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Review

A systems approach to assessing environmental and economic effects of food loss and waste interventions in the United States☆

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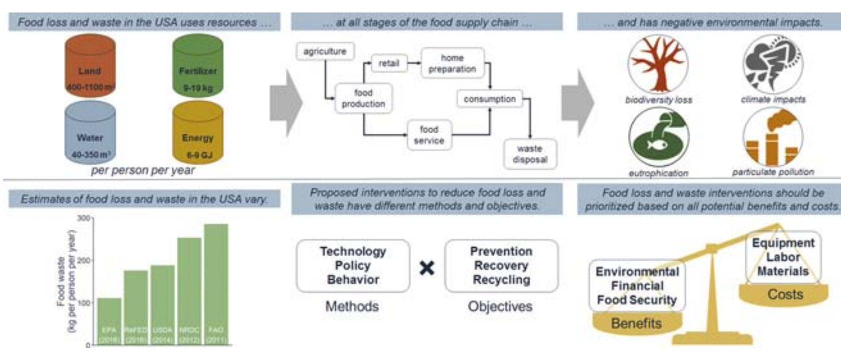
HIGHLIGHTS

- An estimated 30% to 50% of food is lost or wasted in the United States.
- FLW has multidimensional upstream and downstream environmental impacts.
- FLW prevention efforts may have greater environmental benefits than recovery.
- Better measures of environmental impacts associated with interventions are needed.
- FLW interventions should be evaluated within an economic analysis framework.

GRAPHICAL ABSTRACT



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ABSTRACT

Reducing food loss and waste (FLW) is critical for achieving healthy diets from sustainable food systems. Within the United States, 30% to 50% of food produced is lost or wasted. These losses occur throughout multiple stages of

Abbreviations: BTU, British thermal unit; CDC, Centers for Disease Control and Prevention; CEC, Commission for Environmental Cooperation; CH_4, methane; CO_2, carbon dioxide; EEIO, environmentally extended input-output; EPA, U.S. Environmental Protection Agency; ERS, Economic Research Service; FAO, Food and Agriculture Organization; FDA, U.S. Food and Drug Administration; FLW, food loss and waste; FWRA, Food Waste Reduction Alliance; GHG, greenhouse gas; IPCC, Intergovernmental Panel on Climate Change; K_2O, potash; LAFA, Loss-Adjusted Food Availability; LCA, life-cycle assessment; MMT, million metric tons; MSW, municipal solid waste; N_2O, nitrous oxide; NGO, nongovernmental organization; NH_3, ammonia; NH_4, ammonium; NHANES, National Health and Nutrition Examination Survey; NO_3, nitrate; NRDC, Natural Resources Defense Council; P_2O_5, phosphorus; PO_4, phosphate; ReFED, Rethink Food Waste Through Economics and Data; USDA, U.S. Department of Agriculture; VNF, virtual N factor; WARM, Waste Reduction Model; WRI, World Resources Institute; WWF, World Wildlife Fund.

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the food supply chain from production to consumption. Reducing FLW prevents the waste of land, water, energy, and other resources embedded in food and is therefore essential to improving the sustainability of food systems. Despite the increasing number of studies identifying FLW reduction as a societal imperative, we lack the information needed to assess fully the effectiveness of interventions along the supply chain. In this paper, we synthesize the available literature, data, and methods for estimating the volume of FLW and assessing the full environmental and economic effects of interventions to prevent or reduce FLW in the United States. We describe potential FLW interventions in detail, including policy changes, technological solutions, and changes in practices and behaviors at all stages of the food system from farms to consumers and approaches to conducting economic analyses of the effects of interventions. In summary, this paper comprehensively reviews available information on the causes and consequences of FLW in the United States and lays the groundwork for prioritizing FLW interventions to benefit the environment and stakeholders in the food system.

Contents

1. Introduction

Along with shifting dietary patterns and improving food production practices, reducing food loss and waste (FLW) is necessary for achieving healthy diets from sustainable food systems (Springmann et al., 2018; Willett et al., 2019). Within the United States, available estimates indicate that 30% to 50% of food produced is lost or wasted, depending on how FLW is defined (Cuéllar and Webber, 2010; Hall et al., 2009; Venkat, 2011; Rethink Food Waste Through Economics and Data [ReFED], 2016; Gunders, 2012; Buzby et al., 2014; Lipinski et al., 2013). These losses occur throughout the food supply chain from the production stage to the intermediate stages of storage, processing, distribution, retail, and preparation activities, ending with consumers who decide what food to buy, eat, and discard. FLW reduction is especially relevant to improving the sustainability of food systems by preventing the loss of the embedded land, water, energy, and other resources used in food production. Despite the increasing number of studies identifying FLW reduction as a way to increase the sustainability of the food system, we lack the information needed to assess fully the effectiveness of interventions along the supply chain. A broader systems approach to evaluating interventions that accounts for the trade-offs in environmental improvements relative to interventions costs would provide better information for decision-making.

For the purposes of this paper, we use the term “FLW” to describe food (including inedible parts) that was lost at any point in the food supply chain from production to consumption including edible yet unharvested food; food damaged by mold, pests, or inadequate climate control during transport; and food not used or consumed due to spoilage, excess preparation, or preferences and therefore discarded.[1] We use the term “excess food” (including inedible parts) to refer to food not used for its intended purpose but instead sent to secondary sectors to ultimately be consumed by humans or animals as a strategy to prevent FLW. In this paper, we focus on FLW within the U.S. food supply chain from the domestic production and import stages through the domestic consumption or export stages. We consider both primary sectors comprising businesses involved in the direct production and use of food for human consumption and secondary sectors comprising businesses and organizations that handle food that was not used or consumed by the primary sectors but can still be used for human or animal consumption.

Stakeholders in the food system need information on which to base their decisions regarding FLW, such as a better understanding of the quantity of edible FLW generated across types of foods and stages of production, options for preventing or mitigating FLW, incentives and barriers for FLW reduction, and the effectiveness of interventions from an environmental and economic perspective. Relevant stakeholders include local and national governments that can implement initiatives to reduce FLW through regulation or informational campaigns; private businesses that can change their operations and use new technologies to reduce FLW; consumers who can change their food purchasing, preparation, and consumption behaviors to reduce FLW; and nongovernmental organizations (NGOs) that conduct research, advocate for policies, or implement FLW interventions in communities. Among the NGOs that promote FLW reduction efforts are the Food Marketing Institute (FMI), Grocery Manufacturers Association (GMA), Natural Resources Defense Council (NRDC), ReFED, Rockefeller Foundation, Waste & Resources Action Programme, World Resources Institute (WRI), and World Wildlife Fund (WWF). With the increasing emphasis on FLW reduction across stakeholders with different perspectives, it is critical to develop analyses to prioritize reduction efforts from a cost-benefit perspective.

[1] Throughout this paper, we combine food loss and food waste because multiple, differing definitions are used in practice, but the definitional differences do not affect our focus on assessing interventions to reduce one or the other or both.

The purpose of this paper is to synthesize the available literature, data, and methods to provide a framework and conceptualization for assessing the full environmental and economic effects of interventions to prevent or reduce FLW in the United States. Although our approach and recommendations may apply in multiple countries, we focus on the United States in this manuscript. Relevant data and models are readily available for the United States, and the interventions we are considering are most appropriate to address the drivers and consequences of FLW in high-income countries such as the United States. We reviewed and assessed existing methods and data used as the basis for evaluating FLW interventions in terms of environmental benefits and cost-effectiveness. We considered FLW management at all stages of the food system from farms to consumers when assessing the cost-effectiveness of interventions.

This paper is organized as follows. We first describe the context regarding growing concerns about FLW; the causes and magnitudes of FLW along the supply chain; data and methods used to estimate FLW and its environmental impacts; the range of environmental impacts associated with FLW; types of interventions to reduce FLW; and, finally, approaches to analyzing the economic impacts of FLW interventions. We conclude by recommending a way forward for modeling the environmental improvements associated with selected FLW interventions and for prioritizing investments in interventions.

