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Full length article

On-farm food loss in northern and central California: Results of field survey measurements

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ABSTRACT

Prevailing estimates of food loss at the farm level are sparse and often reliant upon grower surveys. A more comprehensive review of food loss at the farm level using field surveys is required to gain an adequate understanding of the depth of this issue. This paper details the results of 123 in-field surveys and 18 in-depth interviews of 20 different, hand-harvested field crops performed largely on midsize to large conventional farms in northern and central California. We also provide estimates of the percentage of fields that go unharvested, commonly known as walk-by fields. The results show that food loss is highly variable and largely dependent upon the crop, variety, market price, labor costs, grower practices, buyer specifications, and environmental conditions. On average, we found 11,299 kg/ha of food loss at the farm level, which equates to 31.3% of the marketed yield. When walk-by losses are included, this figure rises to 33.7%. Our paper also demonstrates that grower estimates are typically very unreliable for estimating on-farm food losses. Actual, measured edible food loss exceeded growers' estimates by a median value of 157%. Strategies to utilize this lost produce could play a significant role in reducing the impact of agriculture on the environment and providing food for the rapidly growing population.

1. Introduction

With increased attention on climate change, food security, and diminishing resources, reducing food loss and waste is often pointed to as a solution. Globally, FAO estimates that one-third of all food produced is lost or wasted (Gustavsson et al., 2013). In the US, the NRDC estimates as much as 40% of food produced goes uneaten (Gunders, 2012). ReFED (2016a) estimates that 21% of water, 19% of fertilizer and 18% of cropland is devoted to food that never gets consumed, an area equivalent to the cropland in the US states of Kansas, Nebraska, and North Dakota (Bigelow and Borchers, 2017).

Currently, most food loss and waste research focuses on post-harvest, retail, and consumer levels, where business practices as well as consumer behavior and preferences have been found to be the major drivers of loss (Parfitt et al., 2010; Hodges et al., 2011; Buzby and Hyman, 2012; ReFED, 2016a). This research generally differentiates between food loss and food waste, although we note that there is ambiguity in the usage of the two terms and to some extent the terms have been used interchangeably. Food waste is typically defined as food that is lost purposefully or as a result of carelessness and takes place at the distribution, retail, and consumer levels (Hanson et al., 2016). Food loss is ordinarily defined as food not intended to be lost but instead occurs due to limitations or quality issues in agricultural production caused by market prices, environmental factors, diseases, or pests (Hanson et al., 2016). In order to determine what policy approaches might minimize and mitigate food waste *and* loss, it is imperative to develop accurate estimates for every stage of the supply chain.

Compared to downstream studies of food loss and waste, little attention is given to farm-level losses. Farm-level food loss is defined as food that is either not harvested or lost between harvest and sale (Gunders, 2012). Our focus is on a narrower definition of farm-level food loss, used by some authors, e.g. Johnson et al. (2018a), that focuses on crops that are left in the field and not harvested. For simplicity, we use the terms farm-level food loss, on-farm food loss, and primary production food loss interchangeably to refer to farm-level, unharvested food. This definition of food loss can be separated into two major categories. The first is product left behind in harvested fields, often because it does not meet market standards or because market prices are

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too low to justify harvesting. The second is product left behind in fields that are never harvested at all, known as "walk-by" fields in the industry. Similar to food loss at other levels of the supply chain, farm-level food loss contributes to climate change, pollution, overuse of water, agricultural chemicals, and other resources, ecosystem services loss, and encroachment on key habitats (Foley et al., 2005; Carpenter et al., 1998; Tubiello et al., 2015; Vitousek et al., 1997).

Most of the relatively few studies that discuss on-farm food loss rely on grower interviews to estimate produce left in fields. FAO's 2011 estimate of 20% losses for fruits and vegetables in Europe (Gustavsson et al., 2013) was based on losses of only three crops (carrots, onions, and tomatoes) (Davis et al., 2011) and the rejection rate of fruits and vegetables by British supermarkets (Stuart, 2009). The carrot and onion data were based on grower questionnaires (Davis et al., 2011) and the tomato estimate is listed as assumed (Gustavsson et al., 2013). The ReFED (2016a) report is widely cited for its food loss estimate of 20% for fruits and vegetables. The technical appendix (ReFED, 2016) indicates that the data were obtained from a study by Berkenkamp and Nennich (2015) that relied on grower interviews.

Beausang et al. (2017) and Water Resources and Action Program (WRAP) (2017) contend that grower estimates can be unreliable given the difficulty growers have in estimating their own loss numbers. Nonetheless, few studies have quantified on-farm food loss using in-field measurements. The lack of direct measurements of on-farm food loss is likely due to a number of factors, including the resources required to undertake such a study, the difficulty in identifying, contacting, and convincing growers to cooperate, the high variability inherent in agricultural production requiring the measurement of multiple fields, food safety concerns that limit researchers access to fields, and lack of incentive to measure losses that are not landfilled, as is the case for losses at other levels of the supply chain (Hartikainen et al., 2018).

The studies that have quantified on-farm food losses typically evaluate only a few crops. This is likely due to the complexity of investigating numerous crops with varying characteristics and the resource intensiveness of performing field surveys. For example, one study examined farm-level losses of carrots, onions, and field peas in Nordic countries, finding losses of 22%, 12.5% and 17.5%, respectively (Hartikainen et al., 2018). Another report by Strid and Eriksson estimated primary production lettuce losses at 17.6% (Strid and Eriksson, 2014). Arguably, the most comprehensive study to date on the topic was performed by Johnson et al. (2018b), who conducted 68 field surveys on 8 different crops and found an average of 42% of marketed yield left in the field.

