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Food waste and the food-energy-water nexus: A review of food waste management alternatives

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ABSTRACT

Throughout the world, much food produced is wasted. The resource impact of producing wasted food is substantial; however, little is known about the energy and water consumed in managing food waste after it has been disposed. Herein, we characterize food waste within the Food-Energy-Water (FEW) nexus and parse the differential FEW effects of producing uneaten food and managing food loss and waste. We find that various food waste management options, such as waste prevention, landfilling, composting, anaerobic digestion, and incineration, present variable pathways for FEW impacts and opportunities. Furthermore, comprehensive sustainable management of food waste will involve varied mechanisms and actors at multiple levels of governance and at the level of individual consumers. To address the complex food waste problem, we therefore propose a "food-waste-systems" approach to optimize resources within the FEW nexus. Such a framework may be applied to devise strategies that, for instance, minimize the amount of edible food that is wasted, foster efficient use of energy and water in the food production process, and simultaneously reduce pollution externalities and create opportunities from recycled energy and nutrients. Characterization of FEW nexus impacts of wasted food, including descriptions of dynamic feedback behaviors, presents a significant research gap and a priority for future work. Large-scale decision making requires more complete understanding of food waste and its management within the FEW nexus, particularly regarding post-disposal impacts related to water.

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1. Introduction

Food waste is a social problem with far-reaching consequences, many of which are incompletely or inadequately characterized by current frameworks. For instance, while the impact of food waste to global food security may be theorized, the full range of socioeconomic and environmental consequences related to food production and waste are only beginning to emerge. Interactions among food waste, water and energy resources, environmental quality, and social justice suggest that broad-scale changes to food production and waste management may curb inefficiencies and externalities on many levels. Food waste is a complex problem, and one that likely requires a combination of technology-based solutions and direct public interventions and incentive structures to alter consumer disposal behaviors. This requires attention at three levels; first, at the individual unit of analysis, a focus on the behavior of consumers in response to regulatory incentives and self-motivated waste prevention actions; second, at the local level, a focus on the governance mechanisms that may minimize food waste by residential, commercial and institutional actors; and third, at higher levels of governance, investments to large-scale application of technological advancements seeking to capture waste and extract alternative forms of energy and materials. Food waste may never completely be eliminated, however there are significant opportunities to minimize waste and convert what is disposed into useful forms of energy.

Herein, we review and conceptualize the problem of food waste within the framework of the Food-Energy-Water (FEW) nexus. The objectives of this work are to (1) characterize food waste within the FEW nexus by defining potential fluxes of mass, energy, and water, (2) describe system dynamics, including feedbacks between human behavior and FEW impact, and (3) isolate gaps in current knowledge that must be addressed before the food waste-energy-water nexus can be fully operationalized in a quantitative sense.

2. Food waste background

2.1. Food loss and waste definitions

Definitions of food loss and food waste vary considerably (Table 1). Notably, items removed from the food supply chain during pre- and post-consumer phases are not consistently delineated within various definitions, suggesting need for internationally-recognized definitions of food loss and waste (Xue et al., 2017; Pink, 2016). The United Nations Food & Agriculture Organization (FAO) Global Initiative on Food Loss and Waste Reduction provides a framework defining food loss and waste, from which we adopt working definitions (FAO, 2014). Herein, *food loss* encompasses any decrease in quantity or quality of food through the food supply chain, for any reason. *Food waste* is a subset of food loss, and consists of material intended for human consumption that is not consumed. FAO acknowledges that the threshold at which food loss becomes food waste is not sharply defined (FAO, 2014). Food loss and waste have traditionally been differentiated based on the level at which edible food was removed from the supply chain, with food losses occurring earlier in the supply chain and food waste occurring in later stages, where consumer behavior is a factor (e.g. Parfitt et al., 2010). However, the definitions have become more nuanced, such that the root causes and motivations of actors involved in food waste are now the factor differentiating food waste from food losses. In general, food waste occurs due to some mismanagement in the food supply chain or the conscious decision to dispose of edible items. Food waste is largely seen as preventable food loss. For example, food that spoils due to temperature mismanagement during storage, spoilage due to harvest or processing inefficiency, or consumers throwing edible food away fit the definition of food waste. In light of the ambiguity between food loss and food waste, the term *food loss and waste* has been widely used by management entities. From a quantitative mass perspective, food loss and waste is equivalent to food loss, since food waste is a subset of loss. However, food waste directs emphasis to the differential processes and conditions that cause preventable food waste versus non-preventable food loss. This becomes problematic, however, when discussing treatment of food that is wasted (i.e. FAO definition) or disposed because it is inedible (i.e. European Commission (EC) definition). Therefore, the literature generally discusses food loss and waste collectively because of the inability to, even conceptually, separate them once they are disposed (Chaboud, 2017).

2.2. Scale of the food waste problem

It is challenging to estimate the amount of food waste and its global variability; as discussed above, available data often do not permit strict calculation of food waste. Available evidence suggests that food loss and waste represent a considerable portion of the global food supply, roughly one-third of food produced globally by weight, or one of every four kilocalories produced (FAO, 2011). Silvennoinen et al. (2015) found that in the Finnish food service system, around 20% of food served is wasted just in the processes of preparation and handling. Betz et al. (2014) estimated that storage, preparation, and serving losses, combined with plate waste in Switzerland, totaled around 18% of food grown. In the

Table 1
Definitions of food waste (adapted from Thyberg and Tonjes, 2016).

