey diagrams in Figs. 3–5 show that 1.9, 1.3, and 0.75 units of produce are wasted for every unit of cherries, onions, and plums consumed, respectively. For example, in order to consume 1 kg of cherries, 2.9 kg of cherries need to be grown on the farm; 0.45 kg will be wasted on the field; 0.20 kg will be spoiled during transportation from farm to retail; 0.23 kg will be thrown away at retail stores, and 1.0 kg will be thrown away at home.

On-farm and consumer-level food-loss ratios vary significantly across the different produce, while the farm-to-retail and retail-level loss ratios are similar. Consumer-level food loss is the top contributor to total food loss, adding about one-half for cherries, onions, and plums. On-farm losses contribute about a half to the total food loss for onions.

The model considers 34 main life-cycle inventory (LCI) parameters associated with each produce's supply chain, including food loss ratios in each phase, transportation distances, refrigeration duration, emission factors of energy, fertilizer, biocides, packaging materials, and waste management practices, etc. (Energy Star®, 2020; Fricke and Becker, 2010; Hottle et al., 2017; Karakaya and Özilgen, 2011; Nahlik et al., 2016; Sanjuán et al., 2014; Taptich and Horvath, 2014; Tassou et al., 2012; Vink and Davies, 2015). Table 3 presents the key parameters and assumptions for environmental assessment of cherries, onions, and plums. The detailed LCI parameters can be found in the *Supplementary Material* (Tables S10.1–S10.9).

Uncertainty assessment. We performed Monte Carlo simulation to explore the uncertainties in the 34 parameters used in our model. The probability distribution functions of the parameters can be found in the *Supplementary Material* (Tables S10.1–S10.9). 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 and packaging emission factors were based on the existing literature (Baker et al., 2019; Hottle et al., 2017; Johnson et al., 2018; Sturges et al., 2019; Vink and Davies, 2015). Based on how much confidence we had in the accuracy of data, we assumed uncertainty ranges of 20% for the emission factors for electricity, fuels, refrigeration, transportation, and materials used on the farm, and uncertainty ranges of 50% for the emission factors of food and packaging waste management and refrigeration time. Triangular distributions were assigned to the parameters because they are appropriate here and are commonly used to present uncertainties of parameters in LCA (Björklund, 2002; Heard et al., 2019; Huang et al., 2020; Lloyd and Ries, 2007; Qin and Suh, 2017). We conducted 10,000 iterations for each produce. The ranges, which indicate 95% uncertainty intervals of the simulated results, are presented as error bars in Fig. 6.

3. Results and discussion

The 100-year global warming potential (GWP) results are illustrated in Figs. 6–8. The total GHG emissions (E_t) for one packaging size of

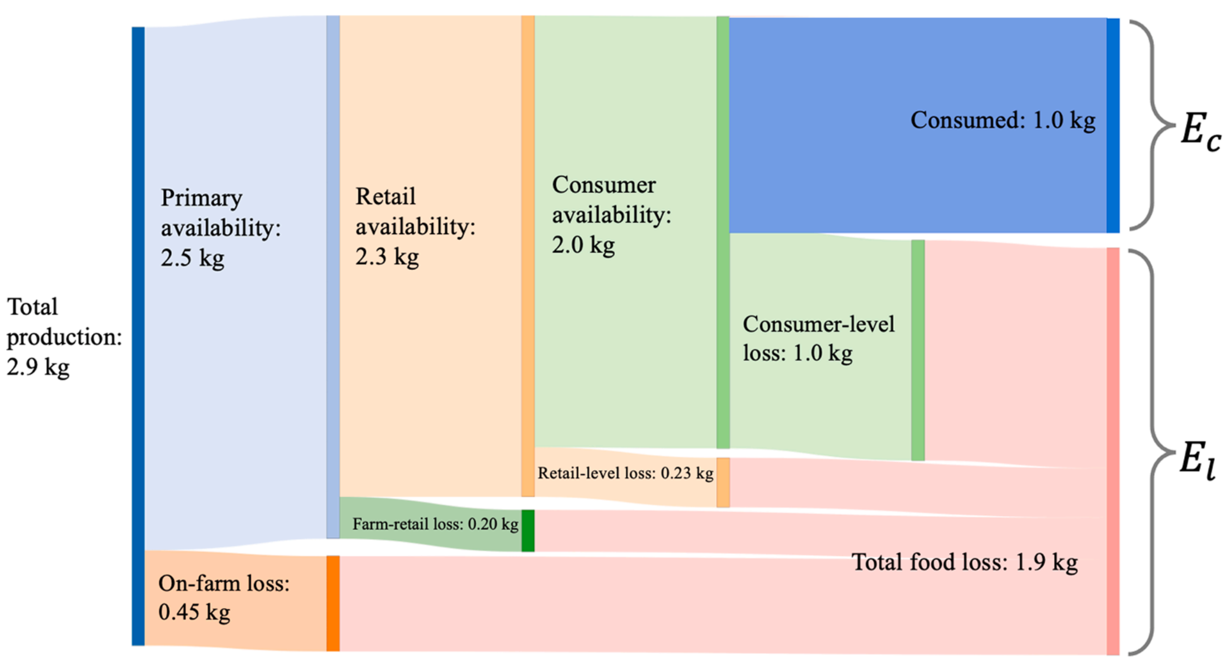

Fig. 3. Sankey diagram for the production and food loss of one kilogram of cherry consumption. E_c covers the life-cycle emissions for consumed food from production, packaging, transportation, and refrigeration in the truck, retail store, and consumer's home. E_l covers the cradle-to-grave emissions from total food loss.