Our study builds on recent research measuring on-farm food loss. We examine on-farm food loss in California, an important, diverse agricultural region. California presents an ideal location to study farm-level food loss due to its great crop diversity and agricultural importance both in the US and globally. In 2017, California was a top producer of all our surveyed crops for which data were available, ranking first among US states for all crops except tomatoes and watermelon where the state ranked second (no data were available for green beans and Napa cabbage) (United States Department of Agriculture (USDA), 2018).

The study's primary focus is to report measurement-based results of farm-level food loss, including estimates of fields not harvested or "walked-by." We compare our measurements to grower estimates to investigate the reliability of growers' estimates. Another contribution of the study is that we develop an approach to estimate the losses for crops harvested multiple times. Finally, we discuss the various factors that affect food loss at the farm-level and we conclude by discussing some ideas for reducing farm-level food loss.

2. Methods

In this section we discuss our definition of food loss, the grower selection and interview process, methods used to collect, measure, and categorize farm-level food loss, grower estimates of food loss, and, finally, how we calculated farm-level food loss for the various crops.

2.1. Region and crop selection

The motivation for this study arose from discussions with Second Harvest Food Bank of Santa Clara and San Mateo Counties. Executives of Second Harvest noted that two of the most productive valleys in the world, the Salinas Valley, often referred to as the "Salad Bowl of the World" and California's Central Valley, are located close to the metropolitan area served by the food bank. These valleys are approximately 100 km and 130 km, respectively, from the large metropolitan area of San Jose, California and the broader region known as Silicon Valley. A study commissioned by the food bank found that in the two counties it serves, 720,000 people, or nearly 27% of the population, were at risk of hunger (Hayward, 2017; Bacho, 2017).

Our study examined crops that were hand harvested and packaged in-field as we believed these crops to have the highest untapped potential for recovery. When a crop is machine-harvested, very little produce is left in the field unless the grower "walks by," i.e. decides not to harvest, the entire field or a portion of it. Moreover, machine-harvested crops are typically sorted post-harvest in a packing shed, making it easier to divert excess production to other uses, such as processing, juicing, etc.

During the summers of 2016 and 2017 we worked with 34 midsize to large growers to conduct in-field, post-harvest measurements of produce remaining in the field for 20 crops in 123 fields. We surveyed crops with a variety of characteristics, focusing on those crops that we believed had the highest recovery potential. For artichokes and cantaloupes, substantial differences in loss rates between varietal types warranted reporting the results for the varietal types separately. Therefore, some of the tables contain additional crop rows because of the reporting of two varietal types for both artichokes and cantaloupes.

2.2. Growers visited

Mandatory county pesticide release documents were consulted to identify the area and variety of crops planted by local northern and central California growers. Growers were then contacted in order to secure their agreement to participate in the research. Because of the difficulty in setting up field visits, we selected growers based on their willingness to participate.

2.3. Defining food loss and edibility

The definition of farm-level food loss and the collection, measurement, and categorization of unharvested produce used in this research was inspired by the FLW Standard (Hanson et al., 2016). We defined food loss as product intended for human consumption that was either not harvested or left in the field after harvest. This fits the FLW Standard destination category of "not harvested/plowed-in." The definition of food loss we use also fits closely with the FUSIONS food waste definition, "Food waste is any food, and inedible parts of food, removed from the food supply chain to be recovered or disposed (including composted, crops ploughed in/not harvested, anaerobic digestion, bio-energy production, co-generation, incineration, disposal to sewer, landfill or discarded to sea)" (EU Fusions, 2016). Additionally, our definition is similar to Food and Agricultural Organization (FAO's) (2013) definition of food loss, "Food loss refers to a decrease in mass (dry matter) or nutritional value (quality) of food that was originally intended for human consumption. These losses are mainly caused by inefficiencies in the food supply chains, such as poor infrastructure and logistics, lack of technology, insufficient skills, knowledge and management capacity of supply chain actors, and lack of access to markets. In addition, natural disasters play a role."

Prior to visiting the fields, we developed written protocols for each crop. Because of the many differences in planting, cultivating, and harvesting the 20 crops it was important to prepare the research teams with detailed protocols for conducting field surveys. For example, crops have different diseases and maladies that affect them. Therefore, it was necessary for each researcher to understand what diseases and maladies to look for, and whether or not these problems render the crop inedible or simply unmarketable.

Produce was deemed edible, and therefore food loss, if it lacked damage from disease, rot, pests, machinery, or other sources. Product that had been cut off plants and thrown onto the ground was collected and weighed if it otherwise fit the edibility requirements. We reasoned that if the harvesting practices were to change to accommodate unmarketable product, this currently discarded product could be harvested, avoiding contact with the ground. In the case of disagreement between researchers or uncertainty as to the edibility of produce, researchers were instructed to not include the produce in measurements. This conservative protocol likely resulted in the underestimation of the amount of edible food loss.

2.4. Field measurements

The in-field research was conducted for 20 crops (Table 1) in northern and central California in Contra Costa, Merced, Monterey, San Benito, and Stanislaus counties from early June to early September in both 2016 and 2017. When scheduling visits, we stressed the importance of collecting unharvested produce directly behind harvest crews to ensure that the produce we collected was as fresh as possible. For some crops that deteriorate rapidly in the field, such as leafy greens, this was extremely important, whereas for field-stable crops that do not deteriorate rapidly in the field, such as melons, the survey could be conducted several hours after harvest without impacting the results. Before entering any field, a company representative, typically a field manager, was interviewed to gain a better understanding of growing conditions, including varieties grown, bed and plant spacing, field maladies, weather problems, reasons for produce being left behind, market fluctuations, market specifications, and other relevant information. A particularly important piece of information collected was the grower estimate of on-farm food loss. If a grower was unsure as to the amount of post-harvest remaining edible product, no response was recorded.