Organization	Definition
Food and Agriculture Organization of the United Nations	Removal of food which is fit for consumption from the supply chain, or removal of food which has spoiled or expired due to economic behavior, poor stock management or neglect
European Commission	Food (including inedible parts) lost from the food supply chain, not including food diverted to material uses such as bio-based products, animal feed, or sent for redistribution
United States Environmental Protection Agency	Uneaten food and food preparation wastes from residences, commercial and institutional establishments
US Department of Agriculture	A subset of food losses; occurs when an item still edible at the time of disposal is not consumed
World Resources Institute	Food fit for human consumption that is discarded—either before or after it spoils; either the result of negligence or a conscious decision to throw food away

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United States, food waste generation is estimated at approximately 0.28 kg/person/day (Thyberg et al., 2015), or approximately 31% (by weight) of food available at retail and consumer levels (Buzby et al., 2014). This food waste estimate may be conservative, given that the study neglected food waste that occurs at the farm-to-retail level. However, even this conservative estimate of waste translates to over 130 billion pounds of food, valued at over $US160 billion dollars, and represents a loss of 1250 kcal/person/day out of available 3800 kcal/person/day available to Americans. Notably, the majority of food waste in the US (68%) occurs after consumers had purchased food from a retailer (Buzby et al., 2014). This pattern is consistent with global analyses indicating more absolute and per capita loss and waste in the developed world, especially by consumers, as compared to the developing world (Xue et al., 2017; Kummu et al., 2012; Lipinski et al., 2013; FAO, 2011). For instance, in 2009, food loss and waste in North America and Oceania was estimated as 1520 kcal/person/day (Lipinski et al., 2013), which encompasses an estimated 115 kg of food thrown away that year by each consumer (FAO, 2011). The same year in South and Southeast Asia, food loss and waste was estimated as 414 kcal/person/day, encompassing 11 kg of waste by each consumer (Lipinski et al., 2013; FAO, 2011).

3. Characterizing food waste within the Food-Energy-Water nexus: A proposed conceptual model

We propose a conceptual model (Fig. 1), in which food waste influences the FEW nexus via two interconnected mechanisms, both of which are driven by human behavior and decision making. In both production and waste management phases, food waste impacts to the FEW nexus are driven by individual consumer choices (Fig. 1, number 1) made during food purchasing, consumption and disposal, as well as collective decision-making at the societal level regarding methods of food production (Fig. 1, number 2) and food loss and waste management (Fig. 1, number 3) (e.g., landfilling versus anaerobic digestion). All food produced, whether consumed or wasted, demands resources including energy, water,

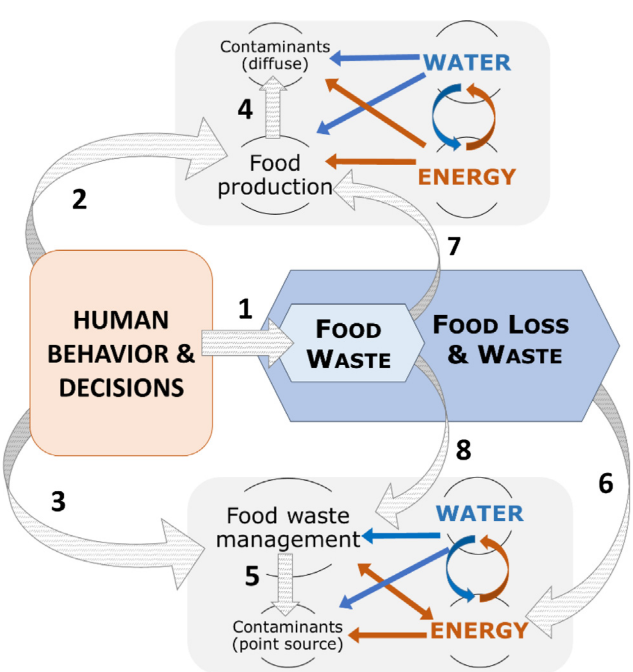

Fig. 1. Food loss and waste impact to the FEW nexus in food production and waste management phases.

fertilizers, herbicides/pesticides, land, and labor (Gustavsson et al., 2011). Water and energy are consumed directly in the production of food, for instance when water is withdrawn for irrigation, or when energy is used to transport irrigation water, process and ship food, or to create chemical fertilizers and pesticides/herbicides. Indirectly, water is contaminated by agricultural runoff (Fig. 1, number 4) (Ribaudo et al., 2011) or used in energy production (Lampert et al., 2016). Similarly, management of wasted food entails costs within energy and water sectors. Energy is consumed during food waste collection and transportation, and to treat or assimilate contaminated effluents generated during waste management (Fig. 1, number 5). Biogas produced by degradation or heat generated during combustion of food loss and waste are potential energy sources (Fig. 1, number 6). When less food is wasted, more food is available without the need for increased agricultural production (Fig. 1, number 7), and there is less food waste and food waste contamination to be managed (Fig. 1, number 8).

