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Estimating on-farm food loss at the field level: A methodology and applied case study on a North Carolina farm

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ABSTRACT

Current estimates of food loss at the farm level are either carried forward from decades-old estimates that rely on data from small farms using alternative agricultural practices, or they are based on grower estimates reported during interviews. A straightforward protocol adaptable to many crops is necessary to provide comparable data that can begin to fill gaps in knowledge on food loss in the US. Accurate estimation of on-farm losses for fruits and vegetables can inform ongoing national food loss and waste discussions and farm-level business decisions that hold potentially positive impacts for farm viability and resource-use efficiency. This paper describes a straightforward methodology for field-level measurement and demonstrates its utility on six vegetable crops harvested in 13 fields of a 121-hectare North Carolina vegetable farm.

In this case, results showed that on average, approximately 65% of the unharvested crop that remained in the field was of wholesome, edible quality, although the appearance may not meet buyers' specifications for certain markets. The overall estimated average of vegetable crops that remained unharvested, yet were wholesome and available for recovery, was 8840 kg per hectare on the case study farm. The portion of the grower's reported total marketed yield that remained unutilized in the field averaged 57%, a figure greatly exceeding current estimates of farm level loss. Developing strategies to utilize these losses could enable growers to increase the amount of fresh produce moving into the supply chain, and represent a path towards sustainable intensification of vegetable crop production.

1. Introduction

As worldwide interest in the problem of food waste has soared, an important part of the supply chain is often overlooked: food loss that occurs at the farm level, sometimes referred to as primary production. In the US, a report by the Natural Resource Defense Council in 2012 sparked renewed discussion by estimating that food intended for human consumption is lost or wasted along the supply chain from the producer to the consumer at a rate of 40% (Gunders, 2012; Gunders et al., 2017; Hall et al., 2009). However, this calculation does not include food that never reaches the supply chain, such as unharvested crops or crops that remain in the field after the primary harvest (Hall et al., 2009). Food loss during production contributes to significant losses of freshwater, cropland and fertilizer (Kummu et al., 2012), in addition to capital investments in labor and equipment. Since the crop's use is not maximized, these resources are not used efficiently. Utilizing the entire crop produced could increase yield without increasing land or chemical input usage. This means that reducing farm level losses may be a path towards sustainable intensification, defined as producing more food without increasing negative environmental impacts (Garnett and Godfray, 2012; Pretty and Bharucha, 2014). As the global population continues to increase, debates continue over whether the US needs to increase yield in commodity and other crops. An increased need for food and high rates of food insecurity have historically translated to a push for increasing crop yield, and vegetable growers continually seek to maximize their production with improved varieties, custom fertility, targeted irrigation, and complex pest and disease management strategies. An alternate way to increase the amount of food coming from farms would be to reduce losses, improving sustainability while increasing food availability (Beddington et al., 2012; Kader, 2003, 2005; Nellemann et al., 2009).

Discussion of food loss at the farm level now centers on recent estimates from just a few organizations, without basis in field measurement. The Rethink Food Waste through Economics and Data (ReFED)

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(2016) reported estimate of over 9.2 billion kilograms of food lost at the farm level annually in the US was derived from 16 grower interviews that concentrated on farms of less than 5.7 ha primarily using alternative growing practices (Berkenkamp and Nennich, 2015). The ReFED estimate also relies on Annual Vegetable Summary data, which reports on the area left unharvested for each crop, but does not include crops from fields that may have been harvested several times, then abandoned or destroyed (USDA-NASS, 2017a). Gustavsson et al. (2011) estimate for the Food and Agriculture Organization of the United Nations suggests that 20% of fruit and vegetables in North America are lost at the farm level, which includes both the field and packinghouse. Their estimate is not based on their own inquiry or field-level measurement, but instead cites other literature, which in itself is not based on field measurement (Cappellini and Ceponis, 1984; Golumbic, 1964; Harvey, 1978; Kader, 2005; LeClerg, 1964; Parfitt et al., 2010). Additionally, these earlier articles approximate losses based on estimated loss to plant pathogens. These estimates may no longer apply to modern vegetable production, as techniques, varieties, and efficiency have all improved.

Globally, researchers agree more study is needed to quantify the amount of edible crops that is lost at the production level and what factors contribute to these losses. This is needed to understand the opportunities available for further utilizing crops either for profit, or to supplement the emergency food system that can positively impact public health (Gunders, 2012; Gunders et al., 2017; Harvey, 1978; Kantor et al., 1997; Lundqvist et al., 2008; Neff et al., 2015). The World Resources Institute has developed a standard for reporting food loss and waste, the Food Loss and Waste Accounting and Reporting Standard, which ensures consistency in reporting across the supply chain (Lipinski et al., 2016). While that document helpfully documents criteria for developing reliable measurement techniques in general, it does not provide specific guidance on techniques to estimate losses at the production level.