Plots, demarcated by flags, were selected and ranged from 4 to 12 rows wide by 25–100 feet (7.6–30.5 meters) in length. To ensure a representative sample, and because individual harvester thoroughness can vary dramatically, multiple, adjacent rows were surveyed within each plot. Due to the vast differences in harvesting time for each crop and the limited resources of the study, plot sizes were designed to take a team of three to four researchers one to two hours to complete. For crops with a large amount of unharvested, edible product remaining, such as Romaine hearts, plot sizes of 4 rows by 25 feet (7.6 m) were standard. For crops with relatively little remaining edible product, such as sweet corn, plot sizes of 10–12 rows by 100 feet (30.5 m) were typical. The average plot size for each crop is presented in Table 2. The plot location was selected by the team, with the help of the grower contact, to ensure that a representative area of the field was chosen. To avoid edge effects, all plots were positioned at least 30 feet (9.1 m) from the field's border.

Once demarcated, the team collected all edible produce in each row. Inedible portions, such as cauliflower stems and watermelon rinds, were harvested and included in the measurements, in accordance with industry harvesting methods and the FLW Standard definition for food loss, which includes associated inedible parts (Hanson et al., 2016). The produce collected in each row was weighed with electronic hand scales and recorded.

Table 1
Crops Surveyed by Number of Cuts[a].

Single-cut Crops	Multiple-cut Crops (average number of cuts)
Bunch spinach	Artichokes, annual (5–10)
Celery	Artichokes, perennial (20–35)
Green leaf lettuce	Broccoli (2–3)
Iceberg lettuce	Brussels sprouts (2)
Napa cabbage	Green beans (1–2)
Romaine hearts	Green/red cabbage (2–3)
Romaine lettuce	Cantaloupe, Long Shelf Life (LSL) varieties (2–5)
Roma tomatoes	Cantaloupe, Western Shipper (WS) varieties (7–12)
Round tomatoes	Cauliflower (2–3)
Sweet corn	Kale (2–6)
	Strawberries (50–70)
	Watermelon (3–5)

[a] The approximate number of cuts was averaged over multiple grower interviews. The actual number of cuts varies significantly based on variety, grower, market prices and product conditions.

2.5. Extrapolation of survey measurements

Upon completion of the surveys, the food loss for each row was summed to arrive at the loss in kilograms for each plot. We estimated the loss in kilograms/hectare by multiplying the total amount of unharvested produce in the plot by the inverse of the plot's proportion of a hectare.

Finally, in order to estimate the proportion of the crop left unharvested, as performed in most food loss studies, reliable data on marketed yield was required. County average yields from publicly available crop reports were used as a proxy for individual field production estimates. County data were favored over grower estimates of yields due to concerns about the reliability of estimates obtained while the harvest was in progress. The percent of edible produce left unharvested for each field and crop was calculated by dividing the kilograms/hectare loss estimate by the county average yield and multiplying by 100%. This method was utilized for every crop except green beans, for which county data were unavailable. Instead, growers' production estimates were averaged and used as the denominator for calculating the proportion of the crop left unharvested.

2.6. Loss estimate calculations for multiple-cut crops

The scope of this study included two distinct crop types: single-cut and multiple-cut. As their names suggest, single-cut crops are harvested once, and multiple-cut crops are harvested more than once. The breakdown of the crops based on the typical number of cuts can be found in Table 1. For single-cut crops, the measurement of food loss was straightforward. Measurements were taken by collecting the edible produce left in the field immediately after harvest. For multiple-cut crops, the measurement was more complicated. Ideally, field surveys would be performed at every stage of the harvest to obtain a full picture of the food loss. However, due to food safety concerns and limited resources, this was not the case. Therefore, edible loss that occurred at earlier stages of the harvest was not accounted for in our measurements. Estimating this loss was not as simple as multiplying the measurements by the number of total cuts due to harvest practices that strongly influence the percent left behind at each cut. Moreover, even if the percent left behind was constant for each cut, the shape of the yield curve made it necessary to account for the changing volume of production.

In order to estimate full-season food losses for multiple-cut crops, we conducted in-depth interviews in the summer and fall of 2018 to understand how production, yields, and loss vary throughout the growing season. We conducted at least two interviews per crop and continued interviewing growers until we developed a comprehensive understanding of the pattern and amount of these losses.

The pre-final cut losses were estimated based on the harvesting practices and qualities of each individual crop. For field-stable crops, such as artichokes and broccoli, the process was relatively straightforward. Because the crops do not deteriorate rapidly in the field, most product that was left unharvested early in the production season was either harvested at a later cut or remained on the plant and was still edible and visible when our field surveys were performed after the final cut.

Crops that were harvested numerous times and lack field stability, such as Western Shipper (WS) cantaloupes, were more challenging. For these crops, it was necessary to estimate the amount of edible, unmarketable loss at each cut that would not be on the plant, or edible, after the last cut when field measurements were taken. Cantaloupes that were taken off the plant and discarded into the furrows are an example of this type of loss. Strawberries presented the most difficult case since our field measurements were taken not after the final cut, but at varying points throughout the final two thirds of the six- to eight-month harvest season. To calculate the full-season losses for strawberries, we obtained weekly production reports from growers that enabled us to extrapolate our measured losses to the whole season.