3.1. Current gaps in understanding the food waste FEW nexus

Our proposed framework isolates where understanding of the FEW system must be enhanced. Burgeoning awareness to future food and resource security has sparked an interest in characterizing the resources used in food production (Pelletier and Tyedmers, 2010). Resources dedicated to producing food have been well-documented in the literature and quantified over varied geographies and scales (Finley and Seiber, 2014). For instance, the per capita annual water footprint (i.e. sum of blue, green, grey water according to Hoekstra et al., 2009) of agricultural production in the United States is estimated at 2400 m^3 (Hoekstra and Mekonnen, 2012). Similarly, the energy resources dedicated to US food production have been estimated to range between 8 and 16% of annual energy consumption (Heller and Keoleian, 2000; Pimentel and Pimentel, 2003; Canning et al., 2010; Cuellar and Webber, 2010). The variability of water and energy footprints across specific agricultural products has been a subject of much analysis. Hoekstra (2008) estimated the water footprints of various vegetable and grain products to range from 0.06 to 0.9 m^3 per kg, while the water required to produce a single pound of conventionally-raised beef was estimated to be up to 10 m^3 (Mekonnen and Hoeksrta, 2010; Zonderland-Thomassen et al., 2014). On a caloric basis, calories produced per cubic meter of water range from 1000 to 7000 for corn, 500–2000 for rice, and 60–210 for beef (Molden, 2007). Energy costs of producing grain versus meat are likewise unbalanced, with meat, dairy and eggs consuming one to two orders of magnitude more energy per unit mass than vegetables and grains (Cuellar and Webber, 2010).

Resources used to produce the subset of food that is wasted have also received attention from the research community. Cuellar and Webber (2010) estimated that 2% of the energy consumed in the United States is dedicated to the production of wasted food. In a global-scale analysis, Kummu et al. (2012) estimated that 27 m^3 of water is used annually per capita in production of food that is wasted, while FAO (2013) estimated 162 m^3 water per capita. Water and energy associated with production of wasted food is thus relatively understood; by contrast, little is known about the FEW nexus impacts that are incurred after wasted food has been disposed (Fig. 1, number 8). In particular, few frameworks and little empirical data are available to estimate the comprehensive hydrologic impacts of wasted food. The few inquiries to wasted food and water (Kummu et al., 2012; FAO, 2013) have equated the hydrologic footprint of food waste with direct resource use in food production phases. Notably absent from prior study is an estimation of resource impact incurred in post-disposal phases. Hydrologic effects related to food waste management therefore represent a significant gap in the literature, and one

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that precludes the comprehensive understanding of FEW impact. Management of wasted food and related contaminants following disposal involves unknown quantities of water and energy, magnitudes of which perhaps vary widely depending on the waste management mechanism (Fig. 2) or boundary conditions (e.g. generation rate). Additionally, the potential for recycling food waste constituents to recover energy and nutrients creates potential for nonlinear relationships between fluxes of food waste, energy and water. Characterizing the complex problem of post-disposal FEW nexus impacts of wasted food, including descriptions of dynamic feedback behaviors, presents a significant research gap and a priority for future research (see Section 6).

4. Reducing food waste: A problem of human behavior with solutions in social policy

As discussed above, a large proportion of food waste in industrialized nations is generated by consumers (FAO, 2011; Lipinski et al., 2013; Buzby et al., 2014). Much social science research regarding food waste is thus centered on the drivers of consumer behavior (Thyberg and Tonjes, 2016). In past analyses, the vast quantities of food wasted in the United States have been regarded as just one more element of the modern "throwaway society," a culture of wastefulness spawned by rising affluence and a general indifference to larger issues of consumption, over-consumption, globalized capitalism, and environmental degradation. In the past few years, a substantial literature has emerged on personal, social, and demographic aspects of household food waste, containing useful empirical clues about how to change wasteful behaviors. One critically important theme is that food waste is the consequence of household food provisioning routines, contingencies that result from busy and hurried lives, social relationships and conventions that surround the traditions of the "family meal," and larger social aspects of contemporary food practice (Evans, 2012).

4.1. Root causes of food waste related to consumer behavior

Recent reviews (Pearson et al., 2013; Quested et al., 2013) enumerate nine "behavioral drivers" that result in household food waste. (1) Consumers are unaware or don't care. Studies show consistently that people are unaware of the impacts related to food waste (Neff et al., 2015) and are even unaware of how much food is wasted in their own households. In one large Australian survey (Pearson et al., 2013), fewer than one in ten felt that their house-

