On the Measurement of Food Waste*

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On the Measurement of Food Waste

Abstract

According to the Food and Agriculture Organization (FAO) of the United Nations, a quarter to a third of all the food produced worldwide is wasted. We develop a simple framework to systematically think about food waste based on the life cycle of a typical food item. On the basis of our framework, we identify problems with extant measures of food waste and propose a more consistent and practical approach. In doing so, we first show that the widely cited, extant measures of the quantity and value of food waste are inconsistent with one another and overstate the problem of food waste. By misdirecting and misallocating some of the resources that are currently put into food-waste reduction efforts, this overstatement of the problem could have severe consequences for public policy. Our framework also allows documenting the points of intervention for policies aimed at reducing the extent of food waste in the life cycle of food and to identify interdependencies between potential policy levers.

Key words: Food Waste

JEL classification: Q11, Q18, L66

If one is to believe the rhetoric put forth in recent years in various policy documents and media accounts, food waste is one of the—if not *the*—defining food policy issues of our time. As with many other food policy issues, ranging from famine to genetically modified foods and from undernutrition to obesity, food waste elicits an almost visceral reaction, most likely due to the social norms and value judgments associated worldwide with the wasting of food.

Yet unlike many other hot-button food policy issues,[1] there is a dearth of credible empirical evidence on the extent, cost, and causes of food waste. Indeed, the evidence on food waste comes into two broad categories. On the one hand, the evidence that purports to have external validity tends to be found in the gray literature, i.e., in various policy documents and reports from advocacy groups and nongovernmental organizations. The evidence that purports to have internal validity, on the other hand tends to focus on narrow applications and is more likely to be found in peer-reviewed journals. Though this general tradeoff between internal and external validity is not a problem that is unique to food waste, effectively none of the evidence on food waste can make claims to having both internal and external validity—a situation that is problematic, to say the least, when it comes to an issue as emotionally charged as food waste.

We cannot claim to be providing evidence that has both internal and external validity. Rather, our contribution is to steer the research agenda in that general direction by asking three related questions about food waste. First, how confident can we be in extant estimates of the quantity of food waste given unsatisfactory definitions and measurement issues? Second, how confident can we be in extant estimates of the value or cost of food waste, given that many such estimates rely on retail prices when food is often wasted well before the retail stage? Third, from a conceptual perspective, what are the points of intervention for policy during the life cycle of a typical food item, and are potential policy outcomes at those intervention points interdependent?

Current estimates of the quantity of food waste in the United States range from 35 million tons (EPA, 2015) to 103 million tons (FAO, 2011). On the technological side, there have been efforts to analyze the content of food waste to estimate whether the food that goes wasted can be repurposed (e.g., Cuellar and Webber, 2010). On the consumer side, efforts are currently underway to understand consumer awareness, attitudes, and behavior (Neff et al., 2015; Qi and Roe, 2016; and Wilson et al., 2017). Finally, combining various calls to reduce food waste in order to address global food insecurity and climate change, the Rockefeller Foundation's ReFED study group suggests an extensive set of solutions to reduce food waste. One important limitation of the limited literature on food waste is that the definitions for food waste used differ substantially, which results in wildly differing estimates and, in the limit, different approaches to the problem of food waste. This paper takes a step back from that literature in order to propose a framework aimed at unifying research efforts on food waste.

Given the importance of sound measurement as the basis of sound policy making, the contribution of this paper is threefold. First, we provide a precise definition of food waste which focuses on food actually wasted rather than on food that is merely removed from the supply chain. Second, we provide a systematic way to think about the cost of food waste which, much like the use of value added in calculating an economy's gross domestic or national product, solves the problem of overvaluation of food wasted due to double counting. Third, we document the various points in the life cycle of a typical food item at which policy makers can intervene, and identify interdependencies between these points of policy intervention.

The remainder of this paper is organized as follows. In section 2, we present a stylized description of the life cycle of a typical food item, from the moment it becomes usable to the moment it is either productively used or wasted. This framework allows identifying those points along the life cycle where food waste can occur, and we use it in section 3 to compare alternative definitions of food waste and propose our own definition, which we believe is more accurate and useful in tackling the problem of food waste. In section 4, we look at the measurement of the cost (or value) of food waste. Section 5 discusses other measurement issues including the measurement of food flow to various phases of food life cycle that have implications for policy. Having discussed policy in section 5, we conclude in section 6 with directions for future research.

The Life Cycle of Food

The life cycle of a typical food item is comprised of phases that occur within its supply chain and phases that occur once food is removed from its supply chain (i.e., phases of food loss).[2] A generic, stylized food supply chain has four distinct stages from upstream to downstream: (i) growers, (ii) processors,[3] (iii) retailers,[4] and (iv) consumers. As food moves down the supply chain, food loss occurs when food is taken out of the supply chain at any stage. Food that is lost either goes to the landfill, is put back into the food supply chain, or goes to nonfood albeit productive uses.