The objective of this paper is to describe a method for better estimating amounts of available marketable and edible produce that remain in the field, based on the results of field-testing a method on 13 fields of vegetable crops grown on a 121-hectare North Carolina farm in 2016. The aim of presenting this case study is to demonstrate the use of the method through sampling and scaling of data to better understand what amount of fresh vegetables are lost in the field. Use of this protocol offers growers and others a better understanding of what amount and quality is left after the primary harvest. Growers may use the information for more informed decision-making when weighing potential returns vs costs of harvest. Food recovery organizations may use the data collection method to manage workflow and volunteers in surplus food management. Additionally, use of the method can be further tested and validated by food waste researchers, and the estimates generated can inform policy-making related to field losses for fresh produce.

1.1. Prior measurement studies

Field measurement of remaining, surplus, or unmarketable vegetable crops in the US can be complicated to coordinate and resource-intensive, and results in data from a single time point. Field sampling techniques provide a more concrete starting point for estimation in comparison to a grower's visual or perceived estimate of what remains in the field. This technique overcomes the limitation of underestimation that often occurs when visual estimates are reported (WRAP, 2017). Field sampling is considered to be a good choice of method when losses are unknown (Hartikainen et al., 2017) and losses need to be monitored on an ongoing basis (WRAP, 2017).

A few studies involving field measurement of vegetable losses within similar production management systems to the US industry have been completed in Europe. Hartikainen et al. (2017) used field measurement in combination with a variety of other methods to determine losses in carrot and onion in Nordic countries. Strid et al. (2014) used field measurement to assess lettuce crops in Sweden, and WRAP (2017) assessed lettuce in the UK. For carrots, sample areas of approximately 20 m^2 were harvested, samples were weighed, and the losses per meter of row calculated (Hartikainen et al., 2017). Numbers of piles of onions were left in the field, and average size piles were weighed and the edible but unutilized portion of the crop was calculated from these samples (Hartikainen et al., 2017). Both of these studies resulted in data that was not reported due to a low sample number (Hartikainen et al., 2018). In the lettuce study in Sweden, sample areas of 24 to 30 m^2 were marked and harvested, heads were collected, and the remaining crop per square meter was calculated (Strid et al., 2014). Researchers in the UK measured row lengths of unharvested areas of lettuce, calculating losses from the data (WRAP, 2017). Hartikainen et al. (2018) determined through questionnaire responses that 26% of the carrot crop and 15% of the onion crop is unutilized but considered to be edible in the Nordic countries. On average, 16.8% of the head lettuce crop, or approximately 3200 kg/ha of edible and inedible quality (excluding the outer leaves collected), was left unharvested in the field in Sweden (Strid et al., 2014). The lettuce left unharvested in the UK study was estimated at 19% of the marketed crop (WRAP, 2017). Providing a protocol for data collection across many crops could lay the groundwork for consistent data collection, prompting aggregation of data across regions and time points, thus enabling a better estimate of the true amount of on-farm losses.

Other related studies in developed countries and the US have used qualitative methods such as interviews and surveys to report growers' estimated rates of edible produce lost at the primary production level. Almost all of the interview-based studies have emphasized the imprecision or inaccuracy that may be present in their estimates, one describing a "reluctance to disclose" data (Milepost Consulting, 2012), along with wide variability and no way to confirm the estimates (Berkenkamp and Nennich, 2015; Hartikainen et al., 2017; Rogers, 2013; Snow and Dean, 2016; WRAP, 2011). The variability in reporting and data collection method makes the figures reported by these studies difficult to synthesize. The US studies both focused on farms less than 8 ha in size (Berkenkamp and Nennich, 2015; Snow and Dean, 2016), which may be able to reduce losses through strategies such as direct marketing to the consumer, which has been recommended as a solution to food loss on-farm (Gunders, 2012). While a large number of American farms are small, vegetable farms with positive profit rates providing significant yields to the nations' vegetable supply are generally larger than 40 ha, thus indicating a need for studies that work with farms of this size (USDA-ERS, 2013).

In 2016, North Carolina ranked in the top 10 states for US production of tomatoes, cucumbers, bell peppers, snap beans, watermelons, squash, cabbage, and sweetpotatoes (USDA-NASS, 2017a), making the state an ideal location for vegetable production research in many crops. The average farm in North Carolina is family owned (93.54%) and has been in operation for more than ten years (89.18%) (USDA, 2015). North Carolina has over 48 thousand farms averaging 69 ha, which is less than half the average farm size in the country (USDA-NASS, 2017a,b).