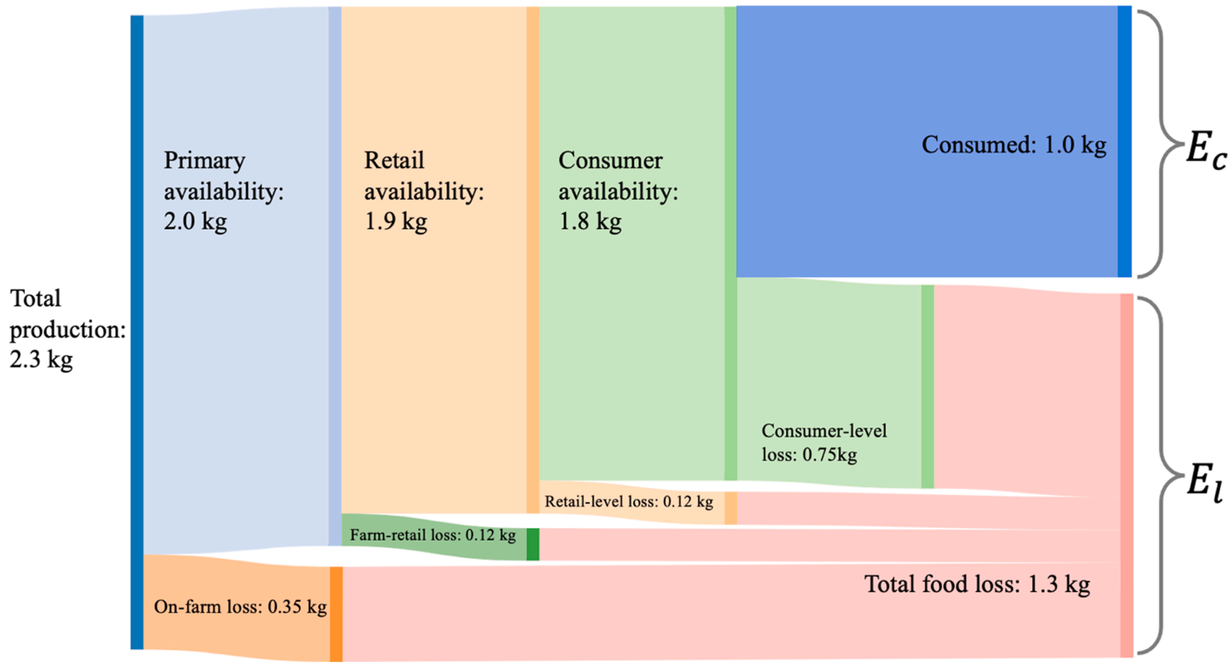

Fig. 4. Sankey diagram for the production and food loss of one kilogram of onion consumption.