Figure 1 depicts the food flow in a stage i of the food supply chain. For example, suppose that the grower stage (g) represents the upstream sector where food is produced. At this stage, total availability of food (Q_g) either flows to the downstream sectors ($(1-\ell_g)Q_g$) or leaves the food flow at proportion $\ell_g \in [0,1]$. A portion of food that is lost ($d_g \ell_g Q_g$), where $d_g \in [0,1]$, could be diverted back to the supply chain for food use by efforts such as gleaning or creating markets for ugly produce[5]. Another portion of food lost ($r_g \ell_g Q_g$), where $r_g \in [0,1]$, is recovered for nonfood use such animal feed, bio-fuel production, fertilizer, and so on. The remaining portion of food lost $(1-d_g-r_g)\ell_g Q_g$ goes to the landfill. The figure also shows that not all the food loss that is diverted to food use is eventually consumed ($c_g \in [0,1]$). A portion of the diverted food loss goes to the landfill $(1-c_g)d_g \ell_g Q_g$ due to food waste stemming from handling, cooking, and neglect by consumers.

All the parameters of the food flow in Figure 1 appear in the phases of food loss, determining the proportion of food that flows outside of its supply chain. Hence, these parameters represent intervention points, or policy levers. For example, to the extent that $\ell_g > 0$, policies can be directed to reduce the burden of food loss at the grower level. Also, if a type of food flow is not potentially relevant for policy, it is not depicted in Figure 1. For example, a portion of the recovered food for nonfood use may also end up in landfill. Yet, this is not depicted in Figure 1, because we assume the amount of food that goes through such a phase is likely negligible and unlikely to be relevant for policy.

The foregoing mapping of sources of food waste applies to food systems, both in developed as well as developing countries (Hodges et al., 2011).[6] The difference across various types of foods, across industries, and across countries lie in the foregoing parameters at each stage of the supply chain. The loss parameter along the supply chain, for instance, depends largely on infrastructure and technology. Technologically more advanced and efficient food industries in developed countries imply smaller loss parameters at the farm and intermediary levels than nascent value chains in developing countries. In contrast, social norms and individual accountability likely contribute to smaller loss parameters at the household level in developing countries, where food can represent up to 85 percent of the average household's budget (Barrett and Dorosh, 1996) than they do in the United States, where the budget share of food is slightly less than 10 percent (USDA, 2016). Similarly, the range of opportunities to divert lost food to alternative productive uses varies across contexts. In developing countries, where the prevalence of home gardens is high (Hou, 2006), a relatively higher proportion of food might become fertilizer than in developed countries, where home gardens are less common.

Definition and Measurement

The Food and Agriculture Organization (FAO) of the United Nations defines food waste as follows (FAO, 2016):

> Food loss is defined as "the decrease in quantity or quality of food." Food waste is part of food loss and refers to discarding or alternative (nonfood) use of food that is safe and nutritious for human consumption along the entire food supply chain, from primary production to end household consumer level.

Similarly, when discussing food loss versus food waste, Buzby et al. (2011) write, which is adopted in the report by the USDA Economic Research Service (ERS) (Buzby et al. 2014, p. 1):

> Food loss represents the amount of food postharvest, that is available for human consumption but is not consumed for any reason. It includes cooking loss and natural shrinkage (for example, moisture loss); loss from mould, pests, or inadequate climate control; and food waste.

> Food waste is a component of food loss and occurs when an edible item goes unconsumed, as in food discarded by retailers due to color or appearance, and plate waste by consumers.

The European Union's FUSIONS—"a project about working towards a more resource efficient Europe by significantly reducing food waste," which ended in July 2016—defines food waste as follows:

> Food waste is any food, and inedible parts of food, removed from the food supply chain to be recovered or disposed (including composed [sic], crops ploughed in/not harvested, anaerobic digestion, bio-energy production, co-generation, incineration, disposal to sewer, landfill or discarded to sea) (FUSIONS 2016, p. 7).

Finally, the US Environmental Protection Agency's (EPA) food waste estimate is described as follows (EPA, 2016):

> The amount of food going to landfills from residences, commercial establishments (e.g., grocery stores and restaurants), institutional sources (e.g., school cafeterias), and industrial sources (e.g., factory lunchrooms). Pre-consumer food generated during the manufacturing and packaging of food products is not included in EPA's food waste estimates.

These four definitions of food waste are all lacking in some form. Based on Figure 1, according to the definitions of the FAO, ERS, and FUSIONS, food waste is the sum of the "landfill" and the "recovered for nonfood use" parts. Counting food recovered for nonfood use as food waste is an important shortcoming of these definitions for two reasons. First, if recovered food is used as an input, such as animal feed, fertilizer, or biomass, to produce output, then, by definition, it is not wasted. However, there might be economic losses if the cost of recovered food is higher than the average cost of inputs in the alternative, nonfood use. Second, the definition creates practical problems to measure food waste because the measurement requires tracking food loss in every stage of the supply chain and its proportion that flows to nonfood uses.