Reporting food loss and waste in other parts of the supply chain, such as the retail or household level, is often undertaken with a sampling and data extrapolation method (Lipinski et al., 2016). Estimating yield potential at the beginning of the season uses the same strategy, and the sampling method recommended here exceeds that which is recommended to growers, which is 3.05 m of one row (Maynard and Hochmuth, 2007), for more replicable accuracy. The method detailed in this report is purposefully straightforward and adaptable to a wide range of crops and categorizes the remaining crops broadly to enable use by growers and researchers interested in quickly gathering comparable data on food loss.

1.2. Description of the Farm used for the Field test cast study

The farm highlighted by the case study is owned and managed by a multi-generational family, and has been in operation for over sixty years. The case study farm is a mixed vegetable and commodity farm of approximately 121 ha, producing vegetable crops on over half of that area.

The selected farm is located in an important production region of the state, and produces the following for the fresh market: cabbage (*Brassica oleracea*), summer squash (*Cucurbita spp*), long green cucumber (*Cucumis sativus*), green bell pepper (*Capsicum annuum*), and eggplant (*Solanum melongena*). An assortment of vegetable grades corresponding to USDA grades (USDA-AMS, n.d.) and pack styles from the farm are sold to retailers, foodservice distributors, and through produce brokers along the US east coast. This farm employs a broker to sell what is harvested. There is no branding associated with the farm, and contracted agreements for volume or price are not used in negotiations with buyers. This farm operation also performs packing and shipping activities, employing a total of 20–50 workers each year.

2. Methods

This section describes in detail the method for collecting field samples to estimate the amount of produce remaining in the field. In brief, samples are collected, sorted, weighed and recorded, then that information is used to calculate estimates of the amount of produce remaining in the field per hectare. The crops evaluated as examples in this case study were: cabbage, summer squash (including yellow squash and zucchini), long green cucumber, green bell pepper, and eggplant.

This evaluation could be considered a food loss and waste inventory and complies with the Food Loss and Waste Accounting and Reporting Standard (Lipinski et al., 2016) by reporting all elements of the scope of the method and case study. The global reporting standard was developed with required elements for reporting food loss and waste in order to provide basis for comparison across regions. The required elements include the material type, the intended market and category according to the World Health Organization, the life cycle according to the United Nations Statistics Division, the time of data collection, and the final destination of losses (Lipinski et al., 2016). The material type collected in this study was food and its associated inedible parts, such as short stems. Vegetables sampled were intended for fresh market and were sold unprocessed, as identified in the fresh vegetable category [GSFA 04.2.1.2] (FAO-WHO, 2016). The life cycle corresponds with ISIC Rev. 4 code 0113, which denotes the hierarchy of: Agriculture, forestry and fishing; crop and animal production; growing of non-perennial crops; and growing of vegetables and melons, roots and tubers (UNSTATS, 2017). Pre-harvest losses, such as losses due to seeds' failure to germinate or plant loss during the growing season, were not considered, and no packaging or water was included in measurements. Samples were collected in 2016 in North Carolina, USA, and the food reported as lost was left in the field, ultimately being destroyed or incorporated into the soil.

2.1. Information needed prior to sampling

The calculations used to generate estimates are based on kilograms of produce remaining per plant; therefore, having accurate information on plant and row spacing are critical. Buyer quality specifications vary by product and by buyer; therefore, a range of size, shape, appearance quality, and maturity specifications provided by the grower were used to categorize produce that was considered marketable (Table 1). The grower's reported yields were used to compare the crop's amount remaining in the field to that which had been harvested. Additionally, depending on field size, planting date, and speed of harvesting crew, the interval between harvest dates can vary by farm or field. The harvest interval is the time between harvests that allows the remaining crop to reach maturity. In this study, an attempt was made to collect samples following the typical harvest interval after the grower made the decision to discontinue harvesting the field. However, this interval was

Table 1
The range of produce quality indicators covered in each category of marketable, edible, and inedible vegetables collected after the primary harvest in a field demonstration of a produce loss measurement protocol in North Carolina. Crops evaluated included cabbage (*Brassica oleracea*), summer squash (*Cucurbita spp*), long green cucumber (*Cucumis sativus*), green bell pepper (*Capsicum annuum*), and eggplant (*Solanum melongena*). Marketable quality according to USDA grades refers to vegetables displaying maturity and appearance quality that meets buyers' current quality specifications. Unmarketable but edible refers to vegetables that are of optimum maturity, but do not meet desired quality specifications for size, shape, or surface blemishes. Inedible quality refers to vegetables displaying visibly diseased, decayed, or sun-scalded areas, that are over-mature, or have physical damage.