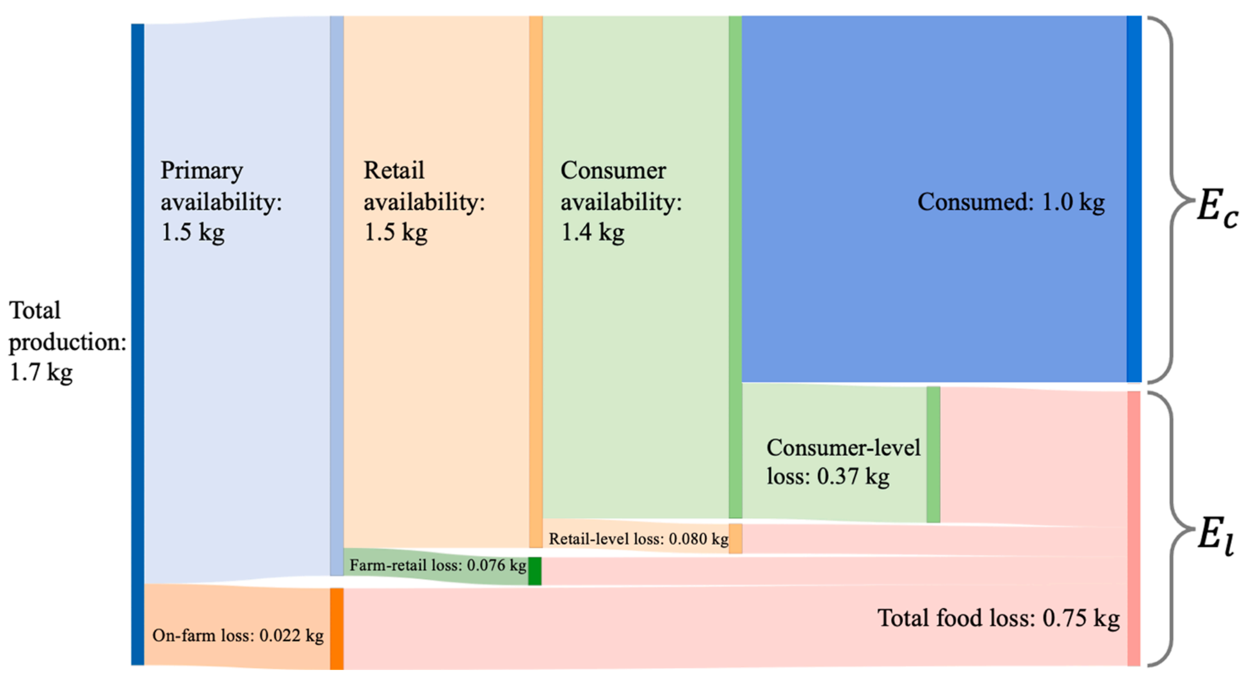

Fig. 5. Sankey diagram for the production and food loss of one kilogram of plum consumption.

consumed fruits and vegetables, accounting for farm production, packaging, transportation, refrigeration during transportation, retail operations, home refrigeration, food loss, and waste management are shown in Fig. 6. To put the results for cherries, plums, and onions into context, and be able to make stronger points, with more data, about the significance of farm production, packaging, transportation, and food loss, we pulled into the analysis 6 additional fruits and vegetables for which California supplies more than 50% of U.S. production: strawberries, avocados, lemons, celery, oranges, and tomatoes. The first four we have assessed previously in (Qin and Horvath, 2020a, 2020b), and oranges were partially analyzed in (Bell and Horvath, 2020). A tomatoes analysis we have not yet published (Bell et al., 2021). The analysis of alternative packaging and food loss for oranges and tomatoes has not yet been published. The Sankey diagrams and the probability distribution functions (Tables S10.1–S10.9) for the six are included in the *Supplementary Material*. Tables S2 and S3 presents the key parameters and assumptions.

The U.S. retail packaging sizes for avocado, lemon, onion, orange, plum, and tomato are one unit, and for strawberry, cherry, and celery are 454 g (1 pound) (U.S. Department of Agriculture, Agricultural Research Service, 2019). Food loss contributes 61%, 49%, 44%, 40%, and 40% to the total emissions (E_t) of cherries, onions, plums, strawberries, and celery, respectively. Transportation contributes 42%, 33%, 33%, 31% to the total emissions of tomatoes, plums, celery, and onions, respectively. Cherries and strawberries are packaged in PE pouches and

Table 3
Key LCI parameters and assumptions used in the study.

	Unit	Cherry	Onion	Plum
Assumption				
Transportation distance from farm to retail	km	300	300	300
Transportation distance of waste	km	30	30	30
Refrigeration period in retail	Day	3	0	0
Refrigeration period at home	Day	2	0	0
Emission factor				
Truck transportation (Taptich and Horvath, 2014)	kg CO_2 eq./(kg*km)	0.00036	0.00036	0.00036
Transportation refrigeration (Tassou et al., 2012)	kg CO_2 eq./(m^3*km)	0.0025	0.0025	0.0025
Retail refrigeration (Fricke and Becker, 2010; Sanjuán et al., 2014)	kg CO_2 eq./(m^3*day)	2.0	2.0	2.0
Paperboard packaging (Karakaya and Özilgen, 2011)	kg CO_2 eq./kg	1.1	1.1	1.1
PET packaging (Hottle et al., 2017)	kg CO_2 eq./kg	2.7	2.7	2.7
PE packaging (Hottle et al., 2017)	kg CO_2 eq./kg	1.9	1.9	1.9
PLA packaging (Vink and Davies, 2015)	kg CO_2 eq./kg	0.62	0.62	0.62
Home refrigeration (Energy Star, 2020)	kg CO_2 eq./(m^3*day)	0.80	0.80	0.80