Unlike the other three food waste measures, the EPA's measurement of food waste does not count food that is recovered for productive nonfood use, as food waste. The EPA's measurement only includes food that ends up in a landfill from the retail and household stages of the food supply chain. That is, any waste resulting in the first two stages of the supply chain, viz. the grower and processor stages, are not counted in the EPA's measure. Considering Figure 1, according to the EPA, food waste is a strict subset of what we define below as food going to the landfill.

Another inconsistency between these definitions is that the FAO and ERS definitions only apply to edible and safe and nutritious food, whereas the definitions of the FUSIONS and the EPA apply to both edible and inedible parts of food. Finally, the ERS and EPA definitions of food waste exclude the food that is not harvested at the farm level.

We propose a definition of food waste which overcomes all the shortcomings of the definitions discussed here. Specifically, our definition leads to an unambiguous way of measuring food waste as well as the costs associated with food waste. Our definition also remains agnostic about what constitutes a productive use of food, whether "productive use" means that food is used for human consumption, as fertilizer, as animal feed, or as fuel. As long as food does not end up in a landfill, it is not wasted. In addition, our definition of food waste includes food that is wasted at all stages of the supply chain. This will ensure that the value of food waste takes into account the stage at which food is wasted, instead of measuring the cost of all food waste at the retail price.

Given the foregoing, we provide the following definition of food waste:

Definition 1 *Let $\bar{y}$ denote the quantity of food produced. Let $k \in \{1, ..., N\}$ denote the N potential productive uses for food. For each productive use, a certain amount of food $y_k < \bar{y}$ is employed. Food waste is any quantity $w > 0$ such that $w = \bar{y} - \sum_{k=1}^{N} y_k$.*

The definition simply states that "food waste" is the difference between the amount of food produced (i.e., $\bar{y}$) and the sum of all food employed in any kind of productive use, whether food or nonfood (i.e., $\sum_{k=1}^{N} y_k$). It should thus be apparent from our definition that the other definitions presented above—that is, the FAO's, the ERS's, and the EU's FUSIONS' definitions—overstate the quantity of food waste.[7]

In order to highlight the differences between our definition of food waste and existing definitions, we generate a numerical example of our definition of food waste and show how it differs from the four other definitions. For the purpose of the numerical example we make simplifying assumptions that the parameters of our model are equal in each stage of the supply chain, such that $\ell_g = \ell_p = \ell_r = \ell_c$, $d_g = d_p = d_r = d_c$, etc., where g refers to growers, p refers to processors, r refers to retailers, and c refers to consumers. Assume that the total quantity of edible food produced, $Q_g = 100$, and let the loss parameters $\ell_g = \ell_p = \ell_r = \ell_c = 0.2$, lost food diverted for food use $d_g = d_p = d_r = d_c = 0.25$, the proportion of diverted food that is eventually eaten $c_g = c_p = c_r = c_c = 0.1$, and the proportion of food loss that is recovered for nonfood use $r_g = r_p = r_r = r_c = 0.25$. The definitions of FUSIONS and EPA apply to all food, edible and inedible. Therefore, in order to estimate food waste according to the FUSION and EPA definitions, we make an assumption about the proportion of food stuff that is inedible. We assume that all food is 120% of all edible food production.

The first column in Table 1 reports the quantity estimates of food waste from the numerical example showing our estimate is smaller than those based on the definitions of the FAO, ERS, and FUSIONS, and greater than the EPA's. Our definition accounts for food that goes to the landfill, which is directly measurable, from all stages of the supply chain. Nonetheless, our proposed framework is useful even when one does not agree with the definition of waste. The framework developed in section 2 and explored further in the remainder of this paper can also be adapted to different definitions of food waste, and thus be used in creating guidelines for policy intervention.

The Value of Food Waste

The previous section shows that widely used definitions of food waste do not provide a coherent measure of food waste and that the quantity of food waste is overestimated unless its measurement explicitly accounts for the potential recovery of food after food is removed from the supply chain. As a result, extant estimates of the value of food waste—its price or cost per unit (e.g., pounds or kilograms) times its (overstated) quantity—are also problematic. In this section, we explain that extant estimates of the value of food waste are doubly problematic, because the measurement of the value of food waste involves an additional complexity regarding the per unit value of food waste. In particular, we show that the extant measures of the value of food waste that rely on transaction prices of food—the price at which food flows from an upstream stage to the downstream—overestimate the value of food waste.

