Community-based food waste modeling and planning framework for urban regions

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Abstract
Food waste management (FWM) is a growing challenge in urban regions. Despite increasing concerns about the ensuing environmental pressure, economic inefficiency, and social disparity, quantitative studies of FWM are still limited. This study proposes a scalable model of food waste generation and community-based planning framework that aims to provide data references and policy strategies that help transform urban challenges of FWM into opportunities. In contrast to the existing tools and programs that only focus on large generators (e.g., supermarkets), this study proposes an inclusive approach that also includes small generators (e.g., convenience stores and restaurants) and pairs food waste generators with local users for food reuse and recovery. The generic model was implemented in a case study in Chicago, where residents were found to generate nearly twice as much food waste as businesses on an annual basis. The Chicago case study also demonstrates the spatial mismatch between food waste generators and potential users, suggesting the need of system-wide coordination and planning as well as the inventory modeling at the community level.

Keywords
Food Waste; Material Flow Analysis; Sustainable Communities; Urban Sustainability; Waste Management

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Note
One tonne is equivalent to 1,000 kilograms, or 1.102 short tons (as commonly used in the U.S.).

Introduction
Urban food system planning has drawn increasing attention from researchers, policy-makers, and the public. One in seven people in the U.S., or about 42 million Americans, are food insecure (Feeding America, 2017). Meanwhile, 47.5 million tonnes of food, most of which are actually edible, are discarded each year and end up in landfills (Hoover, 2017; U.S. EPA, 2016a). Only 5% of discarded food is composted and just 1% is reused for human consumption (U.S. EPA, 2016a, 2016b). Disposing food discards in landfills not only constitutes an environmental burden, but also limits the recycling of nutrients, such as phosphorous, which is essential for food production and human growth but only exists in finite amounts on Earth (Abdulla, Martin, Gooch, & Jovel, 2016; Baccini & Brunner, 2012; Cordell, Drangert, & White, 2009; Elser & Bennett, 2011).

The hierarchy of food waste management (FWM) suggests that priority should be given to waste management options with higher-end values in the order of source reduction, human consumption, animal feed, industrial uses, and composting (U.S. EPA, 2012b). Preferable end products can include recovered food for human use, animal feed, soil amendments from composting, and bio-fuel from anaerobic digestion (Girotto, Alibardi, & Cossu, 2015; Levkoe & Wakefield, 2011; Thyberg & Tonjes, 2016; U.S. EPA, 2012a). Landfilling is the least preferable solution and yet the most commonly employed (U.S. EPA, 2012b).

Existing practices of FWM clearly contribute to economic inefficiency, environmental pressure, and social disparity along the food value chain (Miller et al., 2016). From the perspective of policy making and infrastructure planning, sustainable FWM faces several major barriers. Essentially, uncertainties in food discard volume and quality, in addition to compliance with perceived food safety and public health regulations, contribute to the high cost of planning, handling, and recovery. In addition, emerging FWM regulations and tools have only focused on large generators, such as manufacturers and wholesalers. Small-scale generators (e.g., residents and restaurants), while making up 84% of total food waste disposal in the U.S. (Business for Social Responsibility [BSR], 2013), are largely unregulated.

Another important gap is the connections between food waste generation and food scrap uses. Composting is often the sole focus of existing food waste diversion programs, but in many cases zoning restrictions and inadequate infrastructure do not support composting activities. Therefore, food waste is co-mingled with other types of municipal solid waste (MSW) and sent to large, remote disposal facilities. As for the strategy of recovering food for the highest potential (i.e., human consumption), a growing number of companies and organizations, such as Feeding America, Spoiler Alert, Zero Percent, Copia (formerly Feeding Forward), Community Plates, and Food Cowboy, have launched programs and technology platforms over the past few years that connect the sellers or donors of surplus food with local partners and food banks. However, the scale of these program remains small; further, citywide or centralized systems that match the excess food with potential uses are lacking. Given the uncertainties about the volume of surplus food at individual locations, decentralized operations present challenges for inefficiencies in collection, drop-off, delivery trips, and, potentially, the reliability and long-term viability of program implementation.