2. Growing concerns about FLW

The emphasis on reducing FLW has resulted in numerous campaigns to increase awareness and change behavior on both the supply and demand sides of the food system. In addition to demand-side FLW reduction efforts, the United States and other developed countries have focused on actors in the middle of the food supply chain—processors, transporters, manufacturers, retailers, and the foodservice industry. In 2016, the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Agriculture (USDA) launched the US Food Loss and Waste 2030 Champions, a program to incentivize and recognize the efforts of organizations toward reducing FLW by 50% by the year 2030 (EPA, 2018b; USDA, 2018b). In October 2018, USDA, EPA, and the U.S. Food and Drug Administration (FDA) signed a formal agreement to affirm the agencies' shared commitment to reducing FLW under the Winning on Reducing Food Waste initiative. Private-sector actors in the United States have also pursued FLW initiatives, the most notable of which is the Food Waste Reduction Alliance (FWRA), a joint effort between GMA, FMI, and the National Restaurant Association (FWRA, 2013) that aligns with Target 12.3 of the United Nations Sustainable Development Goals. These and many related efforts focus on providing guidelines, resources, and incentives to actors on the supply side to reduce, redirect, and dispose of FLW sustainably and efficiently (see also Rockefeller, 2018). In developed countries, the production (farm) level is often not a major focus of FLW reduction efforts, but North American estimates suggest that as much as 20% (Lipinski, 2016) to 42% (Johnson et al., 2018) of production is lost at the farm level. In the United States, efforts to reduce FLW at the production phase of the food supply chain often focus on creating new market opportunities and linkages for otherwise unused products (Food and Agriculture Organization [FAO], 2011; Lipinski, 2016) and on technological solutions to reduce unwanted spoilage by improving packaging and transportation (ReFED, 2016).

In developed countries such as the United States, a substantial portion of FLW occurs at the final nodes of the food system with the consumer both at home and in foodservice settings, such as restaurants and institutional or corporate kitchens (Lipinski, 2016; FAO, 2011). In the United States, public agencies like USDA and FDA offer extensive resources to help consumers improve their food storage and preservation skills to reduce unintentional spoilage (USDA, 2018a; FDA, 2017). Public awareness campaigns have focused on both the environmental and economic benefits of reducing food waste (NRDC, 2016; ReFED, 2018). However, the diffuse nature of food systems within the final nodes of the supply chain and the difficulty of directly mandating or even incentivizing behavioral changes among consumers make intervening at the consumer level challenging.

Despite these difficulties, there are increasing efforts to engage consumers through upstream efforts to reduce FLW. Two recent examples include creating new markets for fresh produce and other foods that would be refused in traditional marketplaces for aesthetic reasons and simplifying expiration date labels on food products (Calvo-Porral et al., 2017). For example, "ugly produce" campaigns, which encourage the consumption of imperfect produce, began in Europe and have spread to many countries (Benson et al., 2017; Moore, 2017). In the United States, an industry is emerging to recover and resell imperfect fruits and vegetables, including companies such as Imperfect Produce, Hungry Harvest, and Ungraded Produce, although recently some retailers have dropped imperfect product because of low sales (Choi and McFetridge, 2019). Likewise, several nongovernmental organizations are leading efforts to create policies that standardize expiration date labels (Broad Leib et al., 2016), to provide healthy and safe food to low-income consumers that has adequate remaining shelf life but is no longer accepted by retailers (Daily Table[2]), and to educate the public about how to make safe decisions using these labels to minimize the unintentional discarding of still-edible food (NRDC, 2013).

Advocates for reducing FLW cite potential improvements in the sustainability and efficiency of the food system. Sustainability concerns associated with FLW include the environmental, economic, and social impacts of FLW (Papargyropoulou et al., 2014), and efficiency concerns relate to the resources used in food production (Garrone et al., 2014; Kummu et al., 2012; Porter and Reay, 2016). Recent influential reports have specifically cited reducing FLW as a key component for increasing the environmental sustainability and efficiency of the food system, including the recent Lancet EAT report (Willett et al., 2019) and the Intergovernmental Panel on Climate Change's (IPCC's) most recent report (IPCC, 2018). The types of impacts of FLW noted as affecting environmental sustainability include the effects on climate, land use, water quality, water use, fertilizer use, pesticide use, and emissions (Conrad et al., 2018; Kummu et al., 2012; West et al., 2014; Willett et al., 2019). Other studies cite reducing FLW as a driver for increasing environmental sustainability of the food supply system without citing specific types of impacts (Aschemann-Witzel et al., 2017; Mourad, 2016; Shafiee-Jood and Cai, 2016). In contrast, improving the sustainability and efficiency of the food system is not specifically mentioned as a driver in U.S. federal government initiatives to reduce FLW, although general concerns about food security and the environment are noted (USDA, 2019).

As calls to action gain momentum, the question remains: how should stakeholders prioritize FLW reduction efforts? We can consider prioritization in the context of cost-benefit analyses where we compare the benefits of reducing FLW to the costs of those initiatives. The benefits of reducing FLW arise from improvements in the environment and food security, in addition to direct financial benefits to companies and consumers if reduction efforts increase efficiencies (Ellison et al., 2019). However, increased efficiencies come at a cost: for example, although more frequent grocery shopping may reduce FLW within households, the additional costs of such trips must be accounted for (Landry and Smith, 2019). In addition, if households need to purchase less food, then retailers and manufacturers will experience a reduction in sales revenue. Environmental benefits, which result from reductions in the use of resources to produce uneaten food and emissions from FLW collection, transport, and treatment or disposal, are likely easier to quantify than benefits from reduced food insecurity. Reducing FLW can help ensure that sufficient land, water, and other resources are available to produce food for a growing population and thus contribute to food security (Kummu et al., 2017; Ellison et al., 2019) while limiting

[2] See https://dailytable.org.

pressure on natural resources. In fact, prevention of FLW ranks among the most significant actions that global society can take to reduce the environmental impacts of the food system and to reduce humanity's pressure on the planet (Willett et al., 2019). Technological improvements to the food system and a global transition to more sustainable eating habits must be combined with substantial FLW reductions to bring the overall impact of the food system below planetary boundaries for greenhouse gas (GHG) emissions, cropland use, blue water use, and fertilizer use (Springmann et al., 2018), while sustainably feeding nearly 10 billion humans by 2050. In most developed countries, the available food supply vastly exceeds the caloric requirements of the population. In the United States, an average of 4000 cal per capita are available for consumption (USDA, ERS, 2015), but men and women consume an estimated 2400 and 1800 cal, respectively, per day on average based on What We Eat in America (U.S. Department of Agriculture, Agriculture Research Service, 2018). Yet, approximately 12% of the U.S. population is considered food insecure (USDA, ERS, 2017); thus, FLW interventions that focus on redistributing excess food can also benefit the population, although costs of redistribution must be considered.

The externalities associated with FLW in the United States make a clear case for evaluating FLW reduction initiatives within an economic framework. FLW can be viewed as a *negative externality* if those who discard edible food do not incur the external costs to society, such as environmental costs (de Gorter, 2014). In other words, if the transaction price does not include the external costs associated with the environmental consequences of food production, processing and distribution, and disposal, then FLW could create a negative externality. Although some have argued that the estimated costs of FLW are overstated (Bellemare et al., 2017), a full-cost accounting approach for FLW could go beyond the direct market price of foods and account for the noninternalized costs associated with depleting natural resources and ecosystems (FAO, 2014). However, to the extent that FLW leads to higher levels of food production that increase prices of inputs used in production and thus food prices, the costs of FLW may be priced into the food.

3. FLW along the supply chain

FLW occurs at every step in the global food supply chain beginning with agricultural production and ending with consumers (Fig. 1). Imports and exports enter and exit the food supply chain at multiple points, including as raw commodities, ingredients, and finished products. Food items are distributed through grocery stores and other retail outlets for use in home food preparation and through restaurants and foodservice operations for consumption away from home. For the purposes of this paper, we focus on impacts of the food supply chain within the United States, including production of commodities and foods exported out of the United States and production and consumption of foods derived from imports.

Within the global food supply chain, upstream processes of production and post-harvest handling account for approximately 54% of FLW, and the remaining 46% of loss occurs during processing, distribution, and consumption (FAO, 2013). In upstream processes, crops are unharvested because of pests, disease, weather, and failure to meet quality standards (Bloom, 2010; Lipinski et al., 2013; Commission for Environmental Cooperation [CEC], 2017). During food production, FLW occurs because of degradation, damage, and trimmings from food preparation. At retail stores and restaurants, FLW occurs when food nears its expiration date, becomes blemished or bruised, or is not purchased (Bloom, 2010; Lipinski et al., 2013). Food damaged during transportation, handling, and storage between all steps of the food supply chain can result in FLW, often because of inadequate refrigeration during food transportation (CEC, 2017). FLW in consumer homes stems from excess purchases and preparation, food degradation, and consumer preference (Buzby et al., 2014; Schuster and Torero, 2016).