Our definition of food waste implies that the cost of food waste is equal to total value of the food that goes to the landfill at each stage of the supply chain. Recall that we have assumed four distinct stages in the food value chain: (i) grower, (ii) processor, (iii) retailer, and (iv) consumer. At each stage, the price of food waste is equal to its average cost; for example, the price of food waste at the grower level, p_g, is equal to the grower's average cost of production. Transactions take place between consecutive stages of the food supply chain—that is, between the grower and the processor, between the processor and the retailer, and between the retailer and the consumer, and for each of those transactions, downstream agents incur additional costs. The price of food waste at the processing (p_p), retail (p_r), or consumer (p_c) levels may include additional transactions costs (e.g., the costs of transportation, processing, marketing, shopping, and so on). Because each stage of the supply chain adds to the cost of food, it follows that $p_c > p_r > p_p > p_g$.

Estimates of the cost of food waste are almost surely overestimated due to two important problems regarding the valuation of food waste. The first problem—which applies to all extant estimates of the cost of food waste, is that these estimates value food waste at the transaction price of food $\mathscr{P}_i$ $i \in \{g, p, r\}$, which is equal to the average cost of food (or price of food waste), p_i, and per unit markup that the seller may charge, μ_i, (i.e., $\mathscr{P}_i = p_i + \mu_i$). Hence, for example, evaluating food that is wasted at the retailer stage at $\mathscr{P}_r$ would overestimate the cost of food waste by μ_r.

The second problem, which is less common but much more severe, is that some of the estimates of the cost of food waste value all food waste, regardless of where it occurred in the supply chain, simply at the retail transaction price $\mathscr{P}_r$ (e.g., the ERS estimate of the cost of food waste). This procedure may closely approximate the value of food that is wasted at the retailer and consumer stages w_r and w_c provided that retailer markups and consumer shopping costs are negligible. But using $\mathscr{P}_r$ to value the food that is wasted at the grower and processor stages w_g and w_p could severely overstate the value of upstream food waste, simply because $\mathscr{P}_r w_g > p_g w_g$ and $\mathscr{P}_r w_p > p_p w_p$.

Formally, the total value of food waste is overestimated because extant estimates $\tilde{V}_j$, $j =$ 1, 2, compute it such that

$$(1) \quad \tilde{V}_1 = \mathscr{P}_g w_g + \mathscr{P}_p w_p + \mathscr{P}_r (w_r + w_c),$$

or

$$(2) \quad \tilde{V}_2 = \mathscr{P}_r (w_g + w_p + w_r + w_h),$$

when in fact the true value of food waste $\hat{V}$ is such that

$$(3) \quad \hat{V} = p_g w_g + p_p w_p + p_r w_r + p_c w_c,$$

and so $\hat{V} < \tilde{V}_1 < \tilde{V}_2$.[8]

The foregoing discussion is limited to the monetary value of waste, which one can think of as accounting costs in the theory of the firm. But the total cost of food waste also includes the costs—monetary or otherwise—associated with the social and environmental costs of food waste, which one can think of as economic costs. And as in the theory of the firm, the economic costs are larger than the accounting costs.

Thus, one shortcoming of $\hat{V}$ is that it ignores externalities. Food waste has both social and environmental costs. In the former case, the wasting of food is associated with internal and external norms of conduct which might impose social (in the form of social sanctions) or hedonic (in the form of feelings of guilt) costs on those who waste food (Evans et al., 2012). In the latter case, the food that goes to landfills emits methane and CO_2 as it decomposes (Hall et al., 2009), both of which contribute to climate change. Additionally, the environmental costs of food waste include the environmental impacts of depleting resources (e.g., water and land) in order to produce food that is eventually wasted.

Another shortcoming of $\hat{V}$ is that it ignores the landfill-related costs of food waste. That is, the opportunity cost of using the landfill space devoted to food waste, the cost of transporting food waste to the landfill, the nonmarket value of lost ecosystems, and so on (FAO, 2011).

That being said, our measure $\hat{V}$ of the value of food waste does no worse than either $\tilde{V}_1$ or $\tilde{V}_2$ when it comes to omitting the value of those externality and landfill-related costs, since both $\tilde{V}_1$ or $\tilde{V}_2$ also ignore those costs. We know of no credible estimate of the sum of those external costs.[9]

In order to highlight the difference between our method and the existing methods of estimating the costs of food waste, we generate from Table 1 an estimate of the cost of food waste using the numerical example introduced in the previous section, making simplifying assumptions on the cost at each stage of the supply chain. We assume that the average costs of production at the grower, processor, retailer and consumer levels are $p_g = 0.4$, $p_p = 0.6$, $p_r = 0.8$, and $p_c = 1$, respectively. These costs are applied to all food lost at their corresponding stage that eventually ends up in landfill. In addition, where applicable, we assume that sellers charge a markup value of 10% of the costs.