Such challenges in urban areas can be particularly significant given the high density of urban development and large volume of food generation. What is underappreciated, however, is the advantages of density and diversity in urban regions that may help transform these challenges into opportunities in terms of FWM (Figure 1). For example, the prospect of economies of scale in food scrap collection can lead to cost savings. Additionally, urban areas with extensive and diverse businesses (e.g., restaurants, shops, medical centers, and universities) have significant opportunities for alternative FWM strategies (Brinkley, Birch, & Keating, 2016; Evans-Cowley & Arroyo-Rodríguez, 2016; Schupp, Getts, & Otten, 2018). Recovering, recirculating, and reusing waste discards can create new job opportunities and foster community

Figure 1. Challenges and Opportunities of Food Waste Management (FWM)
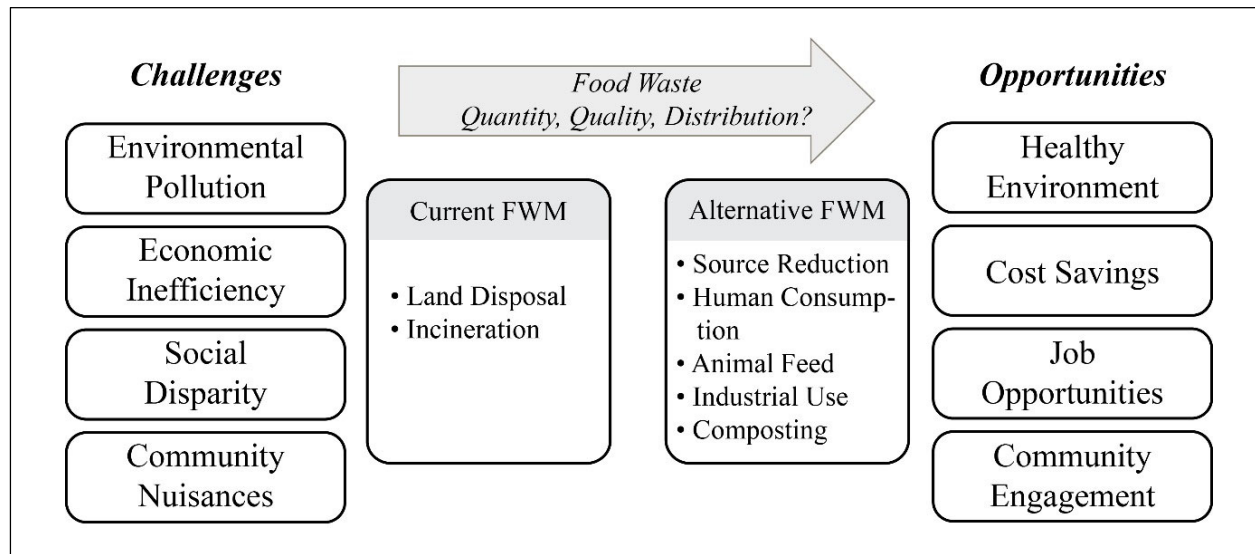
engagement while achieving environmental benefits (Ai & Leigh, 2017).