The interviews were used to develop consensus estimates for food loss at the various stages of the harvest season for all multiple-cut crops. These estimates were used to calculate full-season loss estimates based on the single-cut field measurements that were taken for each multiple-cut crop.

2.7. Losses from walk-by fields

Another significant source of loss for some crops is from walk-by fields that are never harvested. This ordinarily happens when the market price is below the cost of harvesting and packing the crop. In rare instances, a crop is so damaged by disease or pests that it is not harvested because there is little edible production. During the course of the summer and fall 2018 interviews, we interviewed growers regarding the frequency and prevalence of walk-by fields that were not harvested due to reasons that did not impact the edibility of the crop (i.e. not including pest- or insect-damaged fields). Because most growers keep detailed records on fields that are not harvested, we believed growers to be a reliable source for estimating walk-by area.

2.8. Comparing grower estimates to in-field measurements of food loss

Prior to the field surveys, growers were asked for their estimate of the unharvested edible produce relative to what was harvested in the specific field that was being surveyed. We present growers' estimates relative to actual in-field measurements, with adjustments for multiple-cut crops, as a percentage of the actual measured losses according to the following equation:

$$Growers' \ Loss \ Estimate \ vs. \ Measured \ Loss \ Percent = \left(\frac{Measured \ Loss - Growers' \ Loss \ Estimate}{Growers' \ Loss \ Estimate}\right)*100\%$$

As an example, if growers estimated losses at 20% but actual losses were 30%, we would see that actual losses exceeded growers' estimates by 50% or ((30 - 20) / 20) * 100%. These individual, relative comparisons were then compiled and the median was calculated. The median was favored over the mean due to the presence of several drastic underestimates that skewed the mean upward.

2.9. Resources employed in the research

As identified by Hartikainen et al. in their 2018 paper, collecting field measurements of food loss is resource intensive compared to surveys and interviews. The initial work includes learning about cropping systems, identifying growers and establishing contacts, designing the project and measurement protocols, designing interview guides and survey records, acquiring supplies (e.g. buckets, measuring tapes, gloves, and scales), and setting up field visits. Once the data are collected, they must be entered, analyzed, and written up for publication. The major expense categories include, wages, travel, and supplies. We estimate direct measurement expenses, including travel, data entry, and initial analysis to be approximately $US400 per completed field survey. The expenses associated with a researcher are not included in this estimate and could easily be two to three times the actual measurement expenses. Such expenses include desk research, survey design, detailed data analysis, and publication of the results and will vary significantly depending on factors such as the prior knowledge of the researcher(s), whether a design is developed from scratch or replicates an existing design, and researcher salaries.

In addition to the expense of collecting field data, field measurements are time consuming. Identifying, contacting, and convincing growers to cooperate can be quite difficult. Actual field measurements require travel to and from the field, meeting with the grower or farm manager, choosing the plot, demarcating the plot, setting up equipment, collecting, weighing and recording unharvested produce, and packing up equipment. A single research team of three people typically conducted one or two, and, at most, three field surveys per day.

2.10. Crop surveys

This two-year study provides detailed estimates of in-field losses for 20 crops located in northern and central California. The average plot size and the number of fields surveyed for each crop are presented in Table 2. The target sample size was at least four fields per crop and was reached for all crops except Brussels sprouts (n = 2), cabbage (n = 2), green beans (n = 2), and kale (n = 1). Most of the participating farms were midsize to large, conventional farms.

3. Results and discussion

3.1. Single-cut crop losses

Table 3 contains the loss estimates for the 10 single-cut crops. We found that there was an average of approximately 11 tons (11,185 kg) per hectare of edible produce left in the field after harvest. This represents a loss rate of 33.1% of the marketed yield.

The crops with the lowest losses were sweet corn, round tomatoes and Roma tomatoes with loss rates of 4.5%, 6.4%, and 8.2%, respectively. However, even for crops where the percentage loss is low, a substantial amount of produce is left in the field. The losses, in kg/ha, were 1086, 3826 and 3689 for sweet corn, round tomatoes and Roma tomatoes, respectively.

At the high end, percentage losses were 113.6%, 43.3%, 42.0% and 39.5% for Romaine hearts, green leaf lettuce, Napa cabbage, and Romaine lettuce, respectively. By weight, the largest losses were for Romaine hearts and celery at 29,926 and 22,152 kg./ha, respectively. Five crops had per hectare losses exceeding 10 tons per hectare: celery, iceberg lettuce, Napa cabbage, Romaine hearts, and Romaine lettuce.

The case of Romaine hearts is especially interesting. We found that more edible crop was left in the field than was harvested for sale. In one Romaine hearts field, there was an estimated loss of almost 68,000 kg/ha. The case is instructive and serves as a reminder of the many reasons for food loss as well as the importance of understanding how each crop

Table 2
Average Plot Sizes and Number of Fields Surveyed for Each Crop.