The second column of Table 1 shows the results of the cost of food waste according to each definition's quantity of food waste estimate and the way in which they apply costs. For our estimate of the cost of food waste, we apply the cost assigned to each stage to the quantity wasted at each stage. The EPA does not discuss how to estimate the costs of food waste, therefore we do not include an estimate for the EPA in our table.

The publications of FAO, ERS, and FUSIONS do not provide a formal description of their cost measures. However, to be able to make a simple comparison using the numerical example we formalize their measures based on their verbal descriptions. Consequently, for the FAO's measure we assign p_g to the food wasted at the farm level, p_p to the food wasted at the processor level, and the transaction retail price $\mathscr{P}_r$ to the food wasted at the retailer and consumer levels. For the ERS estimate, we infer that they use the retail price $\mathscr{P}_r$ for all items that they consider food waste from all stages of the supply chain. Finally, FUSIONS' method uses transaction prices charged at each stage of the supply chain.[10]

The ranking of the estimates show that all those measures overestimate the cost of food waste, with the ERS estimate being the highest. Values are overestimated due to both overestimation of the quantity and price of food waste. For comparison, the third column of Table 1 provides numerical results when all quantity estimates are evaluated at the same price p_i. These results together with the results in column 2 illustrate the overestimation following the use of other procedures relative to our proposal.

Other Measurement Issues and Policy Implications

The previous sections addressed the importance of measuring the quantity and value of food waste accurately. We now turn our attention to the parameters that link various Q variables in the stylized food system laid out in section 2. As we mentioned earlier, those parameters are points of policy intervention. Accordingly, various policies can be implemented to reduce loss (in the form of prevention) or to promote the diversion of food for both food and nonfood uses. While we can freely propose various solutions, we can only monitor the effectiveness of the policies through changes in those parameters, which are important to estimate and subsequently track over time.

As the framework in section 2 shows, the amount diverted for food and nonfood uses depends not only on the rate of diversion but also on the loss rate. Hence, policy interventions are not independent, and a lack of explicit accounting of confounding effects can lead to a misallocation of food waste reduction efforts.

Specifically, at each stage, the quantity of food waste w_i, where $i \in \{g, p, r, c\}$ is such that

$$w_i = (1 - d_i - r_i)\ell_i Q_i + (1 - c_i) d_i \ell_i Q_i, \tag{4}$$

or

$$w_i = (1 - c_i d_i - r_i)\ell_i Q_i, \tag{5}$$

which means that the total quantity $\mathscr{W}$ of food waste is such that

$$\mathscr{W} = \sum_{i \in \{g,p,r,c\}} w_i. \tag{6}$$

From the last two equations, it is obvious that the total quantity of food waste is decreasing in the proportion of food diverted d_i, the proportion of food recovered r_i, and the proportion of diverted food that is eventually consumed c_i at every stage. Similarly, the total quantity of food waste is increasing in the proportion of food lost ℓ_i and in the quantity of food Q_i at each stage. Formally, this leads to the following proposition.

Proposition 2 *For each stage $i \in \{g, p, r, c\}$ of the life cycle of food,*

1. $\frac{\partial \mathscr{W}}{\partial \ell_i} = (1 - c_i d_i - r_i) Q_i$,
2. $\frac{\partial \mathscr{W}}{\partial Q_i} = (1 - c_i d_i - r_i) \ell_i$,
3. $\frac{\partial \mathscr{W}}{\partial r_i} = -\ell_i Q_i$,
4. $\frac{\partial \mathscr{W}}{\partial c_i} = -d_i \ell_i Q_i$, *and*

5. $\frac{\partial \mathscr{W}}{\partial d_i} = -c_i \ell_i Q_i$.

It would be impractical to suggest that policy makers intervene to reduce the quantity of foodstuff Q_i, as this would reduce the food supply, raise food prices, and thus it would likely worsen food insecurity. But the other parameters—that is, d_i, r_i, and ℓ_i[11]—are all actionable at every stage of the food supply chain. In developing countries, where food waste contributes to food insecurity, food waste largely occurs at the production, processing, and distribution stages, before food is purchased by consumers. This suggests specific policy interventions, almost all of which remain to be tested. In contrast, in developed countries, the bulk of food waste occurs after food is distributed to food businesses and retailers and is sold to consumers, which calls for very different yet equally untested policy recommendations.

In addition, policy priorities are defined by the estimated costs attached to the food waste generated at various stages of the food supply chain as well as to their sources. We use cost to define priorities because costs reflect the scarcity of the resources used to produce the product. Because the price of food increases as food makes its way down the food chain, reductions in food waste downstream will reduce the value of food waste more than reductions in food waste upstream, *ceteris paribus*. The EPA's hierarchy of how food loss should be allocated is consistent with our framework. The indirect cost of food diverted is zero if reverted for food use but additional costs would be associated with the quantity diverted for nonfood use.