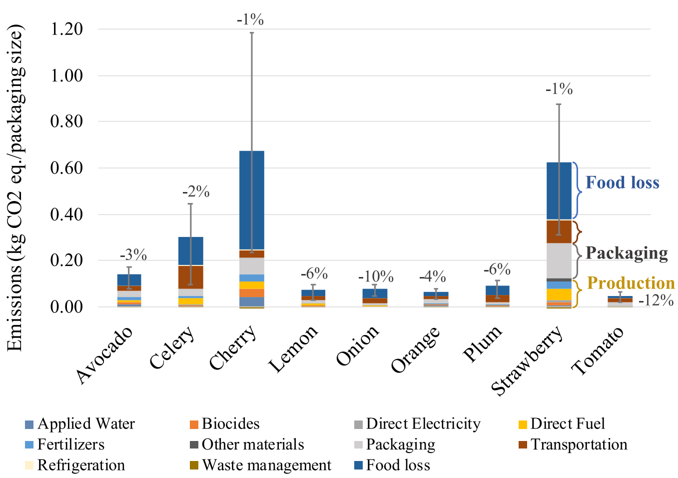

Fig. 6. GHG emissions for 9 fruits and vegetables at the consumer level in typical retail packaging and sizes. The percentages above the bars indicate the changes in GHG emissions when switching from typical packaging to alternative packaging. The typical packaging includes PE produce bags for avocados, celery, lemons, onions, oranges, plums, and tomatoes, PE pouches for cherries, and PET clamshells for strawberries. The alternative packaging includes PLA produce bags for cherries and strawberries, and forgoing packaging for avocados, celery, lemons, onions, oranges, plums, and tomatoes.

PET clamshells, respectively, and the other seven produce are packaged in PE produce bags. Packaging contributes 31%, 25%, 24%, and 20% to the total emissions of tomatoes, strawberries, oranges, and avocados, respectively. Production contributes 31%, 27%, and 22% to the total emissions of avocados, oranges, and lemons, respectively. In general, food loss is the largest contributor to total GHG emissions of produce from cradle to grave. Overall, food loss contributes 19–61% to the total emissions for the nine produce, transportation 14–46%, packaging 11–31%, and production 7.7–30%. The food loss contributions to GHG emissions ranged from 22 to 43% for fresh produce from a previous study of various types of food, while that study only provided the food loss analysis for three fresh produce (Heller et al., 2019). The detailed contribution results can be found in the *Supplementary Material* (Table S11).

Fig. 7 presents GHG emissions due to food loss for the 9 produce per serving size in the four life-cycle phases. The serving sizes for avocados, celery, cherries, lemons, onions, oranges, plums, strawberries, and tomatoes are 0.05, 0.51, 0.14, 0.084, 0.11, 0.14, 0.066, 0.14, and 0.091 kg, respectively. The emissions due to food loss are 0.13, 0.13, 0.028, and 0.022 kg CO_2 eq. for one serving size of cherries, strawberries, oranges, and avocados, respectively. The emissions from consumer-level food loss contribute, on average, the largest fraction of the total emissions because the food loss rates at the consumer level are high, and the consumer stage cumulates all the embodied emissions from the previous phases. The emissions associated with food loss at the consumer level contribute 89%, 82%, 70%, and 70% of the total emissions of food loss for oranges, onions, cherries, and plums, respectively. The food loss emission results from our study are consistent with a previous study that found that more than 40% of food loss emissions occurs at the retail and consumer level (Heller and Keoleian, 2015). On-farm food loss contributes 91%, 44%, and 35% of the total emissions of food loss for tomatoes, celery, and strawberries, respectively.

We also explored how the total emissions of produce would change by switching to different packaging from the consumer side. They can choose to forgo store-provided PE produce bags for avocados, celery, lemons, onions, oranges, plums, and tomatoes, or use PE produce bags instead of PE pouches or PET clamshells for cherries and strawberries. The results of total emissions which used the alternative packaging methods were compared with those using the typical packaging methods, and the percentage changes are indicated in Fig. 6. Switching to no packaging from using PE bags reduced GHG emissions by 12%, 10%, 6%, 6%, and 4%, for one unit of tomato, onion, lemon, and plum, and orange, respectively. For tomatoes and onions, more than half of the emissions due to food loss can be offset by forgoing packaging at the retail stores.

Fig. 8 compares the emissions from one produce bag and one packaging size of produce, including food loss without customer packaging. The emissions from one PE produce bag and one polylactic acid (PLA) produce bag are 0.0044 CO_2 eq. and 0.0014 CO_2 eq., respectively. The emissions of one PE produce bag are 11%, 7%, 7%, 6%, and 6% of the total emissions, including food loss, for one tomato, orange, lemon, onion, and plum, respectively. If we substitute PE produce bags with PLA produce bags, the total food-loss-inclusive emissions can be lowered by 7%, 5%, and 4% for tomatoes, oranges, and onions, respectively.

4. Conclusions

This study has evaluated the GHG emissions of high-value produce, including all life-cycle stages, food loss, packaging, and management of packaging and food waste. The analysis focused on production and consumption in California, but the results are applicable to other states in the United States because the food-loss rates from farm gate to consumer represent the national average, and the study uses typical consumer packaging methods in the United States. However, factors such as transportation distances, refrigeration periods, and emission factors would need to be adjusted in an analysis for another state or region (Cicas et al., 2007) (Vergara et al., 2011).