Crop	USDA Grades	Marketable according to USDA Grades	Edible but unmarketable	Inedible
Cucumber	U.S. Fancy, U.S. Extra No. 1, U.S. No. 1, U.S. No.1 Small, U.S. No. 1 Large	15.2 - 22.9 cm long, 4.4 - 7.0 cm diameter, straight, not miscolored, minimal to no scarring	No size requirements; Quality often observed was curved, yellow-bellied or other miscoloration, misshapen, and healed scarring	Damage, disease, or decay, over-maturity or sun bleaching
Yellow Squash	U.S. No. 1	12.7 - 20.3 cm long, 2.9 - 7.0 cm diameter, smooth skin, characteristic shape, minimal to no blemishes or scratches	No size requirements; Quality often observed was bumpy or ridged skin, uncharacteristic shape, and healed blemishes or scratches	Damage, disease, or decay; Over-maturity indicated by firm, dark, uncharacteristic skin color
Zucchini	U.S. No. 1	15.2 - 22.9 cm long, 3.8 - 6.4 cm diameter, smooth skin, characteristic shape, minimal to no blemishes or scratches	No size requirements; Quality often observed was bumpy or ridged skin, uncharacteristic shape, healed blemishes or scratches	Damage, disease, or decay; Over-maturity indicated by firm, dark, uncharacteristic skin color, or greater than 30.5 cm length
Bell Pepper	U.S. Fancy, U.S. No. 1	Equal to or greater than 6.4 cm in both length and diameter; Dry blemishes characteristic of calcium deficiency are acceptable for processing	Less than 6.4 cm in diameter or length	Damage, disease, or decay
Cabbage	U.S. No. 1	1.36 kg or more is considered desirable. Heads must be firm and free of blemishes or insect damage	No size requirements, free of insect damage	Damage, disease, or decay
Eggplant	U.S. Fancy, U.S. No. 1	15.2 - 25.4 cm long, 8.9 - 11.4 cm diameter, uniform dark purple color, characteristic shape, no blemishes	No size requirements; Quality often observed was non-uniform coloration, misshapenness, or decay in stem area only	Damage, disease, or decay; Over-maturity indicated by brown or tan skin color, and maturing seeds

not reached in all cases, and a few fields were sampled one day later than the interval required for that crop.

2.2. Field sampling method

The sample area in each field was located at random, though care was taken to avoid field edges or obvious areas that were non-representative of the field. Three adjacent rows of 15.24 m length were marked, harvested, and evaluated. In two of the fields, longer rows were sampled. However, as the aim of the project included quickly estimating the amount remaining in the field, the length of sample rows was decreased after determining through ANOVA analysis that there were no significant differences in results between sampling row lengths (Appendix A). Sampling using three adjacent rows accounts for differences in harvesting technique used by farm personnel, with the assumption that typically different individuals are harvesting side by side. However, this sampling scheme does not account for variability in field conditions. Row width was 1.83 m, with the exception of the cabbage and two of the cucumber fields, which were planted in 1.07 m rows.

Rows were harvested separately and each row considered as one observational unit. All vegetables remaining on each plant after the farmer's decision to cease harvest were collected into a harvest container. Harvest knives were used to collect zucchini and cabbage. Harvesting here means that each vegetable was detached from the plant at the time of sample collection. Nothing was collected from the ground or bed that had been previously detached from the plant for any reason. Visibly diseased, decayed, over-mature, sun-scalded or damaged vegetables that remained attached to the plant were also harvested to gather complete data on the marketable, edible but unmarketable, and inedible portions of the crop. The marketable portion refers to that product that meets buyers' current quality specifications—in other words, the quality standards being used by the grower to harvest and pack particular grades, corresponding to, or exceeding the quality described in USDA grades (USDA-AMS, n.d.). Unmarketable but edible refers to product that is edible but not marketable based on currently desired quality specifications (due to size, shape, surface scarring, etc.). Growers often discontinue the harvest due to a perception of poor quality remaining in the field, and by collecting the entirety of the crop remaining on the plant and quantifying these categories, a definitive assessment of how much of the field has succumbed to quality issues can be determined.

Sorting samples into categories:

In this study, the focus was on determining how much food remained in the field that was in condition suitable for human consumption, whether it would be directed by the grower into an alternative market, or donated into the emergency food system. Therefore, as noted above, the categories used were marketable, edible but unmarketable, and inedible, according to the quality standards set by the buyer. Vegetable size and shape were assessed using produce inspection equipment recommended by the USDA-AMS Specialty Crops Inspection Division (USDA-AMS, 2016), and the lead author completed training from this entity to better understand federal produce inspection methods and techniques. Specifically, the Caliper II plastic caliper and the General Purpose Sizer, an aluminum 6-blade set of sizers, were used to determine diameter; an Area Gauge, IA #30 G was used to measure length as well as to size defects and blemishes, and several Visual Aids were used to determine proper color and characteristic shape (USDA-AMS, 2016). A CAS PB300 Bench Scale (CAS Corporation, East Rutherford, NJ, USA) was used in the field to collect weights. This scale is legal for trade, accurate to 0.02 kg when measuring 0–68.04 kg, and portable. Data was recorded in kg for marketable, edible but unmarketable, and inedible categories from each of the three rows separately.