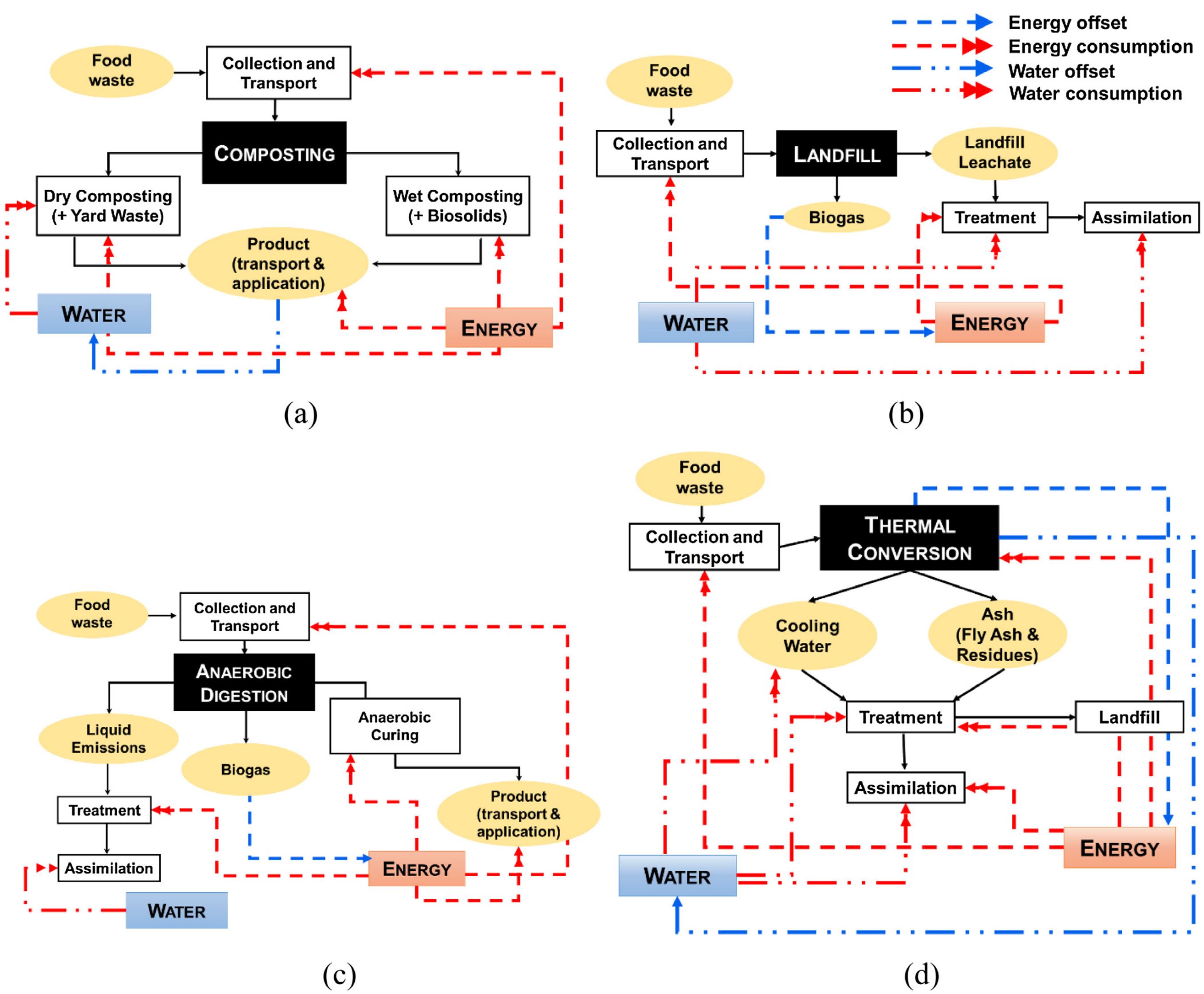

Fig. 2. Energy and water consumption and offsets associated with food waste management alternatives: (a) composting, (b) landfill, (c) anaerobic digestion, (d) thermal conversion (incineration).

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hold was "throwing away more food than they should." In contrast, Evans' (2012) ethnography reports numerous cases where families were quite aware of the amount of food they wasted, were obviously upset and even ashamed about their waste, but were largely powerless to do much about it. (2) Consumers can afford to waste. Another common finding is that affluent households waste more food than poorer households (Pearson et al., 2013), just as affluent nations waste more food per capita than poorer nations. This is evidently not the result of conscious decisions but rather a consequence of the lower marginal costs of food waste to an affluent versus a poorer family. At the same time, an in-depth review of efforts to reduce household food waste (Quested et al., 2013) concludes that the opportunity to save money was a more important motivating factor than any other in promoting less wasteful food practices.

(3) Consumers have high quality standards and (4) high sensitivity to food safety. Overly high standards in what one is prepared to eat is a contributing factor to high food waste. Studies show that "poor quality" or "it's gone off" are oft-cited reasons why food is discarded, even when it remains safe and edible. Studies also show that consumers are uncreative in their use of leftovers (Cappellini and Parsons, 2012; Rozin, 2014; Porpino, 2016). Psychologically, people look on leftovers as "used food" or somehow "contaminated." Watson and Meah (2013) also point out the cross-purposes of public policy in the food waste arena. On the one hand, people are urged to avoid food waste; on the other, they are urged to be cautious about "best by" dates and bacterial contamination.

(5) Insufficient purchase planning results in (6) buying too much food. If food waste is a problem, then the ultimate source of the problem must be that people buy more food than they need. Over-provisioning of the household is identified as a major problem in every study examined. Many foods with a shelf life of less than a week have a high probability of ending up as waste. Even when shopping from a list, consumers will be tempted by sales, Buy-One-Get-One (BOGO) deals, and related marketing practices and end up with food that will never be eaten. Furthermore, many people fail to check how much food is already on hand in the refrigerator or pantry before heading to the supermarket (Farr-Wharton et al., 2014). Dismissive moralizing about these wasteful shopping practices overlooks what Evans calls the "socio-temporal context of food practices," the everyday dilemmas of feeding a family. There is, Evans argues, a serious mismatch "between the rhythms of everyday life and the temporalities of food... Indeed, the materiality of food is unforgiving insofar as the temporalities of its decay render it unable to accommodate erratic work schedules. Viewed as such, for reasons that are fully understandable (being tired and hungry), food that is sitting in the fridge or cupboard requiring time and effort to cook gets displaced by food that does not. Consequently it goes uneaten within the timeframe required, decays and goes to waste."

(7) Deficient kitchen skills leads to (8) cooking too much. In addition to buying too much food, many households cook too much food, thereby generating leftovers that subsequently turn to waste. Part of this tendency is simple uncertainty about how much food to cook per person but another larger share is the cultural preference for sitting down to large meals where everyone gets to eat as much of everything as they desire.

(9) Consumers have a change of plans. Evans' (2012) make the essential point that "food waste results from households negotiating the complex and contradictory demands of everyday life". People may plan with the best of intentions but after a long hard day, the question becomes, what kind of meal can I get on the table in the next 30 min that everyone will eat? The hurried life-style of dual earner households virtually demands that some amount of food be wasted.