The results showed that food loss contributes 61%, 49%, 44%, 40%, and 40% to the total emissions of cherries, onions, plums, strawberries, and celery, respectively. Transportation contributes 42%, 33%, 33%, 31% to the total emissions of, tomatoes, plums, celery, and onions, respectively. Packaging contributes 31%, 25%, 24%, and 20% to the total emissions of tomatoes, strawberries, oranges, and avocados, respectively. Production contributes 31%, 27%, and 22% to the total emissions of avocados, oranges, and lemons, respectively. In general, food loss, transportation, packaging, and production contribute 36%, 28%, 19%, and 19%, respectively, to the total emissions for the nine produce on average. Even when the very impactful food loss is accounted for, packaging contributes more than 6% to the total life-

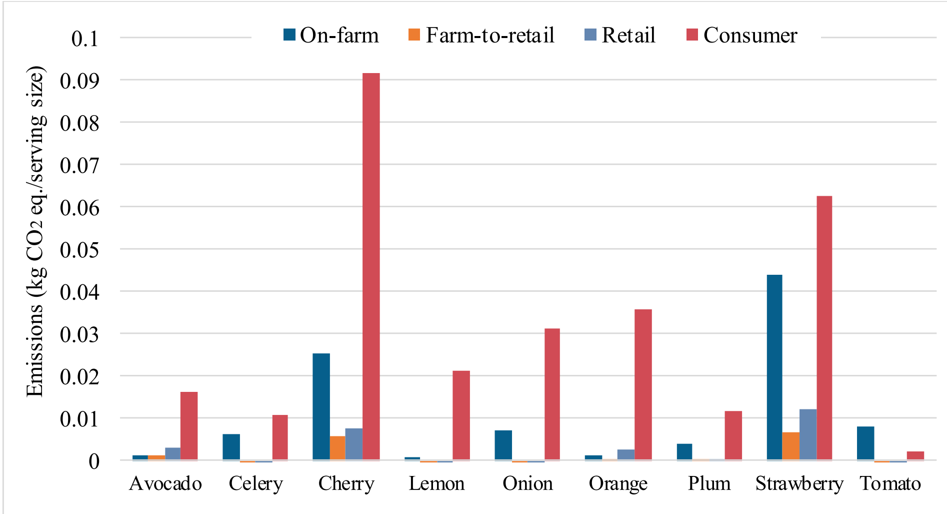

Fig. 7. GHG emissions due to food loss for 9 fruits and vegetables in the four life-cycle phases.

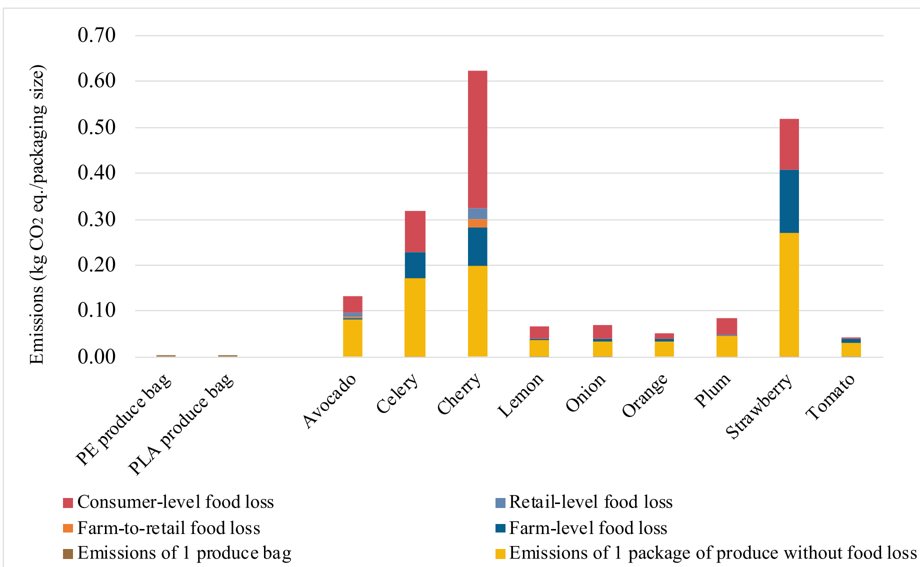

Fig. 8. Comparison between the emissions of one produce bag and emissions of food including food loss from the four life-cycle phases.

cycle emissions for tomatoes, onions, oranges, lemons, and plums.

We have found that consumer-level food loss is the top contributor to total food losses of eight of the nine produce. As much as 80% of the total food loss can be saved at the consumer level. However, the food loss rates are based on the EPA LAFA database, which does not consider regional differences and relies on household surveys on food waste instead of direct measurements. A comprehensive database with measurement data on food loss, including regional characteristics, would be beneficial to understand the actual food loss and associated environmental impacts.