To encourage the sustainable management of food, EPA adopted a food recovery hierarchy summarizing conventional and alternative methods for managing FLW, shown in Fig. 2. The hierarchy presents actions that prevent FLW at the source or divert it from landfills as the preferred methods for dealing with unconsumed food. The bottom two waste disposal methods in the EPA schematic (landfill/incineration,

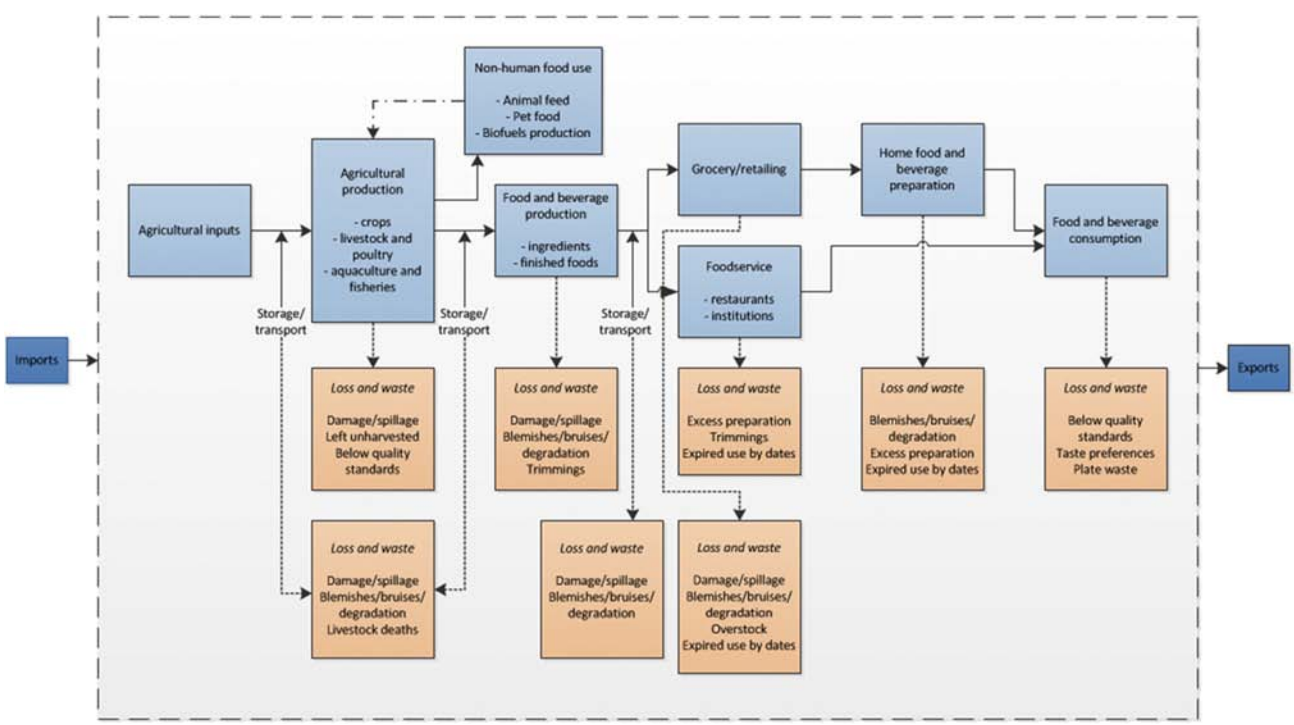

Fig. 1. Food supply chain. Notes regarding system boundaries: (1) Our focus is on environmental impacts of production and consumption within the United States. This includes production of commodities and foods exported out of the U.S. and production and consumption of products derived from imports. (2) Environmental impacts may also occur from secondary uses of waste.

composting) and combustion for energy generation are methods used for municipal solid waste (MSW) disposal and the least favored in the EPA food recovery hierarchy. The amount of FLW in MSW disposal and its ultimate destination are well documented by EPA (2017a) and verified by Thyberg et al. (2015). In 2015, food made up 15.1% (approximately 39.7 million tons) of total MSW; of this total about 2.1 million tons were composted, 7.4 million tons were combusted for energy generation, and 30.3 million tons were landfilled (EPA, 2017a). MSW includes residential, commercial and institutional waste (Thyberg et al., 2015) and accounts for the grocery/retailing, foodservice, and home preparation steps in the food supply chain.

Industrial uses include energy production (through anaerobic digestion or conversion of oil and fats to biodiesel) and use of rendered fats in the animal food, cosmetics, or soap industries. The industrial sector relies on the centralized recovery of specific types of FLW from the production and foodservice industries (e.g., fats, meat scraps, and oil). Additionally, some municipalities anaerobically digest organic waste collected at wastewater treatment plants (EPA, 2017b).

Use of excess food to feed animals is preferable to industrial use but requires collection of appropriate and properly handled food discards. In addition, federal- and state-level laws regulate what can be donated to feed animals (EPA, 2017c). Although feeding food discards to livestock was once common, regulations stemming from disease outbreaks connected to animal feed led to a decline in the practice. By 2007, one study found that only 3% of U.S. hog farms used food discards as feed. Currently, most food discards used as animal feed are diverted from the production or manufacturing stages of the food supply chain (Harvard Food Law and Policy Clinic, 2016). Food discards at the consumer level are generally not used for animal feed because of concerns about safety and variability in composition and nutrition that make it unsuitable (Dou et al., 2018).

Reclaiming excess edible food for human consumption is the most preferable option; however, only an estimated 10% of excess edible food is currently reclaimed in the United States (Gunders, 2012). Reclamation of food destined for disposal can occur from farms, where gleaners recover unharvested produce, and from retailing and foodservice, where unsold food is donated to food banks (Gunders, 2012; EPA, 2017d). FLW can also be disposed of on-site, such as when unharvested crops are plowed under rather than harvested because of crop damage or low market prices (Gunders, 2012).

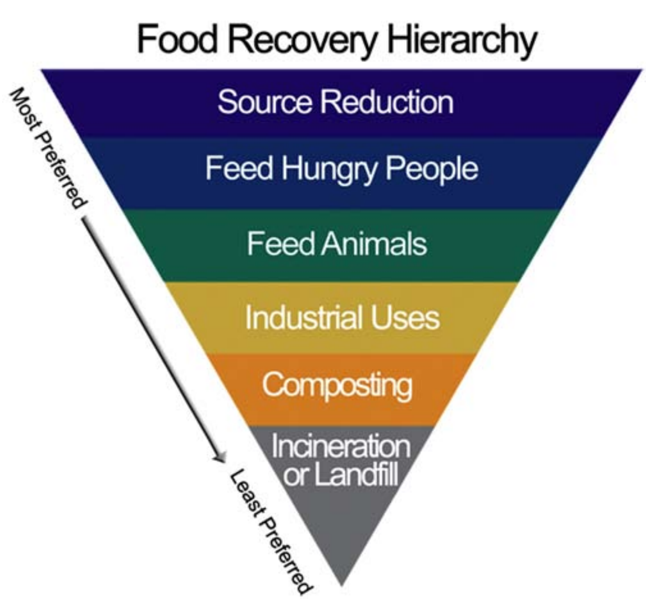

Fig. 2. EPA food recovery hierarchy. Source: U.S. EPA (2018b).

Despite the potential to decrease the environmental impact of FLW, disposal options (except landfill and on-site disposal) are limited by numerous barriers, primarily logistics, lack of reliable partners, and cost. Collection and transportation of FLW is costly (Gunders, 2012) and can be further complicated when the FLW is destined for reuse, requiring special care (EPA, 2017d; Harvard Food Law and Policy Clinic, 2016). Proper handling of food reused for animal and human consumption is critical to avoid illness and is codified in federal and state policies (EPA, 2017d; Harvard Food Law and Policy Clinic, 2016). Potential donors of excess food may be reluctant to donate food because of concerns about liability if donated food causes illness. Although the Bill Emerson Good Samaritan Food Donation Act, a federal statute, waives liability for donors and organizations that distribute donated food in good faith (U. of Arkansas Ag. and Food Law, 2016), companies may be still be concerned about negative publicity and potential lawsuits if donated food causes illness. Food discards destined to feed animals and livestock are subject to a variety of federal and state regulations (Harvard Food Law and Policy Clinic, 2016), thus increasing the challenges of assessing potential risk and liability. Even if donations reach organizations capable of distribution, food donations might still be lost or wasted if they do not match the needs of the organization receiving them or align with consumer preferences (Gunders, 2012).

4. Data and methods used for estimating FLW and its environmental impacts

Although there is no single comprehensive estimate of the FLW generated in the United States each year, recent major studies have estimated the following:

- EPA (2017a): 36 million metric tons (Mt)
- FAO (2011): 89 Mt
- NRDC (Gunders, 2012 taken from Hall et al., 2009): 79 Mt
- ReFED (2016): 57 Mt
- USDA (Buzby et al., 2014): 60 Mt.