4.2. Action to prevent food waste

While the aforementioned behavioral drivers of consumer food waste are well documented, there is comparatively little empirical research that identifies factors that mitigate such food waste at the individual level of analysis (Graham-Rowe et al., 2014). Reducing food waste is often presented as a normative argument, for example the "ethical eating" movement and the more encompassing "alternative food movement" that promotes greater sensitivity to where food comes from, how it is produced, and the costs in labor, energy, water and money involved in its production (Adams and Raisborough, 2010; Johnston et al., 2011; Grauerholz and Owens, 2015). Extant research on reducing food waste by individuals is also prescriptive in nature, including the need for more education on planning and managing food purchases (Girotto et al., 2015).

On the supply chain side, much potential to avoid and minimize food waste may be realized by optimizing production and inventory management to a more comprehensive suite of processes and objectives, including but not limited to the current driver of market demand. Forecasting frameworks that adequately model the stochastic and deterministic aspects of the food production system (Muriana, 2017) are a promising strategy. Traceability throughout the supply chain and real-time information on quality allows for suitably targeting product destinations, for instance to an alternative market rather than disposal (Aiello et al., 2015a, 2015b). Such shelf life-based inventory management policies are associated with higher supply chain performance overall (Aiello et al., 2010). For instance, at the retail level, such information can enable understanding optimal times at which to reroute products near their expiration date from consumer to alternative human or animal uses (Muriana, 2016; Muriana, 2015; Aiello et al., 2014). However, in practice such fundamental change in operations strategy must be incentivized at the correct economic levels. Although reductions in food waste might be desirable from any number of perspectives, from household finances to environmental remediation, "in practice it is not attractive to the business objectives [of the food industry] or to the existing economic systems" (Grizzetti et al., 2013).

Local governments are a key governance component of the FEW system and an important institutional actor in minimizing food waste by individuals. Local governments can have a direct impact on the sustainable and efficient use of water and energy resources through their regulatory powers over land use, and through their allocation of resources for policy and programmatic initiatives. The promotion of urban agriculture strategies such as green roofs, farmers markets, small-scale farming, and food composting are examples of local policy responses to support "alternative food systems" that can potentially result in food waste reduction (APA, 2006; van Veenhuizen, 2006; Hodgson, 2012; Neuner et al., 2011). The high costs of food, greater control over materials used to grow food, the ability to convert under-utilized land into alternative and productive uses, and the sociological and community "bonding" impacts of producing food have spawned studies on small-scale decentralized community farms and land trusts. These and other local and regional policy responses accommodate consumer driven demand for access to locally produced food, generates environmental co-benefits by improving urban biodiversity, and provides economic benefits by reducing food transport and associated costs (Nugent, 1999; Norberg-Hodge et al., 2002). However, research to date is centered on the drivers of behavior in producing more food waste as opposed to the factors that lead to a reduction in food waste behaviors as a result of these and other policy tools (Graham-Rowe et al., 2014; Thyberg and Tonjes, 2016). The rising popularity of decentralized food systems provides one avenue for examining local policy interventions that can potentially lead to reduced food waste.

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Recent studies have attempted to unpack public attitudes toward energy, water and food in order to develop appropriate policy responses. The "nexus awareness" indices developed by Portney et al. (2017) suggest relatively high levels of awareness of the connections among water, energy, and food. People who report a high level of connection between these elements are also supportive of efforts to conserve and protect water and energy and of efforts to promote alternative energy sources. People tend to be less aware of connection between food and energy than connections between water and energy or water and food, and this lack of awareness of the food-energy nexus undercuts support for public policy efforts to affect this nexus. It should be noted that the policy initiatives described in Portney's analysis of the FEW nexus, including "charging higher licensing fees to restaurants that do not follow an approved plan to reduce food waste" are largely designed and implemented by local government entities.

5. Optimizing management of food loss and waste with respect to the FEW nexus

The resource impact of producing food, including wasted food, is substantial (Pelletier and Tyedmers, 2010); however, little is known about the energy and water consumed in managing food waste after it has been disposed. Food loss and waste is one of the largest components of the waste stream by weight in the United States, comprising over 14.5 percent of the total municipal solid waste (MSW) generated (US EPA, 2015). The primary mechanism for managing post-consumer food waste in the Unites States is currently landfill disposal. Estimates of the portion of food waste sent to landfills in the United States vary from 54% to 97% (Levis et al., 2010; USEPA, 2015). Alternatives to landfilling are increasingly promoted to reduce carbon footprints and provide other environmental benefits (Herva and Roca, 2013). However, alternative technologies currently comprise a small fraction of total food waste managed in the United States. For instance, less than 3% of food waste is recovered through composting (US EPA, 2014) and approximately 2.1% of food waste is processed by anaerobic digestion (EREF, 2015). Recovery and recycling are challenged primarily by insufficient capacity of alternative treatment infrastructure and difficulty in separating food waste from the waste stream (Guerrero et al., 2013; Edwards et al., 2016).

Diversion of food waste from landfills to alternative waste management options may be both economically and environmentally justified if the adoption of alternative technologies creates benefits to water and energy sectors. However, little quantitative information is available to compare waste management alternatives with regard to FEW impact, particularly with regard to water and coupled water-energy interactions. While past research has characterized various food waste management alternatives with respect to energy consumption (Eriksson and Spangberg, 2017), pollutant discharges (Levis and Barlaz, 2011), and greenhouse gas emissions (Ebner et al., 2014; Thyberg and Tonjes, 2017), such analyses within a FEW framework has not been undertaken. The following section characterizes treatment options for food loss and waste with respect to potential FEW nexus impact (Fig. 2, Table 2).