Crop	Average Plot Size (m^2)	-Number of Fields Surveyed in 2016 (Number of Organic Fields)	-Number of Fields Surveyed in 2017 (Number of Organic Fields)	-Total Number of Fields Surveyed
Artichokes, annual	278.7	2	0	2
Artichokes, perennial	247.4	2	0	2
Broccoli	209.7	8 (2)	5	13
Brussels sprouts	201.3	0	2	2
Bunch spinach	101.8	7(1)	0	7
Cabbage	90.6	0	2 (2)	2
Cantaloupe, WS	407.5	6 (1)	5	11
Cantaloupe, LSL	247.7	1	0	1
Cauliflower	190.0	8 (2)	2	10
Celery	34.4	8 (2)	1	9
Green beans	57.5	0	2	2
Green leaf lettuce	60.3	0	5	5
Iceberg lettuce	63.2	0	5 (1)	5
Kale	38.7	0	1	1
Napa cabbage	63.5	0	5	5
Romaine hearts	45.2	7 (2)	1	8
Romaine lettuce	56.8	0	6	6
Roma tomatoes	220.6	1	3	4
Round tomatoes	205.3	5	5	10
Strawberries	227.1	8 (2)	1	9
Sweet corn[a]	229.8	0	5	5
Watermelon	298.4	0	4	4

[a] Due to a large change in the dominant variety and its improved production characteristics, data from the 2016 sweet corn fields is not reported.

is grown, harvested, and marketed. In this case, Romaine hearts are grown for the high-valued hearts and the outer leaves are not intended for market. During harvest, workers cut off the outer leaves, taking care to harvest perfectly sized and shaped hearts with no damage, resulting in a great amount of perfectly good, edible Romaine leaves being left in the field. These leaves wilt rapidly and, under current standards, are deemed inedible as soon as they touch the ground. A possible alternative was described by one grower during our 2018 interviews. His company was testing a system in a few fields in which they harvest the outer leaves concurrently with the hearts for sale to the juice market.

Losses associated with Romaine hearts call attention to the importance of how food loss is defined. Because the outer leaves of Romaine hearts are not intended to be harvested and therefore not intended for human consumption the outer leaves would not be considered loss under FAO's definition, but would be considered waste under the FUSIONS definition.

3.2. Multiple-cut crop losses

As explained in section 2.7, deriving seasonal loss estimates for multiple-cut crops is more complex and complicated than for single-cut crops since they may be harvested over a long period. Our single post-harvest measurement of multiple-cut crop losses ran the risk of significantly underestimating the total loss by not accounting for losses that may have occurred at other harvest points. To account for this, we performed interviews with growers to help approximate the full-harvest loss for each multiple-cut crop.

For all of the multiple-cut crops except for strawberries, we measured the loss immediately after the final harvest. For strawberries, we measured the loss during the middle or final third of the season. The results of our in-field, final-cut measurements and our adjusted, full-harvest estimates of losses for multi-cut crops are presented in Table 4. Across all multi-cut crops, losses averaged 11,413 kg/ha or 26.0% of marketed yield.

Several crops' full-season loss estimates increased significantly over their final-cut measurements. The most extreme adjustment was for strawberries for which losses are exceptionally difficult to estimate. Strawberries are harvested twice a week over a period that may extend to eight months. Furthermore, the fruit deteriorates very rapidly in the field. Due to the fruit's fragility, recoverable losses occur after each of the many pickings. For strawberries, our mean measurement of 0.7% after a single harvest was adjusted to 43.8% for the season. This adjustment was primarily based on the proportion of the season's production that occurred during the week when the single measurement

Table 3
Single-Cut, In-Field Crop Loss Estimates.

Crop	Loss (kg/ha)				Loss (percent of marketed yield)[a]			
	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev
Bunch Spinach	1,923	6,703	4,130	2,038	9.7	33.9	20.9	10.3
Celery	8,322	45,851	22,152	12,463	11.4	62.7	30.3	17.1
Green Leaf Lettuce	3,633	15,936	9,223	4,670	17.1	74.8	43.3	21.9
Iceberg Lettuce	6,229	18,671	12,680	4,997	11.1	33.3	22.6	8.9
Napa Cabbage	6,194	25,388	14,736	8,894	17.6	72.3	42.0	25.3
Romaine Hearts	3,651	67,760	29,926	22,636	13.9	257.3	113.6	85.9
Romaine Lettuce	2,967	19,761	10,400	6,601	11.3	75.0	39.5	25.1
Roma Tomatoes	1,972	5,375	3,689	1,447	3.4	13.0	8.2	4.0
Round Tomatoes	819	14,473	3,826	4,237	1.4	24.8	6.4	7.2
Sweet Corn	332	1,543	1,086	578	1.4	6.4	4.5	2.4

[a] Loss as a percentage of marketed yield was calculated by dividing the average kilograms/hectare remaining by the reported marketed yields per hectare from county crop reports.

Table 4
Full-season, Multiple-cut, In-field Crop Loss Estimates and Final-cut Mean Estimates.

Crop	Final-cut Mean Loss Estimates		Full-season Loss (kg/ha)				Full-season Loss (percent of marketed yield)[a]			
	kg/ha	Percent of Marketed Yield	Min	Max	Mean	Std Dev	Min	Max	Mean	Std Dev
Artichokes, annual	1135	8.5	864	1406	1135	383	8.1	8.8	8.5	0.5
Artichokes, perennial	497	4.7	392	602	497	148	3.7	5.7	4.7	1.4
Broccoli	2490	14.9	671	5514	2658	1,361	4.1	32.3	15.9	8.1
Brussels sprouts	2886	12.7	1833	4166	3000	1649	8.1	18.3	13.2	7.3
Cabbage	23,137	47.6	23,797	26,368	25,082	1,818	48.9	54.2	51.6	3.7
Cantaloupe, LSL	2202	5.7	3753	3753	3753	N/A	9.7	9.7	9.7	N/A
Cantaloupe, WS	2716	7.2	3487	7900	5341	1256	9.0	20.4	14.2	3.2
Cauliflower	6701	31.1	2734	18,670	7347	5463	12.7	86.6	34.1	25.4
Green beans	2514	21.4	701	4326	2514	2564	6.0	36.8	21.4	21.8
Kale	9282	34.1	10,507	10,507	10,507	N/A	38.6	38.6	38.6	N/A
Strawberries	676	0.7	14,780	81,051	32,133	21,423	20.3	100.0	43.8	25.7
Watermelon	25,079	56.7	21,128	32,352	25,529	5207	47.0	71.9	56.7	11.6