These estimates vary considerably because of differences in primary data sets used; the types of disposal methods, destinations, and food supply steps included; and whether inedible parts (e.g., eggshells, peels, and rinds) are included. EPA's estimate is lower than others because it is based on MSW and therefore excludes waste generated in agricultural production, distribution, and manufacturing. In addition, EPA's estimate does not account for as many waste destinations as the other estimates. NRDC found that approximately 40% of food is lost or wasted (Gunders, 2012) by examining the difference between the number of calories in the U.S. food supply (developed from FAO Food Balance Sheets) and the number of calories consumed by end consumers (Hall et al., 2009). NRDC then used USDA's food supply and consumption pattern assumptions from 2010 to estimate that 79 Mt of FLW is created per year in the United States.

In contrast to the other estimates, ReFED's and FAO's estimates attempt to consider on-farm losses. ReFED (2016) estimated the quantity of FLW in 2015 based on secondary research and synthesis of results of previous studies on FLW. They also interviewed academics and industry professionals to verify assumptions and data. FAO estimated total FLW in terms of food intended for human consumption that goes uneaten based on 295 kg of food loss per capita for North America and applied to the U.S. population. Finally, USDA estimated that 60 metric tons of food went uneaten in 2010 (Buzby et al., 2014) based on estimates of loss from primary production to retail, at retail locations, and at the consumer level but not including farm-level losses.

4.1. Data sources used in estimating FLW and environmental impacts

Key studies from the past 10 years estimating various impacts of FLW across the supply chain drew on several common data sets for core measurements of food availability and waste (Supplementary Table A). For production quantity (food availability), virtually all studies drew on the FAO Food Balance Sheets, which capture food production, import, export, and utilization at the country level. Studies in the United States often use production data from USDA's National Agricultural Statistics Service of the ERS Food Availability Data System. Estimates of FLW in the United States are most often drawn from the ERS Loss Adjusted Food Availability (LAFA) data set, although several studies calculate estimates using USDA production data and the National Health and Nutrition Examination Survey (NHANES) survey from the Centers for Disease Control and Prevention (CDC). Studies focused internationally and globally draw on the work done by FAO in 2011, in which FAO data (including Food Balance Sheets) were used to estimate FLW along the supply chain. One limitation of the FLW data along the supply chain is that the percentage of the product lost is typically estimated for a single point in time and for a limited range of food production and processing systems. As a result, changes over time due to technological improvements or geographical variation are not well captured in the data.

The data sets used to measure the virtual resources embodied in FLW and the environmental impacts of waste in the United States tend to come from one of only a few sources regardless of the modeling framework used. USDA provides the data used to estimate the fertilizer, pesticide, and land inputs per unit output for food production. Water availability and water use are estimated using either USDA data or published data sets (Mekonnen and Hoekstra, 2011; Hoekstra and Mekonnen, 2012). A few researchers have estimated energy inputs across the food supply chain, such as Cuéllar and Webber (2010), which relied on a number of U.S. government data sets and past empirical studies and estimations to characterize energy use, and Canning et al. (2017), which integrated energy use data provided by the U.S. Energy Information Administration with data from USDA's ERS in an input-output framework. Most studies of FLW impacts include a measure of GHG emissions along the food supply chain, typically derived by averaging multiple published LCA estimates of emissions for specific food items.

4.2. Methods used for estimating environmental impacts of FLW

Several modeling approaches have been developed to account for the environmental impact of FLW resulting from all resource inputs and emissions throughout the entire production, distribution, and consumption process, including cost-benefit analysis, multicriteria decision analysis, life-cycle assessment (LCA), and environmentally extended input-output (EEIO) models (Müller and Sukhdev, 2018). Here, we discuss the two most common methods for estimating the total impact of food, in particular FLW, along the supply chain: LCA and EEIO.

LCA is a concept and approach used to evaluate potential environmental impacts across the full life cycle of a production system from materials acquisition to manufacturing, use, and final disposition. The basic component of an LCA is an inventory of flows—inputs of water, energy, and raw materials and outputs to air, land, and water—of the product system for each stage in the life cycle. The life-cycle inventory is then used as input data to characterize ecosystem and human health impacts using life-cycle impact assessment. These methods typically rely on impact equivalency factors to translate inventory flows to impacts. For example, GHG emissions are often converted to CO_2-equivalent emissions. Most LCA studies derive inventory flow data from published and unpublished literature, government reports and data sets,[3] NGOs, and commercially available LCA databases (such as Ecoinvent). The life-cycle environmental benefits (or impacts) associated with different FLW reduction options can be quantified using these data.

EEIO models are an alternative to a conventional process modeling LCA approach that may be preferable to estimate impacts of FLW generated by the food system as a whole (Leontief, 1970; Hendrickson et al., 2010; Yang et al., 2017). LCAs of individual food products use allocation procedures to account for only the product under study if a single process is involved in the production of multiple commodities. In the system-wide case, summing the impacts across dozens or hundreds of individual LCAs would compound any allocation errors and risk counting the same impacts more than once. Furthermore, detailed commodity-specific information on flows is not readily available across all food types. EEIO models represent a regional or national economy as a matrix of demand coefficients between economic sectors required to produce the final output of the economy, represented as a vector of the value of goods produced by each sector. EEIO models solve a system of equations to generate a vector of the total demand required from each sector, including the intermediate inputs, to satisfy the final demand. For example, producing canned vegetables requires inputs from the fertilizer, transportation, and aluminum mining sectors, among others. For each impact category, a separate matrix represents the amount of resources used or emissions generated per dollar output of each commodity. The product of the environmental impact matrix and the demand vector represents an estimate of the total impacts across the entire supply chain.

Although EEIO is necessarily a coarser method than constructing LCAs for individual commodities, it is useful for generating estimates of system-wide impacts and can provide insight into the overall size of the environmental problem posed by FLW. For example, Reutter et al. (2017) used EEIO to estimate the percentages of water and GHG emissions, relative to the total amounts used by the Australian economy, which are embodied in consumed food and wasted food. Similar work in the United States that uses EEIO to study food system impacts has primarily focused on forecasting differences in fossil fuel consumption (Canning et al., 2017) and water consumption (Rehkamp and Canning, 2018) that would accompany large-scale shifts in American diets. These modeling approaches could be extended to address questions related to FLW reduction.

Recent work using LCA and EEIO to model the environmental impacts of the food system shows promise for increasing our understanding of what environmental impacts are embodied in FLW. For a recent study on the environmental impacts of different diets in the United States, Heller et al. (2018) compiled over 1600 LCA studies of the impact of different food commodities and linked them with consumption data from USDA's NHANES dietary recall survey. A list of the carbon emissions associated with different food items was published as supporting information (Heller et al., 2018). This kind of comprehensive LCA data will enable researchers to determine the differences in intensity of FLW among socioeconomic groups or among individuals with different diets and thus where we can achieve the greatest mitigation impact through FLW reduction. In addition, Boehm et al. (2018) used the National Household Food Acquisition and Purchase Survey with a model combining LCA and EEIO to estimate GHG emissions from food spending. This study is unique because it encompasses more stages of the food supply chain than many previous studies, including emissions generated from the farm until the food is sold to the consumer.

5. Environmental and ecological impacts of FLW

Producing, transporting, processing, and preparing food for consumption require the input of various resources, including (but not limited to) land, fertilizer, pesticides, water, and energy. Food production also results in the emission of pollutants and contributes to other damage to the environment. When food is wasted, these embedded

[3] An example is USDA's LCA Commons (https://www.lcacommons.gov/).