Two main recommendations for reducing food-related emissions from our study include reducing consumer-level food loss and avoiding the use of PE produce bags for produce. Though changing consumer behavior may not be easy, educating consumers about rational purchasing and the environmental impacts of fruits and vegetables may help consumers reduce food loss and their environmental footprint. Studies have suggested that reducing food loss is an effective strategy to reduce GHG emissions, saving about 30% of the total GHG emissions (Clark et al., 2020; Xue et al., 2021). But if the emission intensity at the food production stage is reduced, the effectiveness of GHG reduction will be weakened (reduced by only about 10%) (Hu et al., 2020). Avoiding the use of store-provided PE produce bags can save up to 11% of the total emissions for produce such as onions and tomatoes. However, improved primary packaging can help reduce food loss for fresh and processed food by reducing damage in distribution and handling (Heller et al., 2019; Wikström and Williams, 2010; Yokokawa et al., 2018). Future study is needed to evaluate the impact of forgoing customer packaging in the store, e.g., the use of PE produce bags, on food loss in transporting to and storing the produce at home.

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.

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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2021.105945.

References

Astier, M., Merlín-Uribe, Y., Villamil-Echeverri, L., Garciarreal, A., Gavito, M.E., Masera, O.R., 2014. Energy balance and greenhouse gas emissions in organic and conventional avocado orchards in Mexico. Ecol. Indic. 43, 281–287. https://doi.org/10.1016/j.ecolind.2014.03.002.

Baker, G.A., Gray, L.C., Harwood, M.J., Osland, T.J., Tooley, J.B.C., 2019. On-farm food loss in northern and central California: results of field survey measurements. Resour. Conserv. Recycl. 149, 541–549.

Bell, E., Qin, Y., Horvath, A., 2021. Optimal allocation of tomato supply to minimize greenhouse gas emissions in major US metropolitan markets. Submitted. https://doi.org/10.21203/rs.3.rs-131252/v1.

Bell, E.M., 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.

Birney, C.I., Franklin, K.F., Davidson, F.T., Webber, M.E., 2017. An assessment of individual foodprints attributed to diets and food waste in the United States. Environ. Res. Lett. 12, 105008.

Björklund, A.E., 2002. Survey of approaches to improve reliability in LCA. Int. J. Life Cycle Assess. 7, 64–72.

Bolda, M.P., Tourte, L., Murdock, J., Summer, D.A., 2016. Sample Costs to Produce and Harvest Strawberries: Central Coast Region, Santa Cruz and Monterey Counties. University California Agriculture and Natural Resources.

Camilleri, A.R., Larrick, R.P., Hossain, S., Patino-Echeverri, D., 2019. Consumers underestimate the emissions associated with food but are aided by labels. Nat. Clim. Change 9, 53–58.

Campbell, D., Munden-Dixon, K., 2018. On-farm food loss: farmer perspectives on food waste. J. Ext. 56 (3), 1–8.

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.

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. Manag. 93, 194–208.

Cerutti, A.K., Beccaro, G.L., Bruun, S., Bosco, S., Donno, D., Notarnicola, B., Bounous, 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, 125–135.

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. of Life Cycle Assessment 12 (6), 365–372. https://doi.org/10.1065/lca2007.04.318.

Clark, M.A., Domingo, N.G., Colgan, K., Thakrar, S.K., Tilman, D., Lynch, J., Azevedo, I. L., Hill, J.D., 2020. Global food system emissions could preclude achieving the 1.5 and 2 C climate change targets. Science 370, 705–708.

Clune, S., Crossin, E., Verghese, K., 2017. Systematic review of greenhouse gas emissions for different fresh food categories. J. Clean. Prod. 140, 766–783.

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N., Leip, A., 2021. Food systems are responsible for a third of global anthropogenic GHG emissions. Nat. Food 2, 198–209.

Day, K., Klonsky, K., Sumner, D., Stewart, D., 2016. Sample Costs to Establish and Produce Plums. University of California Cooperative Extension, Davis, CA.

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.

Energy Star®, 2020. US environmental protection agency and US department of energy.

FAO, 2013. Food Wastage Footprint: Impacts on natural resources. FAO.

FAOSTAT, 2019 a. Cherries, area. Food and Agriculture Organization of the United Nations Statistics Division.

FAOSTAT, 2019 b. Crops food and agriculture Organization of the United Nations Statistics Division.

Franke, U., Hartikainen, H., Mogensen, L., Svanes, E., 2016. Food Losses and Waste in Primary Production: Data Collection in the Nordic Countries. Nordic Council of Ministers.

Fricke, B., Becker, B., 2010. Energy use of doored and open vertical refrigerated display cases.

Grant, J., Caprile, J., Sumner, D., Murdock, J., 2017. Sample Costs for Sweet Cherries. University of California Cooperative Extension, Davis, CA.

Hanson, C., Lipinski, B., Robertson, K., Dias, D., Gavilan, I., Gréverath, P., Ritter, S., Fonseca, J., VanOtterdijk, R., Timmermans, T., 2016. Food loss and waste accounting and reporting standard.

Heard, B.R., Bandekar, M., Vassar, B., Miller, S.A., 2019. Comparison of life cycle environmental impacts from meal kits and grocery store meals. Resour. Conserv. Recycl. 147, 189–200.