[a] Loss as a percentage of marketed yield was calculated by dividing the average kg/ha remaining by the reported marketed yields per hectare from county crop reports (except for green beans for which grower estimates were used).

was taken. The rationale was based on discussions with growers, who indicated that the amount of unharvested, edible fruit remaining (not including unripe fruit) correlates closely with the production quantities.

Similar to the single-cut crops, there were large differences in the loss amounts and loss percentages. This was the case even for different types or varieties of the same crop and was the justification for the differentiation between perennial and annual artichokes, and LSL and WS cantaloupes. Perennial artichokes had the lowest losses both in weight and percentage terms with field losses of 497 kg./ha. or 4.7% of marketable yield. Perennial artichokes were the only crop surveyed (among both single-cut and multiple-cut crops) where losses were less than one ton per hectare.

Three multiple-cut crops had losses exceeding 20 tons per hectare, cabbage, watermelon, and strawberries, with losses of 25,082, 25,529 and 32,133 kg./ha. (51.6, 56.7, and 43.8 percent of marketed yield), respectively.

3.3. Total loss estimates including walk-by field losses

Grower interviews revealed that for most crops walk-by fields represented a low percentage of the plantings. For all crops, the average percentage of walk-by fields was 2.4%. Growers indicated that they never walked by artichoke, Brussels sprouts, kale, or strawberry fields. All crops had walk-by percentages of 4% or less, with the exception of green beans, which had a reported walk-by rate of 12.5%. The high percentage for green beans is due to a combination of the strict market demands and the susceptibility of the crop to environmental variations that can result in unmarketable product. Single-cut crops were walked-by at an average rate of 2.6% whereas multiple-cut crops were walked by at an average rate of 2.3%. When green beans are excluded from the calculations, the walk-by rate drops to 1.9% overall and to 1.2% for multiple-cut crops.

Total estimated losses for all crops surveyed, including walk-by losses and losses for harvested fields (as a percentage of marketed yield) are presented in Table 5. We calculated the total losses by adding the walk-by field loss percentage to the loss percentage for harvested fields. This total loss percentage therefore represents the loss due to crops left in the field after harvest as well as the loss due to fields that were never harvested. When the mean walk-by losses for all crops of 2.4% is added to the mean full-harvest losses of 31.3% (11,299 kg/ha) the total losses across all surveyed crops was 33.7% of marketed yield.

Table 5
Loss Estimates for Walk-by Fields, Harvested Fields, and Total Plantings.

Crop	Walk-By Field Losses (% of Planted Area)	Full-season Loss for Harvested Fields (% of marketed yield)[a]	Total Crop Losses Including Walk-by and Harvested Fields (% of marketed yield)
Artichokes, annual	0.0	8.5	8.5
Artichokes, perennial	0.0	4.7	4.7
Broccoli	3.0	15.9	18.9
Brussels sprouts	0.0	13.2	13.2
Bunch spinach	2.6	20.9	23.5
Cabbage	4.0	51.6	55.6
Cantaloupe, LSL	1.0	9.7	10.7
Cantaloupe, WS	0.0	14.2	14.2
Cauliflower	2.0	34.1	36.1
Celery	1.8	30.3	32.1
Green beans	12.5	21.4	33.9
Green leaf lettuce	3.5	43.3	46.8
Iceberg lettuce	2.0	22.6	24.6
Kale	0.0	38.6	38.6
Napa cabbage	3.3	42.0	45.3
Romaine hearts	2.9	113.6	116.5
Romaine lettuce	3.1	39.5	42.6
Roma tomatoes	1.3	8.2	9.5
Round tomatoes	1.3	6.4	7.7
Strawberries	0.0	43.8	43.8
Sweet corn	4.0	4.5	8.5
Watermelon	1.0	56.7	57.7
Surveyed crops (Mean)	2.4	31.3	33.7

[a] Loss as a percentage of marketed yield was calculated by dividing the average kg/ha remaining by the reported marketed yields per hectare from county crop reports (except for green beans for which grower estimates were used). To calculate the mean crop losses (walk-by, full-season, and total), the mean loss percents for the two variety types for artichokes and cantaloupes were used.

3.4. Factors affecting farm-level food loss

Our measurements revealed that there were large differences in loss rates across many categories, including between crops, varieties of a crop, seasons, and fields. This contributes greatly to the complexity of the issue and complicates any attempts to quantify or address the problem. The high variation is evidenced by the relatively large standard deviations and wide ranges for the surveyed crops. For 12 of the crops, the standard deviations were greater than 50% of the mean losses (tables 3 and 4). This reflects the inherent variability of food loss at the farm level, a fact that was frequently emphasized by growers in discussions and interviews. The variations are caused by a number of factors, which we discuss below.