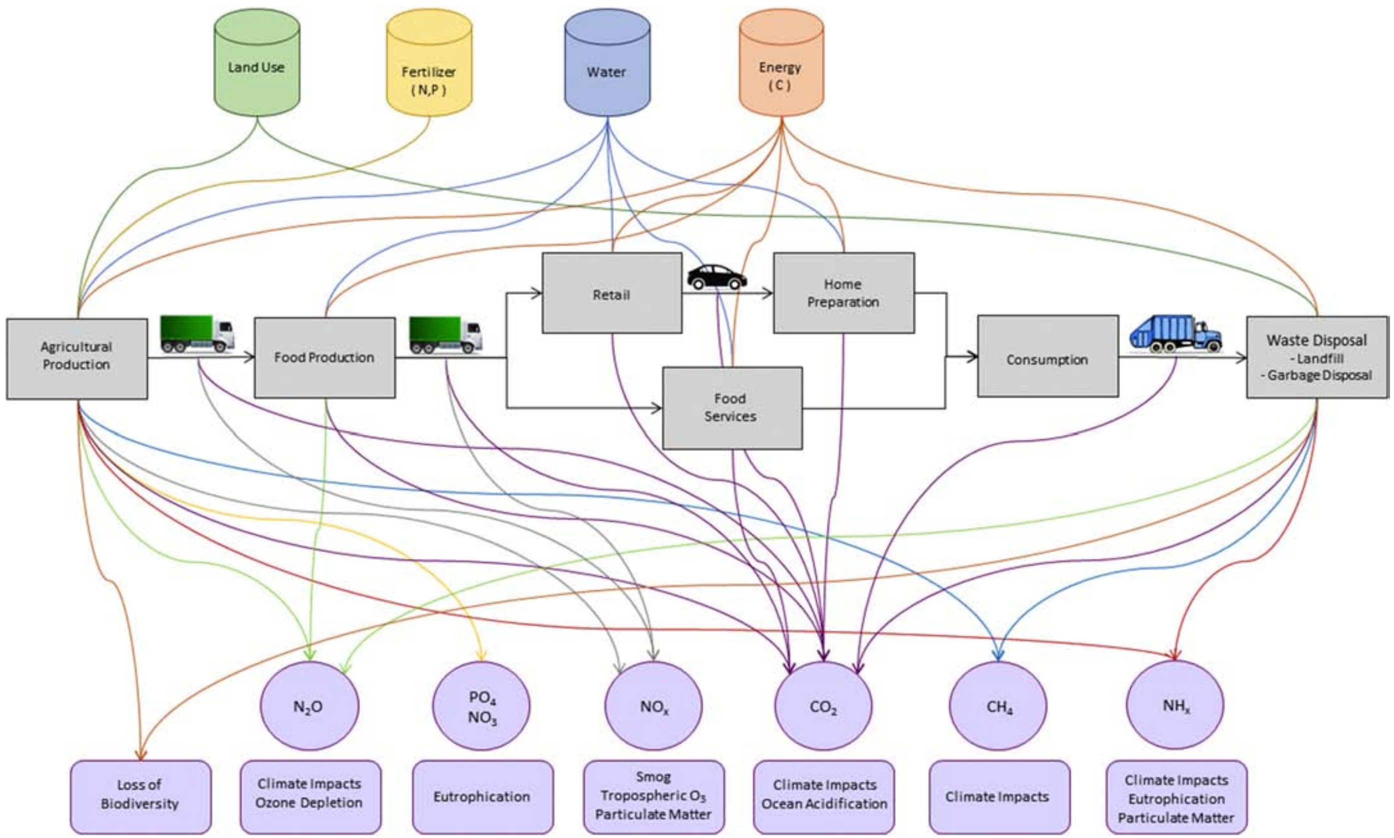

Fig. 3. Flow diagram of resource use, emissions, and ecological and environmental impacts of FLW along the food supply chain. Note: The diagram shows the movement of resources and other inputs throughout the food supply chain across the top and environmental emissions and impacts across the bottom.

resources are also wasted. This section describes the multidimensional upstream and downstream environmental impacts of FLW. First, we provide an overview of the range of resource inputs, chemical species outputs, and corresponding impacts associated with the food supply chain. Then, we review previous estimates of the environmental impacts associated with FLW.

5.1. Resource inputs and emissions

Environmental impacts from FLW along the supply chain stem from both the resource inputs and the resulting emissions (Fig. 3). Environmental impacts include those caused by habitat destruction and disruption (e.g., loss of biodiversity) and by emissions to air, water, and land. For the latter, we considered the impacts associated with emissions that are biologically active (i.e., nutrients), radiatively active (i.e., greenhouse gases), and chemically active (i.e., nitrogen oxides, NO_x) (Fig. 3). Some of the emissions (e.g., phosphate, PO_4) are from just a few locations along the food supply chain, while others are lost at most locations. The next section details emissions, and the following section details environmental impacts.

Resources, such as land, fertilizer, water, and energy, are used at various stages of the food supply chain. Some resources supply chemical inputs; fertilizer supplies nitrogen (N) and phosphorus (P), while energy supplies carbon (C). These inputs travel through the various stages of the food supply chain, undergo chemical transformations, are emitted into the environment in different forms, and result in various impacts. For example, energy is used by trucks as hydrocarbon-rich fuel, combustion transforms the carbon into carbon dioxide, and the trucks emit carbon dioxide to the atmosphere, leading to climate impacts. Other resources may lead directly to environmental impacts solely through their use. No single chemical compound leads to biodiversity loss; converting natural land to farmland alters the natural habitat and the species dependent on the ecosystems. Chemicals associated with FLW are released into the environment in two different ways: first, chemicals physically contained in FLW (e.g., N, P, C) are mobilized into the environment during FLW disposal, and second, chemicals are lost to the environment during production of food that is lost or wasted. Take, for example, nitrogen: N is lost to the environment at all stages of the food supply chain. N used in the production of food items but that is not in the consumed item is referred to as "virtual N." A virtual N factor (VNF) is the virtual N divided by the amount of N in the consumed food item (Leach et al., 2012; Fig. 4). For example, to calculate the flow of reactive N (Nr) in the beef production process, start with 100 units of new nitrogen. For every unit of N consumed, about 13 units are lost to the environment primarily during feed production and manure creation. The same construct can be used for the virtual N associated with FLW. For example, if a hamburger is thrown away, the embodied N in the hamburger is lost to the environment in addition to the N lost to the environment during the production of the hamburger. In the case of a hamburger, virtual N is about eightfold greater than embodied N.

5.1.1. Chemical emissions along the food supply chain

FLW results in chemical emissions to the environment both directly through the transportation, decomposition, and combustion of organic waste and indirectly through the chemicals released during the production of food that is ultimately wasted. In general, the indirect losses are much greater than the direct emissions. Some of the N in FLW is converted by microbes in anaerobic environments to nitrous oxide (N_2O). However, this is a small amount relative to the N lost from the food supply chain during the production of food that is lost or wasted. Another source of N_2O is from the combustion of fossil fuel (i.e., petroleum, coal, natural gas) that is part of the food production process. Nutrients in FLW, including phosphate (PO_4), nitrate (NO_3), and ammonium (NH_4), are lost as the food decomposes or is combusted. During the production process of food that is lost or wasted, the major losses of these ions are from the agriculture step (Fig. 3); nitrate is primarily lost in dissolved form, while ammonium and phosphate are associated with the sediment in agricultural runoff. Emissions of NO_x from FLW occur during transport, burning, and microbial decomposition (e.g., landfills). NO_x emissions are also generated during food production through combustion of fossil fuels (e.g., farm equipment, food transportation) and soil microbial processes (i.e., nitrification, denitrification). CO_2 is emitted along each step of the food supply chain from both direct and indirect sources. Transportation is a major direct source of CO_2 from diesel and gasoline combustion, although Boehm et al. (2018) find that production and manufacturing emissions far outweigh the transportation GHG emissions across all food categories. Retail (i.e., grocery stores) can be a direct source of CO_2 by using natural gas on-site or an indirect source by using electricity produced from fossil fuels. Finally, methane (CH_4) is emitted primarily from agricultural production of food and anaerobic decomposition of FLW in landfills but also from the use of improperly stored or partially combusted natural gas and during the mining of the fossil fuels that are used to produce and transport food.

5.1.2. Environmental impacts of FLW

The potential wide-ranging environmental impacts of FLW include the effects on climate, water, and air and those associated with land use for food production (see Fig. 3). Many of the impacts are interdependent; for example, climate impacts and eutrophication can contribute to loss of biodiversity by altering natural habitat conditions. While some impacts occur on a global scale, others occur primarily on a local scale. For example, CH_4 emissions from landfills and N_2O emissions from agricultural systems are important contributors to climate change on a

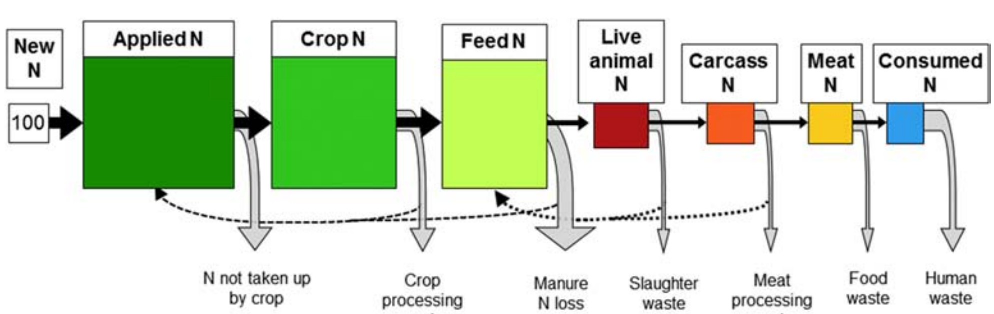

Fig. 4. Nitrogen flows in the beef production process. Notes: (1) The colored boxes show the available N at each stage of the food production process with their areas reflecting the magnitude of N. (2) The black arrows show the N that makes it to the next stage. (3) The start of the gray arrows is the total N wasted, and the end of the gray arrows is the N lost to the environment. (4) The dotted arrows show the N recycled, which is subtracted from the N wasted to find the N lost to the environment. (5) The diagram shows the summation of multiple iterations of the calculations; the iterations determine how recycled N is distributed throughout the system (Leach et al., 2012). In this figure, all N that is used in the production process but is not present in the consumed product is *virtually* embodied in the product (total virtual N = applied N − consumed N).

global scale, but nutrient losses from food waste from along the food supply chain contribute to eutrophication of waters on a local scale.