Heller, M., Systems, U. of M.C. for S., 2017. Food Product Environmental Footprint Literature Summary: Packaging and Wasted Food. State of Oregon Department of Environmental Quality.

Heller, M.C., Keoleian, G.A., 2015. Greenhouse gas emission estimates of US dietary choices and food loss. J. Ind. Ecol. 19, 391–401.

Heller, M.C., Selke, S.E., Keoleian, G.A., 2019. Mapping the influence of food waste in food packaging environmental performance assessments. J. Ind. Ecol. 23, 480–495.

Hitaj, C., Rehkamp, S., Canning, P., Peters, C.J., 2019. Greenhouse gas emissions in the United States food system: current and healthy diet scenarios. Environ. Sci. Technol. 53, 5493–5503.

Hottle, T.A., Bilec, M.M., Landis, A.E., 2017. Biopolymer production and end of life comparisons using life cycle assessment. Resour. Conserv. Recycl. 122, 295–306.

Hu, Y., Lin, J., Cui, S., Khanna, N.Z., 2016. Measuring urban carbon footprint from carbon flows in the global supply chain. Environ. Sci. Technol. 50, 6154–6163.

Hu, Y., Su, M., Wang, Y., Cui, S., Meng, F., Yue, W., Liu, Y., Xu, C., Yang, Z., 2020. Food production in China requires intensified measures to be consistent with national and provincial environmental boundaries. Nat. Food 1, 572–582.

Huang, L., Jakobsen, P.D., Bohne, R.A., Liu, Y., Bruland, A., Manquehual, C.J., 2020. The environmental impact of rock support for road tunnels: the experience of Norway. Sci. Total Environ. 712, 136421.

Johnson, L.K., Dunning, R.D., Bloom, J.D., Gunter, C.C., Boyette, M.D., Creamer, N.G., 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, 243–250.

Karakaya, A., Özilgen, M., 2011. Energy utilization and carbon dioxide emission in the fresh, paste, whole-peeled, diced, and juiced tomato production processes. Energy 36, 5101–5110. https://doi.org/10.1016/j.energy.2011.06.007. PRES 2010.

Khoshnevisan, B., Rafiee, S., Mousazadeh, H., 2013. Environmental impact assessment of open field and greenhouse strawberry production. Eur. J. Agron. 50, 29–37.

Knudsen, M.T., de Almeida, G.F., Langer, V., de Abreu, L.S., Halberg, N., 2011. Environmental assessment of organic juice imported to Denmark: a case study on oranges (Citrus sinensis) from Brazil. Org. Agric. 1, 167.

Lazicki, P., Geisseler, D., Horwath, W., 2016. Onion Production in California. University of California Agricultural and Natural Resources.

Lloyd, S.M., Ries, R., 2007. Characterizing, propagating, and analyzing uncertainty in life-cycle assessment: a survey of quantitative approaches. J. Ind. Ecol. 11, 161–179.

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.

McKenzie, T.J., Singh-Peterson, L., Underhill, S.J., 2017. Quantifying postharvest loss and the implication of market-based decisions: a case study of two commercial domestic tomato supply chains in Queensland, Australia. Horticulturae 3, 44.

Nahlik, M.J., Kaehr, A.T., Chester, M.V., Horvath, A., Taptich, M.N., 2016. Goods movement life cycle assessment for greenhouse gas reduction goals. J. Ind. Ecol. 20, 317–328.

United Nations, 2015. Transforming our World: The 2030 Agenda for Sustainable Development. United Nations Department of Economic and Social Affairs.

O'Connell, N., Kallsen, C., Klonsky, K., Tumber, K., 2015a. Sample Costs to Establish an Orange Orchard and Produce Oranges, Navels & Valencias. University of California Cooperative Extension, Davis, CA.

O'Connell, N.V., Kallsen, C.E., Klonsky, K.M., Tumber, K.P., 2015b. Sample Costs to Establish an Orchard and Produce Lemons. University of California Agricultural and Natural Resources, Cooperative Extension and the Agricultural Issues Center.

Östergren, K., Gustavsson, J., Bos-Brouwers, H., Timmermans, T., Hansen, O.J., Møller, H., Anderson, G., O'Connor, C., Soethoudt, H., Quested, T., 2014. FUSIONS definitional framework for food waste. Proj. FUSIONS Food Use Soc. Innov. Optimising Waste Prev. Strateg. Eur. Union.

Pergola, M., D'Amico, M., Celano, G., Palese, Am., Scuderi, A., Di Vita, G., Pappalardo, G., Inglese, P., 2013. Sustainability evaluation of Sicily's lemon and orange production: an energy, economic and environmental analysis. J. Environ. Manag. 128, 674–682.

Qin, Y., Horvath, A., 2020a. Contribution of food loss to greenhouse gas assessment of high-value agricultural produce: California production, US consumption. Environ. Res. Lett. 16, 014024.