5.1. Landfilling

Carbon and nutrients entering landfills as food waste result in gaseous (NH_3, CO_2, CH_4) and liquid emissions (leachate) or are

Table 2
Example FEW nexus implications of food waste prevention and management.*

Management approach	WATER		ENERGY	
	Consumption	Offsets	Consumption	Offsets
Waste prevention	None	Avoided crop irrigation Avoided waste collection	None	Avoided fertilizer application Avoided waste collection Reduced food transport
Composting	Addition of moisture during processing	Improved soil moisture retention; avoided fertilizer application	Collection of waste (centralized); composting operations, including mixing and aeration	Avoided fertilizer application
Anaerobic digestion	Treatment of supernatant and liquid extracted during dewatering	Improved soil moisture retention	Collection of waste; mixing of waste and other operations Temperature control	Biogas produced** Avoided fertilizer application
Incineration	Ash quenching Cooling water Air pollution control	Recovery of evaporated water	Collection of waste; latent heat of evaporation demand; parasitic consumption during air pollution control; incinerator operations	Heat produced**
Thermal conversion (gasification, hydrothermal conversion)	Assimilation of liquid waste	Recovery of evaporated water	Collection of waste Thermal conversion operations Liquid waste treatment	Fuel produced** Feedstock for chemicals, offset fossil-fuel derived chemicals C sequestration; avoided drying
Landfilling	Assimilation of leachate Bioreactor landfill moisture requirement	On-site leachate irrigation and dust suppression	Collection of waste; landfill operations; transport and treatment of leachate	Biogas produced** C sequestration
In-Sink Food disposal	Grinding and flushing Assimilation	None	Grinding Transport and treatment at WWTP	Avoided waste collection
Drying for animal feed	Cleaning of equipment	Recovery of evaporated water	Collection of waste; heating; latent heat of evaporation demand	Avoided fertilizer application for animal feed production
Co-Digestion at WWTP	Assimilation of supernatant and fluid from dewatering	Improved soil moisture retention when residuals applied	Collection of waste; mixing of waste; treatment of supernatant and fluid from dewatering	Biofuel produced**; nutrient recovery Enhanced methane generation over dedicated AD; Reduced fertilizer application
Biovalorization	Wastewater assimilation Waste pretreatment	Water recovered through evaporation	Manufacturing operations Collection of waste	Avoided fossil fuel based chemicals Direct burning of reject biomass

* Excludes FEW implications of facility construction.
** Benefit declines as offset renewables increase.

stored within the landfill. Energy is consumed in collection of waste and transport to the landfill, transport of leachate to off-site treatment facilities, and in treating leachate to regulatory discharge standards (Fig. 2b). Following discharge, contaminant concentrations, which may exceed local ambient water quality standards for surface or groundwater, must be returned within ambient environmental standards by dilution with large volumes of water (grey water footprint). During anaerobic degradation of food waste in a landfill, complex organic materials (carbohydrates, lipids, proteins) are hydrolyzed to soluble products and ultimately to methane and carbon dioxide through methanogenesis. If the produced methane is collected, it is typically stored and used onsite or injected directly into natural gas pipelines, contributing benefits to the energy sector (Fig. 2b). Some fractions in food waste (lignin and lignocellulosic material) are largely recalcitrant under anaerobic conditions. Therefore, without pretreatment, these fractions may inhibit cellulose bioavailability, resulting in low methane yield (Eleazer et al., 1997). Amini and Reinhart (2011) have shown that diversion of food waste from landfills could result in 9% decrease in methane generation, while only a 1% decline in energy production potential due to the difficulty in capturing methane from the rapidly degrading labile fractions of food waste. Therefore, landfilling is perhaps not the optimum mechanism to exploit biogas production by food waste (Thyberg and Tonjes, 2017).

5.2. Composting

Composting involves the aerobic degradation of organic wastes. Under aerobic conditions, organic materials are converted to carbon dioxide, ammonia-nitrogen, or complex recalcitrant materials often referred to as humic substances. As composting often requires the addition of moisture during processing, water consumption may be a considerable factor in this process (Fig. 2a). Energy is required for operations, including mixing and aeration. Compost can be used as a soil amendment, which sequesters carbon (Hansen et al., 2016), offsets production and use of chemical fertilizers, and enhances soil moisture retention (Doan et al., 2015) reducing irrigation requirements. Composting also produces significantly fewer greenhouse gas emissions and less leachate than landfilling (Adhikari et al., 2009; Saer et al., 2013; Zhao and Deng, 2014), and thus should incur fewer impacts on receiving water bodies. Despite the potential for resource recovery through composting, food waste composting sites comprise less than 10% of all composting facilities in the United States (Platt and Goldstein, 2014).

5.3. Waste-to-energy and waste-to-chemicals

5.3.1. Anaerobic digestion

While still in its infancy in the United States, interest in anaerobic digestion (AD) of organic fractions of waste, including food waste, is increasing and is widely practiced in the European Union (EREF, 2015). The AD process begins with hydrolysis of complex organic polymers to simple soluble molecules, followed by fermentation to a mixture of short chain volatile fatty acids (VFAs) and further conversion of these organic acids to acetate, eventually resulting in methane production. Food wastes contain high quantities of biodegradable organic matter, which are easily converted to VFAs in the AD process, producing usable fuel. Mechanisms of organic degradation in AD are similar to landfills, however, the increased ability to control the AD treatment process results in greater gas yields and collection efficiencies, as well as shorter reaction times (EREF, 2015; Fig. 2c). Energy is consumed in AD through operations and temperature control. Most anaerobic bacteria used in the fermentation stage require mesophilic (30–40 °C) or thermophilic (50–60 °C) conditions, and the performance of AD improves with increasing temperature (Sanchez et al., 2001). While food wastes often have a greater moisture content than other waste fractions, they still are difficult to pump and mix within reactors, requiring energy. Increasingly, "dry" AD systems are being implemented which require little or no added moisture and utilize conveyors or mechanized loaders to move materials. The inability to thoroughly mix the contents of dry AD systems may result in lower gas yields than wet AD.