3.4.1. Crop varieties and varietal types

During the course of the 2018 interviews with several cantaloupe growers, we learned about the distinct characteristics of the three cantaloupe varietal types: WS, Long Shelf Life (LSL), and Extended Shelf Life (ESL). The three varieties are distinguished by their shelf life and flavor qualities. WS are generally considered to have the best flavor but the shortest shelf life. LSLs, were developed to have a significantly longer shelf life, but do not have the same taste quality as WSs. ESLs were developed to satisfy both criteria, and have a flavor quality and shelf life between that of a WS and LSL cantaloupe.

The differences in field stability and harvest period have important implications for estimating the losses for the entire season. Relative to LSLs and ESLs, WSs are harvested over a longer period and are not as stable in the field. Because of these two factors, losses throughout the harvest season are substantial. LSLs and ESLs mature over a shorter period and exhibit greater field stability, resulting in lower losses. Understanding the harvest period, yield curve, and field stability of the WSs was critical to accurately estimating the losses over the entire harvest season. Estimating losses for LSLs and ESLs require very different calculations, highlighting the importance of fully understanding the growth, field stability, harvest, and other characteristics of each crop when attempting to estimate loss for the entire season.

3.4.2. Market prices

Market prices typically vary substantially throughout the growing season and have significant impacts upon the amount of product left behind. Because of the long lag time between planting and harvest, growers cannot quickly ramp up or slow down production to match price swings. Rather, they respond by harvesting a greater proportion of their crop or leaving more of it in the field by loosening or tightening quality standards. When prices are extremely low, growers may "walk-by" a field and disc it under.

3.4.3. Buyer specifications

Losses between growers were also found to vary significantly due to differing buyer specifications, which, of course, are influenced by consumer preferences. For example, some broccoli growers reported that they did not harvest broccoli with unevenly formed crowns because their customers would not accept them. Other growers claimed that this was not an issue for their buyers, and therefore harvested the irregularly-shaped heads.

3.4.4. Increasing labor costs

Agricultural labor costs have significantly increased in California over the past few decades. This leads to increased field losses as growers attempt to reduce labor costs by making fewer passes through the fields to harvest crops. Several growers reported that they have reduced the number of cuts they perform on crops such as broccoli and cauliflower as a direct result of increased labor costs. Higher labor costs also increase the likelihood that a grower will "walk by" a field. Varieties that deliver more uniform crop maturity or increase field stability may lessen the impact of labor costs on farm-level food loss.

3.4.5. Impact of variety improvement and varietal changes

The impact of improved varieties and evolving grower practices on losses was especially apparent in our study. In our 2016 surveys, sweet corn fields averaged losses of 11.2% of marketed yield. A combination of factors, including enhanced varieties and a shift in market preferences towards larger ears of corn, resulted in the adoption of new growing practices (primarily reduced plant spacing) that drove down edible loss to just 4.5% in 2017, more than a 50% decrease. Only the 2017 data are reported in this research.

3.4.6. Environmental factors

Environmental conditions are another significant source of variation in produce losses. For example, growers reported a drastic increase in the prevalence of sunburnt cauliflower heads in the summer of 2016 due to a period of unusually hot, sunny weather. Because sunburnt cauliflower heads are generally unmarketable, the amount of cauliflower left behind increased appreciably during this period. Heat, cold, wind, drought, rain, pests and other environmental factors can all have significant impacts upon crop yields, quality, and loss rates.

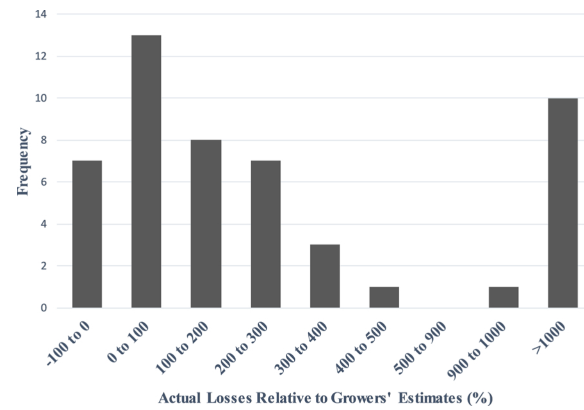

Fig. 1. Distribution of In-field Measured Losses Relative to Growers' Estimates.

3.5. Comparison of grower estimates and field measurements of food loss

Prior to the field measurements, growers were asked to estimate the amount of edible food loss in the specific field being surveyed. Out of the 123 surveys, 50 growers provided loss estimates. No estimate was recorded for growers who felt uncomfortable answering or who could not provide an estimate. Individual comparisons between the grower's estimate and actual findings for each field were calculated and are presented in Fig. 1. The histogram illustrates the distribution of grower loss estimates relative to actual measured losses.

Given the non-normal distribution of the comparisons, we calculated the median and found that the actual measured losses were 157% greater than the growers' estimates. Put another way, actual losses were slightly more than two and one-half times the growers' estimates. For 20% of the comparisons, our results exceeded the growers' estimates by more than 1000%. However, it is also interesting to note that 14% of growers provided estimated losses that exceeded our measured results. Overall, the large discrepancy between the majority of grower estimates and our results suggests that growers either don't have an accurate idea of what is left behind in their fields or, possibly, that the market has skewed their view of what product is edible. Based on our interactions with growers, we believe it is a combination of both of these two factors. There is also the potential that the discrepancy is due to social desirability bias, i.e. because food loss is considered socially undesirable it may be underreported by growers.