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

Qin, Y., Suh, S., 2017. What distribution function do life cycle inventories follow? Int. J. Life Cycle Assess. 22, 1138–1145. https://doi.org/10.1007/s11367-016-1224-4.

Rana, R.L., Andriano, A.M., Giungato, P., Tricase, C., 2019. Carbon footprint of processed sweet cherries (Prunus avium L.): from nursery to market. J. Clean. Prod. 227, 900–910.

Roy, P., Nei, D., Orikasa, T., Xu, Q., Okadome, H., Nakamura, N., Shiina, T., 2009. A review of life cycle assessment (LCA) on some food products. J. Food Eng. 90, 1–10.

Sanjuán, N., Stoessel, F., Hellweg, S., 2014. Closing data gaps for LCA of food products: estimating the energy demand of food processing. Environ. Sci. Technol. 48, 1132–1140.

Shahbandeh, M., 2020. Sweet Cherry Production in the United States in 2019, by State. Statista.

Sturges, M., Kay, M., Johansson, M., 2019. BioPackLCA–closing the gap: extending LCA to reflect the sustainability contributions of bio-based packaging.

Svanes, E., Johnsen, F.M., 2019. Environmental life cycle assessment of production, processing, distribution and consumption of apples, sweet cherries and plums from conventional agriculture in Norway. J. Clean. Prod. 238, 117773.

Takele, E., Bender, G., Vue, M., 2011. Avocado Sample Establishment and Production Costs and Profitability Analysis for San Diego and Riverside Counties. University of California Cooperative Extension, Davis CA.

Takele, E., Daugovish, O., Vue, M., 2013. Costs and Profitability Analysis for Celery Production in the Oxnard Plain. University of California Cooperative Extension, Davis CA.

Taptich, M.N., Horvath, A., 2014. Bias of Averages in life-cycle footprinting of infrastructure: truck and bus case studies. Environ. Sci. Technol. 48, 13045–13052. https://doi.org/10.1021/es503356c.

Tassielli, G., Notarnicola, B., Renzulli, P.A., Arcese, G., 2018. Environmental life cycle assessment of fresh and processed sweet cherries in southern Italy. J. Clean. Prod. 171, 184–197.

Tassou, S.A., De-Lille, G., Lewis, J., 2012. Food Transport Refrigeration. Center for Energy and Built Environment Research Group, pp. 1–25. Sch. Eng. Des. Brunel Univ. UK.

Turini, T., Stewart, D., Murdock, J., Sumner, D., 2018. Sample Costs to Produce Processing Tomatoes. University of California Cooperative Extension, Davis, CA.

UCDavis, 2021. Fresh Plum. University of California Agricultural and Natural Resources.

Tukker, A., Huppes, G., Guinée, J., Heijungs, R., de Koning, A., van Oers, L., Suh, S., Geerken, T., Nielsen, P., 2006. Analysis of the life cycle environmental impacts related to the total final consumption of the EU25. Environmental Impact of Products (EIPRO), European Commission Technical Report. EUR 22284 EN.

U.S. Department of Agriculture, Agricultural Research Service, 2019. FoodData central.

USDA Economic Research Service, 2019. Loss-adjusted food availability (LAFA) data system.

Vergara, S, Damgaard, A, Horvath, A, 2011. Boundaries Matter: Greenhouse Gas Emission Reductions from Alternative Waste Treatment Strategies for California's Municipal Solid Waste. Resources, Conservation and Recycling 57, 87–97. https://doi.org/10.1016/j.resconrec.2011.09.011.

Vermeulen, S.J., Campbell, B.M., Ingram, J.S., 2012. Climate change and food systems. Annu. Rev. Environ. Resour. 37, 195–222.

Vink, E.T., Davies, S., 2015. Life cycle inventory and impact assessment data for 2014 IngeoTM polylactide production. Ind. Biotechnol. 11, 167–180.

Wikström, F., Williams, H., 2010. Potential environmental gains from reducing food losses through development of new packaging–a life-cycle model. Packag. Technol. Sci. 23, 403–411.

Wilson, R., Sumner, D., Klonsky, K., Stewart, D., 2016. Sample Costs to Produce Onions. University of California Cooperative Extension, Davis, CA.

Wiltshire, J., Wynn, S., Clarke, J., Chambers, B., 2009. Scenario Building to Test and Inform the Development of a BSI Method for Assessing Greenhouse gas Emissions from Food. DEFRA, London.

Xue, L., Liu, X., Lu, S., Cheng, G., Hu, Y., Liu, J., Dou, Z., Cheng, S., Liu, G., 2021. China's food loss and waste embodies increasing environmental impacts. Nat. Food 1–10.

Yokokawa, N., Kikuchi-Uehara, E., Sugiyama, H., Hirao, M., 2018. Framework for analyzing the effects of packaging on food loss reduction by considering consumer behavior. J. Clean. Prod. 174, 26–34.