During AD, liquid/solid separation occurs, producing contaminated liquid emissions which must be treated and discharged with potential impact on receiving waters (Fig. 2c), although the potential exists to recover nutrients (primarily nitrogen and phosphorus). The volume of liquid emissions from dry AD (supernatant and dewatering) is much lower than from wet AD. An emerging trend in AD is to co-treat food waste with organic waste in wastewater treatment plants or in farm-based anaerobic digesters where excess capacity is available. Food waste has approximately three times the methane production potential of municipal biosolids (US EPA, 2014) and therefore, its co-digestion can significantly increase energy production in treatment facilities. In 2013, over 150 facilities in the United States were identified as providing co-digestion of food wastes (Koch et al., 2015; Monino et al., 2016). Co-digestion has multiple advantages, including improved methane generation, reduced toxicity potential, and stabilized digestate. Because of synergies of co-treatment, the impacts of reject liquids are reduced, while energy offset potential is enhanced from recovered biogas. In all forms of AD, solid residuals can be applied as compost, providing similar offsets as those described for composting.

5.3.2. Thermal conversion

Due to the typically high moisture content of food waste, combustion is energy-intensive (Fig. 2d). Food waste is therefore traditionally combusted as a part of the MSW stream, where energy for evaporation is provided by other combustible waste materials. Incineration produces heat that can be converted into electricity. Produced ash (incombustible waste and air pollution control residuals) is often landfilled, but has some potential for reuse in construction and concrete. In addition to energy for evaporative demand, FEW impacts of incineration include water and energy needed for ash quenching and cooling as well as air pollution control (Fig. 2d). Ash products of thermal conversion can be used as feedstock for agricultural production (Zhang et al., 2002) or building materials (Arena, 2015), which would offset energy and water required for manufacturing. In addition, incineration generally has a large carbon footprint due to the combustion of plastics which produces CO_2 (Jeswani et al., 2013).

Alternative thermal conversion processes, such as pyrolysis and gasification, may be used to produce syngas and char from organic wastes. Syngas can be used as an alternative to fossil fuels, for instance as fuel, or feedstock for chemicals. Char can be used as a fuel or as soil amendment, resulting in carbon sequestration or moisture retention. Hydrothermal carbonization (HTC) has been promoted as an alternative to food waste incineration, primarily because CO_2-equivalent emissions of HTC may be lower than landfilling, composting, and incineration (Berge et al., 2011; Lu et al., 2012). HTC thermal conversion is a wet and relatively low temperature (180–350 °C) process, which converts biomass to a carbonaceous residue. HTC treatment techniques may be particularly applicable to food waste with high moisture content, resulting in the production of hydrochar with high carbon and energy content (Girotto et al., 2015). The product can be applied as feedstock for carbon fuel cells (Paraknowitsch et al., 2009) or used as a soil amendment (Abel et al., 2013). Water is often added to food waste in the HTC process, and energy is needed for temperature control

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(Erlach et al., 2012). In return, the solid product has a high calorific value that makes it favorable for combustion, pyrolysis, and gasification (Chang et al., 2013; Tremel et al., 2013).

5.3.3. Conversion to renewable chemicals and biofuels

As food waste is comprised of significant quantities of functionalized molecules including carbohydrates, proteins, triglycerides and fatty acids (Lin et al., 2013), it is perhaps a beneficial alternative for developing valorization practices such as chemical production feedstock, cosmetics, pharmceuticals, animal feed, and prebiotics (Ong et al., 2017). As opposed to food itself being cultivated for biofuels (e.g. corn, sugarcane), using food waste to produce these value-added products does not compete with food grown for human consumption and has much lower land requirements. Food waste can serve as a microbial feedstock for a variety of biofuel processes to produce hydrogen (Han and Shin, 2004), methane (Zhang et al., 2007), ethanol (Yan et al., 2011) and biodiesel (Canakci, 2007). Food waste can also serve as a feedstock for chemical products such as furfural, volatile fatty acids, citrus derivatives, and alcohols all of which are precursors to household, specialty, and commodity chemicals (Lin et al., 2013). Food waste is an inexpensive feedstock, however pretreatment such as acidification or heating, is necessary to convert lignocellulosic waste to fermentable sugars, a necessary step to produce ethanol and other chemicals. In addition to pretreatment requirements, any organisms that compete for hydrogen, such as methanogens, which use hydrogen as the reducing agent (Hawkes et al., 2002) must be avoided. All processes are challenged by high capital costs and high energy requirements. Further research is necessary to explore approaches to utilize food waste via chemical/biofuel pathways.

6. Food waste and the FEW Nexus: A “food-waste-systems approach

In addition to relevant institutions, infrastructure and technologies created to address critical problems related to food waste, the effectiveness of policies depend on choices made by individual consumers, and collective investments made by society. Hence, the integration of human/behavioral dimensions with the technical considerations of the FEW waste management system require understanding of the coupled socio-technical systems underlying the food waste-FEW nexus. To this end, we propose adoption of a “food-waste-systems” approach to maximize benefits across food, energy, and water sectors. From a systems perspective, complex systems such as the food waste-FEW nexus should be treated as a whole structure (Davies and Simonovic, 2008). We therefore propose that a holistic modeling approach, perhaps based on our proposed conceptual model of the food waste-FEW system, is required to observe and analyze the system as a whole. A critical element to developing this system will involve describing and quantitatively characterizing the complex feedback mechanisms that exist between human and technical variables.