5.1.2.1. Impacts on climate, water, and air. GHG emissions, including CO_2, CH_4, and N_2O, associated with FLW alter the radiative forcing of the atmosphere and hence lead to global warming. NO_x emissions contribute to the formation of tropospheric ozone, which also contributes to warming. Tropospheric aerosols, formed by reactions involving NO_x and ammonia (NH_3), have the opposite effect and reduce radiative forcings. The resulting aerosols (e.g., NH_4NO_3; $(NH_4)_2SO_4$) scatter solar radiation, resulting in a potential cooling of the atmosphere. N_2O emissions associated with FLW contribute significantly to stratospheric ozone depletion. N and P chemical species are lost to the environment during food production and contribute to eutrophication, the excess enrichment of water bodies with nutrients that increase the growth of plants and algae and lead to hypoxia. N is most closely associated with coastal eutrophication, while P is most closely associated with freshwater eutrophication. CO_2 associated with FLW also contributes to ocean acidification, which is the decrease in the pH of the Earth's oceans, thus negatively affecting ocean life (Anthony et al., 2008). NO_x associated with FLW reacts with volatile organic compounds in the atmosphere to produce ozone (O_3) and smog. Finally, a number of production and distribution processes along the food supply chain release particulate matter into the atmosphere, adversely affecting human health (Vinikoor-Imler et al., 2011).

5.1.2.2. Land use impacts. Land use impacts of FLW include loss of biodiversity and soil degradation. Biodiversity refers to the variety in the world's natural ecosystems (Benn, 2010). Most causes of biodiversity loss can be attributed to an impact either on a species directly (e.g., overhunting, overfishing, competing invasive species) or on associated habitat (e.g., limiting resources through land use change) (World Wildlife Fund, 2018). Converting natural habitat to agriculture can cause soil degradation, which refers to negative impacts on the soil's quality, including decreased soil structure, increased erosion, and reduced nutrient availability. Impacts on biodiversity and soil degradation are diffuse and difficult to quantify. For example, biodiversity is often measured using multiple indices, including deforestation, number of red-listed species, and marine trophic index (FAO, 2013). Additionally, soil degradation has numerous associated impacts yet no consistent definition or measurement method (Bastida et al., 2008; Eswaran et al., 2001).

5.1.3. Variation in impacts across regions: production versus consumption locations

Pre-consumer environmental impacts of FLW associated with the resource inputs and emissions for particular food items vary across geographical regions. This variability arises from differences in climatic and geologic conditions that lead to differences in crop requirements, as well as from variable economic and management conditions. Crop yield (production per unit area) varies spatially (Monfreda et al., 2008), leading to different land requirements for a given unit of food product. Current yields can be increased in some cases by improved fertilizer application and irrigation (Mueller et al., 2012), which would reduce the land area requirements but would increase the nutrient and water requirements. Differences in local geology and soil conditions, as well as nutrient management programs, can drive differences in fertilizer and manure application (Potter et al., 2010; MacDonald et al., 2011), leading to differences in nutrient releases to the environment.

Climatic conditions and soil composition drive regional differences in water requirements for crops (Mekonnen and Hoekstra, 2011), and, in the case of aquaculture, the local evaporation rate and underlying soils contribute to regional variability in water requirements (Gephart et al., 2017). Further, sourcing of water for crops can vary regionally; some areas may receive sufficient precipitation and others may require irrigation from surface and groundwater sources (Mekonnen and Hoekstra, 2011). The energy inputs for crop production, including the energy required for machines, fertilizers, and water, vary regionally with the degree of intensification (Pellegrini and Fernández, 2018). The impacts associated with food production also vary across geographies and can have differential impacts across scales. For example, the water quality impacts of nutrient runoff, including eutrophication potential, can depend on local baseline conditions and interactions with the underlying geology. While water quality and water scarcity issues are most relevant on the local to regional scale, GHG emissions have global consequences.

Post-consumer environmental impacts include those associated with the collection, transport and management of FLW. Variability across geographic regions arises from differences in collection and transport distances and, perhaps more significantly, the process in which FLW is managed. Conventional options for managing FLW include anaerobic digestion, composting, waste-to-energy, and landfill disposal. Each option has its own profile of environmental impacts with landfill disposal generally being less preferable to prevention and recovery alternatives on a GHG emission basis (Hodge et al., 2016). Emissions of methane gas associated with FLW landfill disposal vary substantially depending on whether gas is vented to the atmosphere, flared, or used for energy recovery. Environmental impacts of other post-consumer waste management options, such as conversion to animal feed or other bio-based products, and their regional variability are currently not well characterized.

5.2. Measures of environmental impacts of FLW

Of the many resources used to produce food, literature sources have quantified land area, fertilizers, pesticides, water, and energy embedded in food that is lost or wasted. Table 1 contains a summary of the findings from sources that quantify the resources embedded in FLW along with notes about how each estimate was reached. The resources required to produce food that is lost or wasted can be estimated using government and international data sets of the amount of FLW and the amount of resources consumed by the food sector at large or to produce a given food category. All the sources in Table 1 combine LCAs of resource consumption with inventories of FLW. The five studies referenced in the table rely on different data sources and geographic areas and draw different boundaries around the food system.

Estimates for the emissions and environmental impacts of food production exist in the literature but generally have not been linked to FLW specifically. GHG emissions associated with FLW are the exception; multiple studies have quantified GHG emissions that result from the production and disposal of lost and wasted food (see Table 2). We also found estimates for biodiversity impacts of lost and wasted food, although one is qualitative (FAO, 2013) and the second is highly uncertain (CEC, 2017). Authors of the FAO (2013) study noted that they were unable to provide a quantitative estimate of the biodiversity impacts of FLW because the available data are at a regional scale and not available by commodity.

Although no estimates for smog formation and acidification associated with FLW were identified, Matsuda et al. (2012) reported that these effects are highly correlated with GHG emissions. Smil (2004) also noted that these damages (smog formation and acidification) result from nitrogen emissions from fertilizer applied to crops. The few estimates for environmental impacts and emissions from FLW reflect the fact that these impacts can be difficult to quantify and are not always linearly related to emissions.

5.3. Software tools for estimating nutritional and environmental impacts of FLW

A number of software tools exist to estimate nutritional content and environmental impacts of FLW. These tools were developed by government organizations, NGOs, and businesses for stakeholders including

Table 1
Summary of estimates of the resources used to produce food that is ultimately lost or wasted in the United States.

Source	Year of data	Annual quantity	Standardized quantity[a]	Notes on methodology
Land				
Birney et al. (2017)[b]	2010	1117 m^2/capita	1117 m^2/capita	Includes land to produce animal feed and land required to keep livestock
Kummu et al. (2012)[b]	2005–07	498 m^2/cap	498 m^2/capita	Only considers land to produce crops for human consumption; does not include land to house livestock
Conrad et al. (2018)	2002–2016	30 million acres	405 m^2/capita	Includes land to produce animal feed
Fertilizer				
Kummu et al. (2012)[b]	2005–07	9.3 kg/capita (for North America and Oceania)	9.3 kg/capita	Does not include fertilizer for animal feed
Birney et al. (2017)[b]	2010	19 kg/capita	19 kg/capita	Does not include fertilizer for animal feed
Conrad et al. (2018)	2002–2016	1.8 billion lb nitrogen fertilizer, 1.5 billion lb phosphorus (P_2O_5) fertilizer, 2.3 billion lb potash (K_2O) fertilizer	2.7 kg/capita N fertilizer 2.3 kg/capita P_2O_5 3.5 kg/capita K_2O	Includes fertilizer for animal feed; Used LAFA data for food loss and USDA ag surveys and personal communication for fertilizer application rates
Pesticides				
Conrad et al. (2018)	2002–2016	780 million lb	780 million lb	Applied to cropland
Water				
Hall et al. (2009)	1996	>25% of total freshwater	>352,000 L/capita	Combined water usage of the agriculture sector and food waste percentage
Kummu et al. (2012)[b]	2005–07	42,000 L/cap	42,000 L/capita	Blue water used to produce wasted food
Birney et al. (2017)[b]	2010	54,000 L/cap	54,000 L/capita	Blue water used to produce wasted food
Conrad et al. (2018)	2002–2016	4.2 trillion gallons	53,000 L/capita	Irrigation water
Energy				
Hall et al. (2009)	1996	300 million barrels of oil	1740 trillion BTU	Used average energy requirements to produce 1 kcal of food and approximate food waste in kilocalories
Cuéllar and Webber (2010)[b]	2007	2030 ± 160 trillion BTU	2030 trillion BTU	Estimated energy use for each stage of food production and multiplied by food waste ratios
Birney et al. (2017)[b]	2010	9 GJ per capita	2559 trillion BTU	Applied LAFA FLW ratios to an updated estimate of energy required for food production (extrapolation of Cuéllar and Webber methodology)

[a] Per capita standardization uses U.S. population of 300 million.
[b] Cuéllar and Birney used food loss data from the retail level, foodservice, and consumers. Kummu includes food loss on the farm throughout the rest of the food supply chain (processing, retail, preparation, consumers). Kummu also does not provide country-level geographic resolution, only groupings of geographic areas (North America and Oceania).

businesses and local governments. Users of these tools input basic information on the quantity, type, and disposal method of the waste. Estimates of impact and value are generated from the user input and from underlying data derived from various sources.