3.6. Limitations

In this study, we present findings of farm-level food loss for 20 crops grown in northern and central California, a state in which over 400 crops are grown. The findings may best be thought of as a snapshot of the food loss for these 20 crops over the 2016 and 2017 growing seasons. While the detailed loss estimates may be the best estimates available for many of the crops, several factors should be considered when generalizing the loss figures to other crops, regions, and time periods. First, we used a convenience sample and, although we have no evidence that our results differed from the overall population, it is possible that participating growers and the losses they experienced differed in some way from the population of growers. We also note that the variation between crops is high, as is clearly seen in the data we present. Regional variations are also likely to be significant as soil, climate, and moisture, have major impacts on crop choice, varietal choice, growing methods, etc. Weather is a major factor for crops grown in the US, but has less of an impact on crop production and yields in regions with milder weather and irrigated crops, as is the case in most of California. Furthermore, food loss rates may vary significantly between seasons based on planting decisions, growing conditions, and market conditions. The results of our interviews are also subject to potential bias, including selection bias and sample size.

We note that while the loss estimates for single-cut crops are based on actual field measurements, the full-season losses for multiple-cut crops were partially based on grower interviews. While the majority of growers we interviewed underestimated losses as compared to our field measurements, we believe that their estimates of the pattern of losses is nonetheless useful in estimating full-season losses.

Our crop selection may have biased the overall crop loss estimates. We selected crops that we believed had a high recovery potential. Thus, the average of losses for our selected crops may be higher than what a random selection of hand-harvested crops would yield.

Finally, because we were conservative in determining what left-behind produce was edible, our loss measurements are likely somewhat lower than what is actually experienced with the crops included in this research.

4. Concluding remarks

During the principal growing seasons of 2016 and 2017 we surveyed 20 crops and 123 fields. We interviewed dozens of growers during these surveys and followed up these interviews with more detailed grower interviews in 2018. Farm-level food loss results from a complex mix of factors, which, together, lead to a substantial amount of edible produce left in the field for every crop we surveyed. While it is easy to place the blame on growers, we found no growers who were content with leaving perfectly edible product in the field. No farmer spends thousands of dollars per hectare to plant and grow produce just to leave it unharvested. Rather, decisions to leave produce in fields result from a complex mix of consumer preferences, buyer specifications, marketplace economics, labor costs, weather, and other factors. The growers that we interviewed were willing participants in the study, often spending hours helping our team of researchers, and were genuinely interested in our findings.

4.1. Principal findings

Some of the key findings from our extensive examination of on-farm food loss for hand-harvested crops in northern and central California are:

- There is a large volume of food loss at the farm level amounting to tons per hectare. Across all crops, losses amounted to an average of 31.3% of the marketed yield, representing 11,299 kg/ha of remaining edible product. Total average losses across all 20 crops were 33.7% when walk-by field losses of 2.4% are included. Even when the percentage loss is relatively low, as in single digit percentages, the amount left behind is substantial.
- It is very difficult to estimate the amount of field losses without good measurements, even for growers. Our estimates of food loss, based on actual measurements, were approximately two and one-half times higher than those of growers. To date, most research on field level losses has relied on interviews and surveys with growers. As evidenced by this study and supported by Johnson et al. (2018b); Water Resources and Action Program (WRAP), 2017, and Beausang et al. (2017), relying on grower estimates likely leads to extreme underestimations of edible produce losses. Estimates of on-farm food loss must be much more comprehensive and wider in scope to accurately reflect losses.
- Food loss is a complex and complicated issue. Our field research and grower interviews revealed that the reasons for loss are numerous and often interrelated. Obvious factors, such as market prices, consumer preferences, buyer specifications, and environmental factors, as well as less obvious factors, such as labor availability, crop variety, and harvest method, play a role in the amount of loss.
- Walk-by fields represent a relatively small, but significant, proportion of unharvested, edible produce. Such unharvested fields may present an opportunity for food loss recovery because the crop is concentrated in a small area and could be collected without interfering with the harvest of marketed product.
- Despite the high levels of farm-level food loss, it seems unlikely that a simple, one-size-fits-all solution will solve the problem. Solutions that work for a specific crop, variety, cultivation system, and harvesting method may not work for another. To be successful, food loss recovery must overcome significant barriers, including high labor costs, food safety concerns, and product marketability. Moreover, the distributed nature of the relatively low-value product that is left in the field will make it difficult to efficiently and economically collect and market produce that is currently left in the field.

4.2. Future research and potential solutions

Because detailed measurement studies have only covered a fraction of the crops and geographical areas over one or a few seasons, additional research that addresses the myriad of diverse crops, growing practices, growing regions, climates, labor environments, and market conditions are needed to develop a more comprehensive understanding of farm-level food loss. Research that attempts to better understand the impact of the critical driving forces behind farm-level food loss is needed to support efforts to reduce loss and discover or develop outlets for the vast amount of edible produce that is left in the field.

Just as important as understanding the amount of farm-level food loss and the underlying reasons behind losses is understanding how to reduce the losses. Many ideas have been proposed including utilizing unharvested produce to supply food assistance programs, marketing produce that is cosmetically imperfect, and utilizing secondary markets to make products such as juice, dried produce, or ingredients for processed products. A potential path to these more diversified markets is to utilize concurrent harvesting, whereby product for the fresh market and alternative outlets are harvested simultaneously. Yet another approach to achieving the outcome of more complete harvests is to rethink the incentives of the produce marketing system (e.g. discounting imperfect produce or encouraging the purchase of produce resulting from overproduction) in order to incentivize consumers and retailers to accept or utilize produce that is less than cosmetically perfect. Alternatively, retailers might be encouraged to buy entire fields so that they would be motivated to market the entire crop.

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