It is important to note that the interdependence between policy levers and all other food waste reduction efforts requires cooperation and coordination of all stakeholders in the food system. Otherwise, severe misallocation of resources might occur. For example, investments in technology to promote diversion of food loss to nonfood use might be moot if policy makers could reduce food loss very well. In this sense, our framework helps illustrate strategic policy complementarities when it comes to dealing with food waste. In the simple theoretical framework laid out above, those strategic complementarities emerge when looking at the matrix of second derivatives for $\mathscr{W}$.[12]

For example, the third sub-proposition of Proposition 2 says that food waste is decreasing in the proportion of food r_i recovered in stage i, i.e., $\frac{\partial \mathscr{W}}{\partial r_i} = -\ell_i Q_i$. From that sub-proposition, it is easy to show that $\frac{\partial^2 \mathscr{W}}{\partial r_i^2} = 0$, $\frac{\partial^2 \mathscr{W}}{\partial r_i \partial Q_i} = -\ell_i$, $\frac{\partial^2 \mathscr{W}}{\partial r_i \partial \ell_i} = -Q_i$, and $\frac{\partial^2 \mathscr{W}}{\partial r_i \partial d_i} = 0$. In other words, there are strategic complementarities between recovery in stage i on the one hand and the amount of food produced and the amount of food lost in stage i, but no such complementarities between recovery in stage i and diversion of food back into the food system at that stage d_i. Similar derivations can be done for the other three sub-propositions of Proposition 2.

Another important measurement issue relates to the edible food distinction. Recall that the FAO and ERS definitions only apply to edible and safe and nutritious food. These definitions, however, do not specify what "edible" (or "inedible") and "safe and nutritious" mean, nor do they acknowledge the fact that they are not universally understood in the same way. Indeed, whether something is edible or not is highly context-dependent, and there is no universal agreement as to what foods (or parts thereof) are edible. For instance, though it is uncommon in the United States to consume the skin of kiwifruits, the whole fruit—including the skin—is typically consumed in New Zealand. Similarly, the Chinese consume chicken feet, a part of the animal which most Americans would not consider edible.

In our numerical example, we made a convenient assumption that total food in our definition is largely edible to make our measurements comparable to the major extant ones. Yet, operationalizing the edibility or usability of food stuff in measuring food waste poses a major challenge. The distinction becomes even more challenging to define the further upstream we go on the food supply chain. Indeed, the edibility distinction is implied in the existing definitions of food waste focusing on downstream stages of the food supply chain, where food stuff has been transformed sufficiently into mostly edible parts, ignoring the largest portions of plants and animals produced for food that are discarded out from the food supply chain.

Thus, we argue that the most robust and coherent treatment of food in defining food waste is to ignore edibility and account for whole plants and animals produced for food. Thus, stalks and leaves and hide and bones should be fully accounted for in our calculation, noting the stages where they are discarded from the food supply chain, potentially redirected for food use or non-food use, or added to the landfill. This is consistent with accounting for the cost of inputs used to produce these food stuff and the disposal of all organic matter generated through food production. This is the only way we should be reporting what proportions of total food waste occur at various stages of the supply chain. This treatment would likely result in a larger estimate of the volume of food-related organic waste, but it would also be the most operational if used in conjunction with policy goals set using the same measurement or definition.

Summary and Concluding Remarks

This paper has discussed the measurement of the quantity and value of food waste. Specifically, after presenting the life cycle of a stylized food item—during which that food item goes from the grower to the processor, from the processor to the retailer, and from the retailer to the consumer—we have contrasted prominent definitions of food waste and, finding all of them lacking in some way, provided our own definition. Our definition of food waste essentially boils down to whatever is produced in the food system which ends up at the landfill. As it turns out, our definition illustrates how the quantity of food waste is overstated by most definitions.

We then took a look at the value of food waste, finding that it too is overstated by most extant estimates given that many of those estimates value wasted food at its retail price rather than at other prices found upstream in the food supply chain when applicable. Lastly, we identified the various points along the food supply chain where policy makers can intervene in an effort to reduce the extent of food waste.

Our approach suffers from obvious limitations. Namely, our general and stylized approach does not allow making specific recommendations for policy or research, beyond (re)defining food waste and providing a more accurate way of valuing food waste to point out the various places along the food chain where food gets wasted. Still, the framework and the various parameters we discuss as policy levers should all be the subject of rigorous empirical investigation—that is, of studies that have either internal validity, external validity, or both—so as to inform policy in an effort to reduce the amount of food that goes to the landfill.

Notes

[1]Merriam-Webster defines “hot-button” as “an issue that causes people to feel strong emotions (such as anger) and to argue with each other.”

[2]The FAO (2016) defines food loss as any “decrease in [the] quantity or quality of food.” We return to this definition and to the difference between food loss and food waste in the next section.