EPA's Waste Reduction Model (WARM), currently in its 14th version (EPA, 2018c), is targeted at waste managers and organizations interested primarily in tracking the GHG emissions generated by their waste. It accounts for the energy and emissions associated with transporting waste and operating machinery associated with waste disposal methods such as anaerobic digestion, as well as the emissions saved by converting organic waste to biogas or using digestate as fertilizer. Data for the WARM tool are derived from EPA's GHG inventory and municipal solid waste data collection, among other sources, and the results generated are based on an LCA database. The environmental impact estimates generated by WARM are used by multiple third parties. For example, Leanpath (www.leanpath.com), a software tool designed for culinary organizations, uses WARM estimates to inform organizations about the environmental impact of their food waste transactions and prompt behavioral change.

In contrast to WARM, which is not specific to FLW and focuses primarily on the impacts associated with waste disposal, the recently released FReSH FLW value calculator from the WRI helps users quantify FLW impacts across the supply chain (WRI, 2018). The calculator follows guidelines outlined in WRI's FLW measurement protocol. Users input the quantity and disposal destination of food lost at five different supply chain stages: agricultural production, post-harvest handling and storage, processing and packaging, distribution, and consumption. The waste destinations include repurposing to animal feed or biomaterials, anaerobic digestion, and landfill disposal, among others. The tool produces estimates of the nutritional value embodied in the FLW generated at each step of the supply chain and estimates of GHG emissions, water use, land use, and other environmental impacts, also derived from LCA databases. This tool emphasizes the importance of prevention, especially at later supply chain stages when the lost or wasted food contains more resources.

6. Interventions to reduce FLW

Interventions to reduce FLW can be broadly characterized as prevention, recovery, or recycling (ReFED, 2016). In general, prevention is equivalent to "source reduction" in the EPA Food Recovery Hierarchy (see Fig. 2); recovery is equivalent to "feed hungry people"; and recycling is equivalent to "feed animals," "industrial uses," and "composting." FLW interventions can be undertaken by federal, state, and local governments; private companies, such as food manufacturers, food packaging manufacturers, and technology developers; emergency

Table 2
Summary of estimates of the environmental impacts of FLW.

Source	Year of data	Emissions	Standardized quantity[a]	Notes on methodology
Biodiversity				
FAO (2013) (Food wastage footprint: Impacts on natural resources, summary report)	2007	Qualitative discussion of the impact on food waste by commodity on biodiversity in different regions of the world	N/A	Quantitative biodiversity indicators related to food production are given at a regional level but not by commodity, making it difficult to connect food waste volumes quantitatively to biodiversity impacts
CEC (2017)	2012	$229 million per year (United States)	N/A	Used global values for biodiversity loss per hectare of cropland due to nitrogen eutrophication, phosphorus eutrophication, and pesticide effects. Prices normalized to 2012 dollars and applied to cropland for wasted food. Uncertain estimate: not region specific and large range in cost estimates
Greenhouse gas emissions				
Heller and Keoleian (2014)	2010	1.4 kg CO_2 eq/capita/day (United States)	1.4 kg CO_2 eq/capita/day	Used LAFA data set to estimate losses combined with retail-level food availability and carbon footprints from a meta-analysis of published LCA values; does not include waste before retail step in supply chain
Hiç et al. (2016)	2010	340 g CO_2 eq/capita/day (Northern America)	0.34 kg CO_2 eq/capita/day	Estimated food loss as difference between food availability (FAO) and estimates of human energy requirements for each country; GHG emissions are for agricultural non-CO_2 emissions from FAOSTAT; waste along entire supply chain
Venkat (2011)	2009	368 kg CO_2 eq/capita/year (United States)	1 kg CO_2 eq/capita/day	Estimated food loss using LAFA database; only considers avoidable food waste; used LCA database to estimate GHG emissions from each food category
FAO (2013) (Food wastage footprint: Impacts on natural resources, summary report)	2007	900 kg CO_2 eq/capita (North America and Oceania)	2.5 kg CO_2 eq/capita/day	Used LCA estimates of CO_2 equivalent emissions. Includes agricultural through disposal emissions; used FAO (2011) estimates for food wastage volumes
CEC (2017)	Not given	123 MMT CO_2 eq/year (FLW LCA) and 0.64 MMT methane/year (landfill emissions; United States)	2.5 kg CO_2 eq/capita/day[b]	GHG emissions are for the life cycle of landfilled FLW (excluding retail, foodservice, and consumption steps of supply chain). Methane emissions are the anaerobic decomposition of landfilled FLW. Amount of FLW estimated using FAO estimates for food produced by product group.

[a] Per capita standardization uses U.S. population of 300 million.
[b] The global warming potential of methane used is 25 (EPA, 2018a).

Table 3
Examples of FLW prevention interventions by supply chain stage.
Sources: Adapted from NRDC (2017) and ReFED (2016).

Supply chain stage	Government policy	Technology	Practice or behavior
Farms	• Broaden cosmetic standards for produce to allow more variability	• Apply coatings to products in packing houses to preserve shelf life	• Expand markets for produce not meeting highest cosmetic standards • Facilitate regional food networks to reduce time from harvest to market
Manufacturers	• Implement standardized date labeling system to reduce confusion	• Optimize packaging to smaller or customizable portions • Use cold-chain certified carriers for transporting food • Use packaging technologies that increases shelf life	• Use direct shipments to retail distribution centers
Restaurants & Retailers	• Develop education campaigns for consumers to understand date labels	• Improve ability to track remaining shelf life of food in retail inventory management systems • Implement smart scales and technologies for tracking and recording food waste during food preparation • Use cold-chain certified carriers for transporting food	• Allow prepared foods to sell out near closing time without replenishing • Discount older, slightly damaged items and excess inventory • Eliminate promotions that encourage excessive purchase of repeat items • Enable purchase of smaller or customized portions (bulk bins, staffed deli) • Increase flexibility in contracting terms and grading standards for foods • Prepare smaller batches of food or cook to order • Redesign produce, deli, and seafood displays to use smaller containers • Remove trays and use smaller plates in buffet-style restaurants • Train and reward staff in waste reduction efforts (e.g., optimal product handling and stock rotation)
Consumers	• Conduct large-scale consumer awareness and education campaigns regarding FLW • Educate consumers on meal planning, shopping, storing, and preparing of food to reduce waste • Impose municipal tax or financial penalty for disposal of food waste	• Use smart refrigerators that notify consumers of expiring foods	• Change consumer food waste reduction behaviors in response to educational initiatives

Table 4
Examples of FLW recovery interventions by supply chain stage.
Sources: Adapted from NRDC (2017) and ReFED (2016).

Supply chain stage	Government policy	Technology	Practice or behavior
Farms	• Provide tax incentives to increase farm-level food recovery	• None identified	• Allow gleaning operations on farm
Manufacturers	• Educate potential food donors on donation liability laws • Expand tax incentives for food donations by businesses	• Develop new uses and products from trimmings and by-products	• Divert trimmings, by-products, and excess inventory to alternative uses
Restaurants and Retailers	• Educate potential food donors on donation liability laws • Expand tax incentives for food donations by businesses	• Use apps to notify recipients of available excess food	• Increase donations of unsold foods • Offer produce with lower cosmetic grades • Use damaged product in prepared food offerings • Divert excess processed food and unwanted produce to discount retailers
Emergency Food Providers	• Standardize local and state health department regulations on food donations	• Connect food donors with recipient organizations through technology platform • Process perishable donated foods into longer shelf life products	• Expand temperature-control storage and distribution infrastructure for donations • Increase labor availability to sort and package donations

food providers such as food banks, food pantries, and soup kitchens; and consumers. In the case of government interventions, some actions may be mandated through regulation (e.g., banning food waste in landfills or requiring "best if used by" dates), but others are voluntary actions that individuals or businesses undertake following government or NGO-provided guidance or recommendations.