2.3. Scaling the sample to a total field estimate

By determining how many surviving plants are present in each sample row, and comparing that to the estimated plants per ha (based on the plant and row spacing provided by the grower), a multiplier is generated that provides a realistic estimate of the plant coverage present under the field conditions. Once that plant coverage is calculated, the remaining vegetable weight can be recorded for each category of quality, and the mean weight per plant can be determined. This per-plant loss in each of the three categories provides a starting point for scaling the data to the hectare. An alternative method would be to extrapolate up from the area sampled, which may be more straightforward, but does not reveal estimated per plant losses.

3. Results

Fields were sampled between June 1 and September 28, 2016, and each evaluation required approximately four hours. Using the sampling and scaling method above resulted in some revealing figures. Of the fields sampled, each provided unique results, as the conditions for production, harvest, and marketing were individual to the crop and harvest date. Field size averaged 2.73 ha, and ranged from 1.01 ha to 5.97 ha. The size of the sample taken in each field represented between 0.14% and 0.90% of the total field area.

Sorting the samples into the categories of marketable, edible but unmarketable, and inedible provided a clear picture of the quality of produce remaining in the field. The marketable amount remaining, calculated for each plant in the field (Table 2), ranged from 0.00 kg per

Table 2

Produce samples collected from thirteen fields on a North Carolina farm after the primary harvest ended were sorted into marketable, edible but unmarketable, and edible categories, leading to a calculated weight available per plant and estimated weight available per hectare.

	Calculated weight available per plant (kg)			Estimated weight available per hectare (kg)		
Crop	Marketable	Edible but unmarketable	Inedible	Marketable	Edible but unmarketable	Inedible
Green Cabbage	0.00	0.16	0.03	0	5051	979
Yellow Squash	0.07	0.03	0.09	3644	1364	4556
Zucchini	0.09	0.30	0.40	2356	7636	10140
Yellow Squash	0.02	0.02	0.17	903	650	6671
Cucumber	0.16	0.42	0.05	5453	14733	1584
Cucumber	0.10	0.17	0.05	4316	7159	2066
Cucumber	0.13	0.29	0.14	4574	10207	4762
Cucumber	0.11	0.13	0.06	3613	4103	1898
Bell Pepper	0.08	0.04	0.03	2795	1533	983
Bell Pepper	0.12	0.03	0.20	4197	1018	7136
Eggplant	0.29	1.48	1.02	3627	18528	12842
Yellow Squash	0.03	0.04	0.06	1255	1649	2661
Zucchini	0.05	0.15	0.05	1077	3475	1250
Average	0.10	0.25	0.18	2909	5931	4425

plant in cabbage, to 0.29 kg per plant in eggplant, and averaged 0.10 kg per plant over all crops. Edible but unmarketable produce ranged from 0.02 kg per plant in yellow squash to 1.48 kg per plant in eggplant, and averaged 0.25 kg per plant. Inedible losses ranged from 0.03 kg per plant in green bell pepper and cabbage, to 1.02 kg per plant in eggplant, and averaged 0.18 kg per plant.

Extrapolating this data using the adjusted plants per hectare provides an estimate of the amount remaining per hectare (Table 2). The estimated marketable weight remaining in the field ranged from 0 kg per hectare in cabbage to 5453 kg/ha in long green cucumber, and averaged 2909 kg/ha over all fields sampled. Edible but unmarketable vegetables remaining were estimated to range from 650 kg/ha in yellow squash to 18,528 kg/ha in eggplant, and averaged 5931 kg/ha. Estimated inedible losses ranged from 979 kg/ha in cabbage to 12,842 kg/ha in eggplant, and averaged 4425 kg/ha. Nine of the thirteen fields contained an estimated 2000 kg or more of marketable crop per hectare after the harvest had been discontinued. Three out of the thirteen fields contained an estimated 10 tons or more of edible but unmarketable crop per hectare.

Each field assessment resulted in specific categories expressed, as a percentage of the remaining crop in the categories marketable, edible, or inedible quality, and the average split is included in Fig. 1. The marketable portion of what was left behind in each field averaged 24.37%. The edible but unmarketable portion of what was left in each field averaged 41.45%, and the inedible portion averaged 34.18%.