[3]In the interest of keeping our framework as simple as possible, we conflate wholesalers and processors in one category, which we denote by the generic name of “processors.”

[4]For our purposes, retailers include all businesses and institutions that sell or serve food, such as grocery stores, food markets, restaurants, cafeterias, and so on.

[5]So-called ugly produce consists of fruits and vegetables that are deemed imperfect by the average consumer (Royte, 2016).

[6]Minten et al. (2016) show using a case study of the potato sector in Asia that the extent of food waste in developing countries is considerably less than what commonly cited estimates report.

[7]A recent IFPRI report recognizes the need for a standard definition of food waste—one that adopts a value-chain approach that explicitly addresses food waste at various stages of the value chain and includes pre-harvest losses (IFPRI, 2016). Our definition is broadly consistent with that perspective, with the difference that we do not address food waste due to quality losses, as the IFPRI report encourages analysts to do.

[8]Assuming that consumers’ per unit shopping costs, s_c, are not too large such that $s_c w_c < \mu_g w_g + \mu_p w_p + \mu_r w_r$

[9]Though Hall et al. (2009) try to ascertain the environmental impacts of food waste in the US, their definition of food waste suffers from serious upward bias given that they consider food waste to be equal to the difference between the food supply and the food consumed by the population.

[10]Formally: $\tilde{V}_{FAO} = p_g w_g + p_p w_p + \mathscr{P}_r(w_r + w_c)$, $\tilde{V}_{ERS} = \mathscr{P}_r(w_g + w_p + w_r + w_h)$, and $\tilde{V}_{FUSIONS} = \mathscr{P}_g w_g + \mathscr{P}_p w_p + \mathscr{P}_r(w_r + w_c)$.

[11]Because the parameter c_i represents the proportion of diverted food that is eventually consumed, it is determined by a combination of parameters d, r, and ℓ of the downstream stages.

[12]By "strategic complementarities," we refer in a slight abuse of language to both strategic complementarities as well as substitutabilities.

References

Barrett, C.B., and P.A. Dorosh (1996), "Farmers' Welfare and Changing Food Prices: Nonparametric Evidence from Rice in Madagascar," *American Journal of Agricultural Economics* 78(3): 656-669.

Buzby, J.C., H. Farah-Wells, and J. Hyman (2014), "The Estimated Amount, Value, and Calories of Postharvest Food Losses at the Retail and Consumer Levels in the United States," U.S. Department of Agriculture, Economic Research Service, Economic Information Bulletin 121.

Buzby, J.C., J. Hyman, H. Stewart, and H.F. Wells (2011), "The Value of Retail- and Consumer-Level Fruit and Vegetable Losses in the United States," *Journal of Consumer Affairs* 45(3): 492-515.

EPA (2016), "United States 2030 Food Loss and Waste Reduction Goal," https://www.epa.gov/sustainable-management-food/united-states-2030-food-loss-and-waste-reduction-goal last accessed November 13, 2016

Evans, D., H. Campbell, and A. Murcott (2012), "A Brief Pre-History of Food Waste and the Social Sciences," *Sociological Review* 60: 5-26.

Cuellar, A.D., and M.E. Webber (2010), "Wasted Food, Wasted Energy: the Embedded Energy in Food Waste in the United States," Environmental Science & Technology 44(16): 6464-6469.

FAO (2014), *Food Wastage Footprint Full-Cost Accounting: Final Report*, Rome: FAO.

FAO (2016), "Food Loss and Food Waste," http://www.fao.org/platform-food-loss-waste/food-waste/definition/en/ last accessed November 13, 2016.

FUSIONS (2016), *Estimates of European Food Waste Levels*, Brussels: European Union.

Hall, K., J. Guo, M. Dore, and C.C. Chow (2009), "The Progressive Increase of Food Waste in America and Its Environmental Impact," *PLoS One* 4(11): e7940.

Hodges, R.J., J.C. Buzby, and B. Bennett (2011), "Postharvest Losses and Waste in Developed and Less Developed Countries: Opportunities to Improve Resource Use," *Journal of Agricultural Science* 149(S1): 37-45.

Hou, J.Y. (2006), *Unlocking the Mystery of Homegardens: An Integrative Perspective*, MPS Thesis, Cornell University.

IFPRI (2016), *Global Food Policy Report 2016*, Washington, DC: IFPRI.

Minten, B., T. Reardon, S. Das Gupta, D. Hu, K.A.S. Murshid, "Wastage in Food Value Chains in Developing Countries: Evidence from the Potato Sector in Asia," in *Food Security in a Food Abundant World*, 225-238.

Neff, R.A., M.L. Spiker, and P.L. Truant (2015), "Wasted Food: US Consumers' Reported Awareness, Attitudes, and Behaviors." *PLoS ONE* 10(6): e0127881.