Examples of actual and potential FLW interventions, derived from NRDC (2017), ReFED (2016), and other sources, are shown in Table 3 for prevention-type interventions, Table 4 for recovery-type interventions, and Table 5 for recycling-type interventions. Policy interventions implemented by a government entity at the local, state, or national levels are expected to cause a response from suppliers at different stages of the food supply chain (farms, manufacturers, restaurants, and retailers) or from consumers. Technology interventions generally arise from private-sector research and development processes but could be incentivized by government programs. Finally, "practices" shown in Tables 3 through 5 refer to actions taken by food producers and suppliers, while "behaviors" refer to actions taken by consumers to reduce FLW in response to interventions.

The characterization of an intervention is important from an environmental and an economic perspective because the resource use and emissions vary depending on whether an intervention reduces the need to produce more food, repurposes excess food that has already been produced, or uses FLW for an alternative use such as animal feed or energy generation through incineration. For example, Salemdeeb et al. (2017) found that reducing FLW has 5 to 12 times more GHG savings than anaerobic digestion of FLW for energy generation. In addition, environmental and economic effects vary depending on which entities in the food supply chain respond to an FLW intervention.

7. Approaches to analyzing economic impacts of FLW interventions

Economic analysis can provide information to prioritize investments in FLW interventions based on whether estimated benefits exceed the costs (Ellison et al., 2019; de Gorter, 2014). The cost-benefit comparison differs depending on whether an intervention is driven by a public or private initiative. Public interventions, such as the policies indicated in Tables 3 through 5, will in most cases require direct financial expenditures and time and effort (or opportunity costs) by businesses, consumers, and governments to implement the intervention (Ellison et al., 2019). However, there are distributional implications because the benefits of public interventions accrue to society as a whole from the environmental improvements associated with less resource use in the production of food and fewer emissions from discarded foods in landfills and, potentially, improvements in food security if excess foods are redistributed rather than discarded. Private interventions refer to the voluntary adoption of the technologies or practices shown in Tables 3 through 5 (although these technologies and practices could also be mandated by government through regulation and therefore be considered public interventions).

In general, businesses or consumers will voluntarily adopt a technology or practice that reduces FLW if their private return on investment is positive (Ellison et al., 2019). For example, a company that reduces its food procurement and waste disposal costs by more than the costs of purchasing, installing, and operating an FLW tracking system has an incentive to voluntarily adopt the technology. Similarly, a household that can reduce its food purchase costs by more than the opportunity costs of its time and effort in doing the planning to reduce FLW has the incentive to voluntarily do so. Although it does not factor into a financial return on

Table 5
Examples of FLW recycling interventions by supply chain stage.
Sources: Adapted from NRDC (2017) and ReFED (2016).

Supply chain stage	Government policy	Technology	Practice or behavior
Farms, manufacturers, retailers, and restaurants	• Impose bans or fines for disposing of food waste in landfills (retailers and manufacturers) • Provide incentives for redirecting food waste to other purposes (e.g., renewable energy credits)	• Repurpose food waste through heat-treatment, dehydration, and mixing for animal feed • Use centralized anaerobic digestion for energy production from food waste • Use commercial gray water aerobic digesters to break down food waste • Use in-vessel composting to generate compost from food waste • Use municipal water recovery resource facilities to convert food waste to biosolids for land application	• Divert trimmings and by--products to animal feed • Transport food waste to centralized composting facility
Consumers	• Provide curbside collection of compostable food scraps	• None identified	• Compost food waste on-site at residential locations

investment calculation, companies and households may also derive intrinsic value from the social good that comes from reducing FLW (Landry and Smith, 2019).

From a policy perspective, the decision about whether to mandate an FLW intervention could be based on a cost-effectiveness or a cost-benefit analysis in which the effectiveness or benefit is measured in terms of improvements in the environmental (and potentially food security) consequences of FLW described above. Costs could include wages for personnel, equipment and maintenance, materials and supplies, energy, and outside services (Ellison et al., 2019; Adams et al., 2019). In a cost-effectiveness analysis, impacts are measured in nonmonetary units of effects, but in cost-benefit analysis, impacts are converted into dollar values associated with an intervention (Adams et al., 2019). For cost-effectiveness analysis, each individual impact must be assessed relative to costs individually because environmental improvements are measured in terms of different units. An advantage of cost-benefit analysis is that all impacts are converted to dollar units that can be added together to measure collective impact, but assigning a dollar value to all impacts is difficult (Adams et al., 2019). In particular, because environmental amenities are not traded in markets, nonmarket valuation methods need to be developed and applied. If FLW interventions result in a reduction in pollutants, benefits can be estimated based on reduction in healthcare costs and increase in labor productivity associated with human health. In addition, if FLW interventions result in improvements in ecosystems, benefits can be based on alternative use values such as for recreation or the option value of avoiding irreversible damage to the ecosystem (TEEB, 2010).

Cost-effectiveness and cost-benefit analyses both ignore the adjustments in food and agricultural markets, and corresponding distributional implications, that are likely to occur in response to an FLW intervention. An intervention could affect the demand for food (e.g., consumers may not need to purchase as much food) or the supply of food (e.g., producers lose less volume during the production process), both of which could affect market prices. Rutten (2013) provides a diagrammatic analysis of both partial and general equilibrium effects of FLW reduction. Partial equilibrium analysis focuses only on the market or stage of the supply chain where an intervention occurs. General equilibrium analysis also accounts for how changes at one level of the supply chain affect upstream or downstream markets. For example, a reduction in FLW at the consumer level reduces the demand for food purchased in grocery stores, which causes reductions in food prices at prior stages (retail, manufacturing, farm); however, in response to lower food prices, consumers may subsequently increase their food purchases, thus causing FLW to increase again if they increase the rate at which they waste food. General equilibrium effects could extend to other countries, as reductions in FLW on either the demand or supply side in one country affect trade flows between countries (Okawa, 2015). The magnitude of responses in either the partial or general equilibrium analysis depends on the responsiveness, or elasticity, of consumers and producers to changes in prices and quantities (Rutten, 2013).

Prior economic analyses of FLW interventions have used input-output modeling approaches, including models built on social accounting matrices (Keuning and de Ruuter, 1988), to investigate economy-wide impacts of FLW reduction. For example, Campoy-Muñoz et al. (2017) assessed the effects of FLW reduction on the total economic output and employment of several European countries using social accounting matrices. They found that reducing household FLW would have a greater economic impact than reducing waste in other economic sectors. However, analyses should also consider that the environmental benefits of FLW reduction efforts could be partially or completely offset by a rebound effect if consumers spend their savings from food purchases on other goods and services that burden the environment. For example, to estimate environmental impacts of FLW resulting from consumer-level FLW in Great Britain, Salemdeeb et al. (2017) used a combination of top-down (environmentally extended multiregional input-output model) and bottom-up (life-cycle analysis) approaches. Assuming no rebound effect, the authors' model predicted that reducing FLW by 60% across British households would prevent about 1100 kg CO_2-equivalent/ton of FLW. However, when including the rebound effect assuming that respending is roughly equally distributed among consumption categories, this benefit was diminished by 23% to 59%, depending on scenario details. These questions have only been investigated in a European context, but this work could be extended to the United States.

In summary, cost-effectiveness or cost-benefit analyses could be used to compare and prioritize investments in FLW interventions. A more complete analysis would consider the effects of those interventions on market prices and quantities in the directly affected food and agricultural markets, upstream and downstream food and agricultural markets, and related markets for agricultural inputs or consumer goods. When considering the costs and benefits, interventions aimed at prevention may be less costly and conserve more resources than those aimed at repurposing or redistributing excess foods because the latter require more energy and inputs for the subsequent processes.

8. Conclusion

FLW has substantial environmental consequences and although solutions are being pursued, most have not been assessed in an economic framework. To do so requires developing measures of both the potential environmental benefits and the costs of implementing interventions. Assessment of the environmental benefits and economic costs depends on whether interventions focus on prevention, recovery, or recycling of FLW and whether they are mandated or adopted on a voluntary basis. This paper provides background information for developing an integrated modeling approach for prioritizing investments in FLW interventions while considering costs to industry, consumers, and government relative to environmental benefits. The information synthesized in this paper indicates the importance of prioritizing FLW prevention over recovery and recycling, given the high amount of virtual resources lost when food is wasted, but better data and further research are needed to rank the cost-effectiveness of specific interventions.

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