The amount of produce left in the field is presented as a percentage of the yield marketed from the farm in Fig. 2. Ten fields out of the thirteen evaluated contained marketable produce equivalent to greater than 10% of the marketed yield. Only one field, cabbage, did not contain any marketable produce remaining after the grower's primary harvest. All of the fields evaluated contained produce that was considered edible but would not meet buyers' specifications, representing amounts greater than the harvested and marketed yield. Seven fields contained edible produce in estimated amounts greater than 20% of the grower's yield.

4. Discussion

4.1. Increase in marketable yield could be realized immediately

Current figures in food loss and waste are often reported in estimated percentages. Farm-level losses for fruit and vegetables are most commonly considered to be 20% of the total marketed yield, and includes field and packinghouse losses (Gustavsson et al., 2011). Combining the marketable and edible portions of the remaining produce found in the current study reveals much higher percentages may be lost at the farm level. Considering both the marketable and edible crops

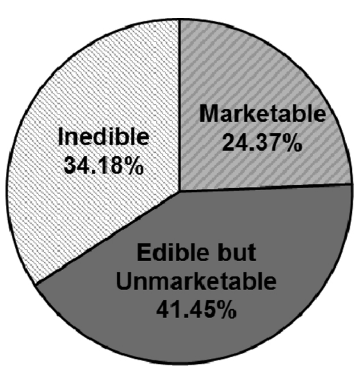

Fig. 1. Vegetable crops remaining in the field after the primary harvest was completed in thirteen fields on a North Carolina farm displayed a range of quality, including marketable, edible but unmarketable, and inedible. The average quality over all fields is shown.

collected in the fields evaluated, the percentage of losses ranged from 12% of the marketed yield in one of the squash fields, to 143% in one of the cucumber fields, and averaged 57%. This provides strong evidence that continuing the harvest would increase fresh produce moving into the supply chain, without increasing the use of land or chemical resources. Even though the increased amount of produce is available to be absorbed into the food supply, an increase in demand for fresh produce overall, and/or a shift in consumer acceptance of produce that does not meet traditional cosmetic specifications, may be required first. Further, an increase in supply may reduce a market price already weakened by the progression of the season, which in turn makes it economically unfeasible for a farmer to continue harvesting.

In this case study of a commercial vegetable farm, which sold only into the wholesale fresh produce supply chain, the remaining amount in the field represented a higher proportion of marketed yield than was reported by other US studies using qualitative methods. Snow and Dean (2016) report 15% of the marketed vegetable crop in Vermont is left in the field, according to grower estimates. Berkenkamp and Nennich (2015) reported a range of 1–20% representing the rate of cosmetic imperfection of vegetable crops, according to grower estimates from their set of interviews. In this study, the yield that was harvested and marketed from the farm was obtained from the grower, rather than calculated using county- or state-level data reported to enumerators. Marketed yields from the case study farm were higher than the 2016 average yield in North Carolina in cabbage, squash and zucchini, and lower than average in bell pepper and cucumber (USDA-NASS, 2017b).

The remaining amount in the field that was considered to be marketable according to current buyer specifications for quality averaged 19% of the yield that was marketed from the farm. This portion of the crop is available immediately when an increase in yield is required, as long as there is an opportunity to market it. This raises the question: Are losses that are estimated by growers and others taking only the marketable portion into account? Interview-based studies rarely make clear if estimates cover all edible produce, or consider only marketable produce as a loss. With improved market connection and reliable, flexible buyers able to accept a wider range of produce quality, growers may be able to justify a complete harvest, making use of both the traditionally marketable quality produce as well as produce of edible quality.

4.2. Remaining vegetables available in much higher quantities than are currently recovered

Vegetable crops may be a good target for recovery. In comparison with cereal grains and meat, vegetables have high recoverability as they do not require processing prior to distribution (Garrone et al., 2014). Combining the marketable and edible amounts found after the primary harvest, the volumes suitable for recovery are potentially vast. The recoverable crop left unharvested after the harvest averaged 8840 kg/ha across crop types, which represents over 80,000 servings per hectare, based on the average serving size for these vegetables of 108.6 g (FDA, 2008). These figures exceed the findings of other studies based on field sampling, which found 3200 kg/ha of lettuce in Sweden (Strid et al., 2014), 2900 kg/ha of carrots in Finland, 3900 kg/ha of carrots in Norway, and 800 kg/ha of onions in Sweden (Hartikainen et al., 2017).