Within a coupled model, we recognize the differential FEW nexus effects possible from action to (1) prevent food waste and (2) manage wastes more efficiently with respect to FEW. Regarding food waste prevention, there is perhaps a direct positive feedback between the proportion of food that is wasted and demand for food production (Fig. 1, 7). Reducing the amount of food that is wasted should reduce demand for food production (though perhaps not linearly), thereby decreasing absolute demands for water and energy in the production phase. While there is perhaps potential to substantially reduce the amount of food that is wasted, for instance by enacting targeted social, behavioral, and policy mechanisms (Section 4), society will always produce some amount of food loss and waste, as well as non-food organics, which must be managed. One may visualize a theoretical minimum quantity of food loss and waste that no amount of technology or attention to consumer behavior may effectively reduce. Like preventable food waste, the unpreventable food loss and waste stream affects water and energy sectors. However, the dynamic feedback that exists between preventable food waste and food production (Fig. 1, number 7) is less strongly coupled to unpreventable loss and waste. As an example, while demand for food production will grow as more food is wasted, the baseline minimum of unpreventable food loss and waste should be a relatively static portion of food produced and thus have little effect to demand. The primary mechanism for unpreventable food loss and waste to affect the FEW nexus is therefore by impact in the post-disposal phase. In this phase, societal decision-making with regard to unpreventable food loss and waste management will determine the cost or opportunity to energy and water sectors. For example, Kiran et al. (2014) estimated that 1.32×10^9 m^3 of methane could be produced annually from global food loss and waste, with an energy potential of 2.6×10^7 GJ. Due to such contrasting feedbacks within the FEW nexus and potentially divergent responses to drivers such as human behavior, it is reasonable to consider the role of preventable food waste separately from that of unpreventable food loss, and to devise solutions that both prevent food waste and manage unpreventable wastes using FEW-efficient technologies. How best to simultaneously broach both fronts is a subject in need of targeted interdisciplinary research and advanced systems modeling. Herein, we develop a set of research priorities and specific questions related to factors that we expect, based on our conceptual model of the food waste-FEW nexus system, to have measurable effect to FEW impacts of food waste.

Priority 1- Public policy and the behavior of individuals: understand linkages between impact awareness and consumer behavior

1. Does increasing public awareness of the FEW nexus lead to lower food waste generation rates and changes in remaining waste characteristics?
2. Do educational modules incorporating FEW data improve the effectiveness of food waste education?
3. Do programmatic initiatives that focus on values and skills of consumers lead to a reduction in food waste?

Priority 2- Food waste management technological solutions: understand comprehensive FEW impacts of food waste

1. How much water/energy is used to manage food waste?
2. How do quantities of water/energy vary across waste management technologies?
3. How does water/energy impact of food waste management compare with magnitudes of water/energy used in food production?
4. How can non-consumptive uses of water in waste management (e.g. grey water) be compared to consumptive water use (e.g. green, blue water) in food production?

Priority 3- Operationalize the food waste-FEW systems nexus through integrative systems modeling: understand system feedbacks between food waste generation and FEW impact

1. What are the feedback mechanisms between variables of the food waste-FEW system that drive food waste generation and FEW impact?
2. What are the rebound effects, if any, of preventive food waste management efforts (e.g. energy and water savings, reduction in demand for food production)?

3. What are possible policies related to food waste reduction which can increase the resilience of the FEW systems? How do these policies affect dynamics of FEW impact?

7. Conclusions

Herein we reviewed and conceptualized the problem of food waste within the framework of the FEW nexus, and proposed a conceptual model outlining the comprehensive impact of food waste within the FEW nexus. Our proposed model incorporates impacts incurred during production of uneaten food and in managing food waste post-disposal. We find that while FEW impacts of producing wasted food have been preliminarily described, little is known about the energy and water consumed in managing food waste after disposal, or how FEW impact may vary across waste management technologies. In particular, hydrologic effects related to food waste management represent a significant gap in the literature, and one that precludes the comprehensive understanding of FEW impact. In addition to providing a full quantitative portrayal of food waste within the FEW nexus, better understanding of variability among potential waste management options can support planning and waste management decisions at community or higher levels. In much the way that individual behaviors, for instance the desire to trend diets away from high-impact products, such as beef, have been shaped by understanding the water, energy, climate and land implications of food systems, decisions regarding waste management may also benefit from similar information. We have begun to fill this knowledge gap with discussion and conceptual mapping of FEW impacts related to several food waste management options. However, we suggest that the ultimate goal should be quantitative operationalization of a food waste-FEW systems approach, for use in answering basic research questions and eventual decision making.

Based upon our model, we propose that FEW impact management requires targeted action geared to two separate, yet interconnected fronts: (1) reduced proportion of produced food that is wasted, and (2) calculated management of unpreventable food loss and waste. Efforts to achieve results on both fronts will necessitate action at different levels, involving varied mechanisms and actors. For instance, programs targeted to individual behaviors embedded within multi-level governance may be most effective at reducing the amount of food that is wasted. By contrast, action on FEW-optimized waste management will require decision making and investments on a collective societal level, requiring political will from leaders as well as buy-in from civil society. To provide the information necessary for such decisions, we highlight the following priorities for targeted interdisciplinary research and advanced systems modeling: understand linkages between impact awareness and consumer behavior, quantify comprehensive FEW impacts of food waste across varied management systems, and characterize feedbacks between food waste generation and FEW impact.

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