ReFED (2016), *A Roadmap to Reduce U.S. Food Waste by 20 Percent*, New York: Rockefeller Foundation.

Qi, D., and B.E. Roe (2016), "Household Food Waste: Multivariate Regression and Principal Components Analyses of Awareness and Attitudes among U.S. Consumers," *PLoS ONE* 11(7): e0159250.

Royte, E. (2016), "How 'Ugly' Fruits and Vegetables Can Help Solve World Hunger," *National Geographic* March.

USDA (2016), "Americans' Budget Shares Devoted to Food Have Flattened in Recent Years," http://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=76967 last accessed November 10, 2016.

Wilson, N.L.W., B. Rickard, R. Saputo, and S.-T. Ho (2017), "Food Waste: The Role of Date Labels, Package Size, and Product Category," *Food Quality and Preference* 55: 35-44.

Figures

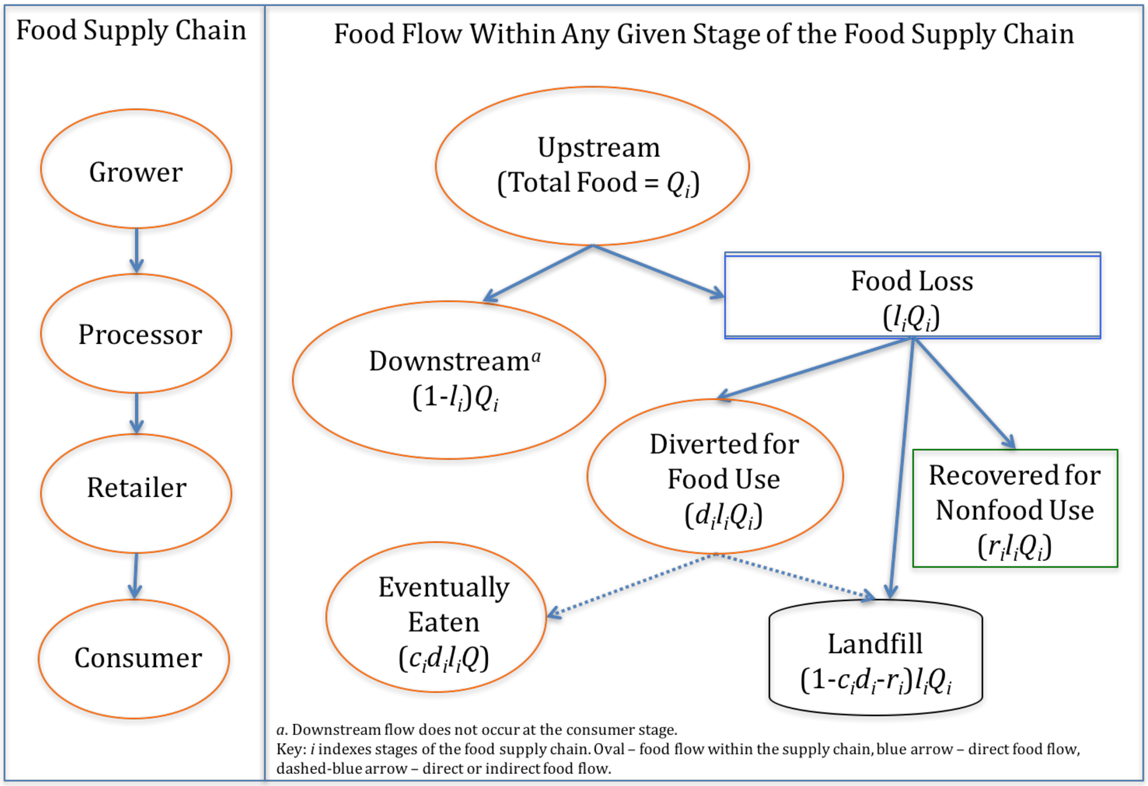

Figure 1. The Life Cycle of a Typical Food Item

Tables

Table 1. A comparison of quantity and cost estimates of food waste across definitions

Food Waste Definition	Quantity Estimate	Cost Estimate	Cost Estimate Using Our Cost Proposal
Our Definition	42.8	27.6	—
EPA	20.0	—	17.8
FAO	57.6	39.6	37.1
ERS	57.6	57.6	37.1
FUSIONS	69.1	47.8	44.6

Note: $Q_g = 100$, $\ell_g = \ell_p = \ell_r = \ell_c = 0.2$, $d_g = d_p = d_r = d_c = 0.25$, $c_g = c_p = c_r = c_c = 0.1$, $r_g = r_p = r_r = r_c = 0.25$, food stuff as a proportion of edible food=1.2
Costs: $p_g = 0.4$, $p_p = 0.6$, $p_r = 0.8$, $p_c = 1$, markup at each stage of the supply chain=10%