An extrapolation of crops remaining in the field to the state or other geographic unit can be used for forecasting recovery efforts, although several limitations exist. The average portion of the marketed yield that could be recovered from two bell pepper fields (21.34%) was multiplied by the yield (28,021 kg/ha) and land in production (971 ha) from North Carolina in 2016 (USDA-NASS, 2017b). The potential for recovery of just this one crop in the state would total 5806 tons, if this farm's management style indicates regional production trends. The Society of St. Andrew, a gleaning organization that operates across the country, recovered 1633 t of fresh produce in North Carolina in 2015, according to their annual report (SoSA, 2016). Gleaning 1633 t of produce

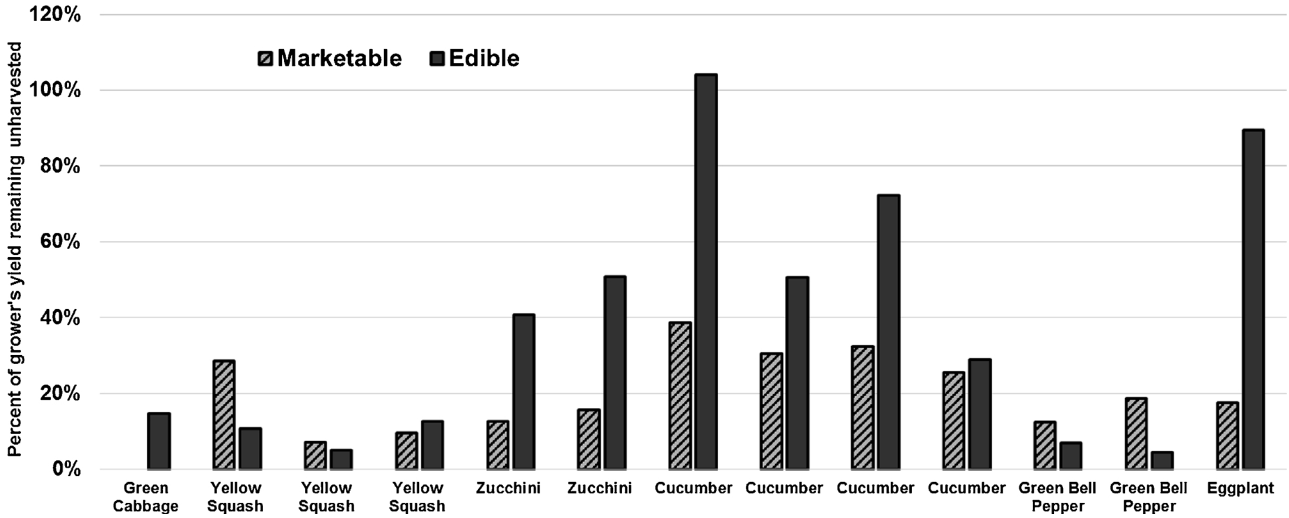

Fig. 2. The marketable and edible crops that were left in the field after the primary harvest was completed in thirteen vegetable crop fields on a North Carolina farm, expressed as a percentage of the grower's reported marketed yield.

required over 10,000 volunteers working during 1305 events (SoSA, 2016). This 3.5-fold difference, between what is available in just one crop, and what is currently recovered in this state, underlines the weighty task ahead of recovery organizations. It is hoped that knowledge of this opportunity will spark interest in developing new strategies for large-scale recovery of remaining crops, reducing environmental impact, and increasing revenue, in addition to new ways to increase the efficiency of traditional gleaning activities, new policy initiatives that take the burden off producers in recovery efforts, as well as further interest in field measurement of losses.

4.3. Metric of kilograms of losses per hectare is suggested for continued research

Field sampling is resource-intensive but straightforward. In order to make estimates as accurate as possible, data collection from the point of production, the field, is a necessary step to determine how much produce is available, whether the interest is to increase grower profitability or to increase the amount of recovered produce. More research utilizing field sampling strategies, either in combination with grower estimates from interviews, or in place of them, will be required to understand which crops have the greatest potential for recovery or for profit. Using a standardized method across many crops allows for a standardized metric for reporting, such as kilograms per hectare. As studies emerge from other regions that report using the same metric, the true value of on-farm losses in the US can be more accurately estimated.

The marketable portion of the crop that remained in the field (average 0.10 kg/plant) meets the criteria of the buyers' specifications for quality, and may be of primary interest to growers. The edible but unmarketable portion of the crop, averaging 0.25 kg per plant, may be of primary interest to recovery organizations or alternative markets promoting the usage of misshapen or mildly blemished produce. Combining the marketable and edible portions remaining into a recoverable weight results in an average of 0.35 kg per plant, an amount exceeding three servings of vegetables according to the dietary recommendations for an average adult (FDA, 2008). With further research, the measure of kilograms of losses per plant generated through these methods may provide an improved metric for estimation in statewide studies such as the Vermont study, which began calculations of farm level losses with a total yield rate of 24,412 kg/ha (Snow and Dean, 2016). Extrapolating the data per plant and to the hectare, based on the adjusted number of plants per hectare, changed the picture somewhat due to plant density, which varies by farm. This variability between farms suggests kilograms of losses per hectare may be a more reasonable unit for comparison among crops.

4.4. Mix of produce quality in the field late in the season makes further harvest high-risk

The marketable, edible, and inedible portions of the unharvested crop present more information for farm decision-making such as whether to continue the harvest in an attempt to further market the crop. As trends in produce marketing change, alternative markets may be able to accept a wider range of cosmetic quality for processing, foodservice, or institutional use. Each field's unique data on what portion is marketable and edible will present challenges and opportunities for further utility.

The combination of edible but unmarketable (41.45%) and inedible quality (34.18%), averaging over all fields evaluated, totaled 76% of the remaining crop. This portion represents risk to a grower who sells into traditional retail markets. If any edible or inedible quality vegetables are mistakenly packed and shipped within the shipment of marketable vegetables, then discovered during inspection or receiving, the entire load may be rejected in the current system, potentially tarnishing the farm's reputation. The grower in this study discontinued the harvest in fields where the edible but unmarketable and inedible quality made up the majority, to avoid this risk. Each field that was evaluated displayed a unique variation of this split. In nine out of thirteen fields, the portion of remaining vegetables having marketable quality made up less than one third of the total amount.

On the other hand, combining the marketable (24.37%) and edible quality, in this farm's case, total 66% of what remains in all fields. With connection to alternative markets that accept a wider range of produce appearance quality, this portion represents the opportunity available to the grower willing and/or able to continue the harvest, or to recovery organizations. Several foodservice distributors, retailers, and other types of direct-to-consumer markets are now offering an "ugly" produce line to provide consumers with lower-priced options that include blemished or misshapen vegetables. Low market prices and a focus on appearance quality represent some market-based factors contributing to losses in the field (Gunders, 2012; Gunders et al., 2017; Milepost Consulting, 2012). Additionally, the available price may not support the cost of additional harvests, which account for the bulk of production costs (Berkenkamp and Nennich, 2015).

4.5. Limitations

A few limitations prevent the use of the measurement protocol presented in this paper to extrapolate available produce to a statewide or national estimate. The case study has been used to illustrate the type of operation-specific data that measurement in the field can provide. Without a high number of replications for each crop, it would be difficult to predict whether data from this North Carolina farm is indicative of trends around the state or nation. Sampling on multiple farms will be required to further understand these initial findings. Farm-specific results like these can, however, be used by individual growers to improve management of certain crops in order to recover more yield, and potentially increase profit from fields that were previously considered finished. Ideally, the time between the last harvest for the grower and field sampling would match the harvest interval currently in use by the grower. When the harvest interval is not met, it can advance a mature vegetable into an over-mature, inedible state, or accelerate the likelihood of disease and damage. It can also advance a small or immature vegetable into the marketable category. In each of the fields evaluated in the current study, the crop was destroyed after an estimate was made of the amount of the remaining crop, in order to plant a subsequent crop. The accuracy of the sampling and scaling method used for estimation here has therefore not been confirmed through a harvest using the grower's field crew.

5. Conclusion

Solutions that improve fresh produce recovery efficiency and utilize the entire crop can contribute to increased profit for growers, support the emergency food system, and contribute to feeding a growing population. Through innovations in the way crops are produced, vegetable yields have grown over time. However, further utilization of crops that are edible but may not meet current buyer standards can increase the available supply of fresh produce in the US, without increasing the amount of land or chemical resources used in their production. This study supports the idea that reducing losses in production should be considered an approach to sustainable intensification of agriculture in the US (Chartres and Noble, 2015).

Field evaluations for this case study have shown that the amount of marketable food remaining in the field can be high in comparison to the marketed amount, which could provide an opportunity for growers to further profit from the crop they are already cultivating. The volume of food that could be recovered for human consumption reveals the potential for recovery organizations to procure even more healthy food. The comparable metric of kilograms per hectare is suggested for future research in this area. The mix of produce quality found after the primary harvest indicates the grower's risk of harvest cost and chance of rejection may outweigh the opportunity provided by continuing the harvest.

Results from field sampling and scaling can provide growers with more information to make decisions on whether or not to continue the harvest. While the data collected for this case study represents a single time point in the life of each field, it has confirmed that estimates derived from historical approximations or interviews could be made more reliable with corroboration through field sampling. Based on these measurements, the estimations of remaining marketable crop will likely increase, which could alter a grower's decision on whether to abandon a field. This project has outlined an efficient method for growers, recovery organizations, alternative markets, or government agencies to use in order to measure and further understand the scale of losses occurring on vegetable farms, and has demonstrated its practical usage on one farm. Further research on the amount, types, and reasons for food loss at the farm level has been recommended, and it is hoped that the method presented here will contribute to its realization.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.resconrec.2018.05.017.

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