Our study directly addresses the unique challenges and opportunities of urban FWM by focusing on four research objectives. First, we aim to develop a generic FWM model that can be adapted to various regions by incorporating community-specific characteristics, such as mixed types of waste generators, demographics, and existing infrastructure related to food donation and landfill diversion. We believe that better measurement of food waste leads to better design of FWM policies and a better understanding that "one size cannot fit all." Instead of referring to the national or state-level average when there are waste data constraints, we aim to demonstrate the opportunities for refining food waste estimates and developing place-based strategies. Second, we aim to capture small waste generators in both food waste volume (FWV) estimates and policy design to facilitate their involvement in food recovery programs that are commonly hindered by data constraints and concerns about economies of scale. Third, we aim to foster local alliances and develop community-based solutions for connecting food waste generators and potential users. Beyond the decentralized programs and platforms discussed above, we aim to provide spatial reference to facilitate system-wide planning and to improve the efficiency of

food recovery and recycling. Fourth, and broadly speaking, we aim to add empirical reference to community-based and life-cycle approaches to FWM that are intrinsically connected to food system planning, The following sections in this paper will review the relevant literature, discuss our scalable FWM model for local planning, and provide a case illustration in Chicago.

It is important to note that the scope of this study is largely limited to food discarded by residential, commercial, and institutional sectors. The industrial and wholesale sectors are excluded mainly for two reasons. First, industrial waste is regulated and managed differently from MSW. Its waste planning and collection processes are different; most food producers and wholesalers have established their own logistics chains that include waste management. Second, to reduce landfill disposal costs, the diversion rate of food residuals in industrial sectors is much higher than in other sectors (BSR, 2012). It is the non-industrial sectors that present the highest potential of landfill diversion and thus are focus of this study.

Review of Existing Studies on Food Waste Volume Estimates

The most fundamental information about food waste, including generation quantity (e.g., weights or bulks), quality (e.g., spoiled or recoverable),

composition (e.g., water content, energy intensity, and perishable ingredients), and spatial location, is not commonly collected at the source. Consequently, FWV is often estimated using parameters from periodic, small-sample surveys. The U.S. Environmental Protection Agency (U.S. EPA) estimated the national aggregated food waste generation from households and businesses based on a range of survey results from individual states (U.S. EPA, 2014a, 2014b, 2016b). The estimates by Business for Social Responsibility (BSR), a non-profit organization, also included industries and their recycled food waste before final user consumption (BSR, 2012, 2013, 2014). However, these aggregated data have limited ability to provide local references (e.g., for a city or community) due to heterogeneous conditions. Although MSW characterization studies in some regions include waste audit data for FWV (e.g., CDM, 2010b; IWMB, 2009), inconsistencies in waste definitions, performance indicators (e.g., recycling, recovery, and diversion), and measurement metrics (e.g., per capita or per employee) present a challenge for comparative studies and prevent direct references across jurisdictions. This section reviews these discrepancies as well as common approaches to FWV estimates in a wide range of surveys, numerical studies, and applied tools.

Definition of Food Waste

Several terms have been adopted in the context of food waste studies, such as food loss, food scraps, and food discards. While these terms are used interchangeably at times, distinctions have been made, particularly between "food loss" and "food waste." Food loss refers to unconsumed, edible food lost throughout the food supply chain, including production, handling, storage, processing, packaging, distribution, and consumption (Buzby, Farah-Wells, & Hyman, 2014). Food waste, when narrowly defined, refers to the food loss in the distribution and consumption stages, such as leftover discards by consumers and commodity discards by retailers due to undesirable looks or expiration (BSR, 2012, 2013; FAO, 2013; WRAP, 2013). In other words, food waste approximates to food discards and is only part of food loss.

Food waste and food loss can also be measured differently. For example, the U.S. Department of Agriculture (USDA) estimates food loss by focusing on the supply data, or so-called Loss-Adjusted Food Availability (LAFA). For food waste or discards, the U.S. EPA and other organizations (e.g., BSR and ReFED) focus on the consumption side and adopt sectoral adjusted generation factors that are inferred from waste characterization studies.

Another relevant term is "recoverable" food, which we refer to as food discards and surpluses that are still suitable and safe for human consumption. We differentiate recoverable food in our study because it highlights potential opportunities for strategic FWM to achieve even greater benefits than composting and other methods along the FWM hierarchy.

Food Waste Generation and Diversion Rates

As waste auditing is costly and is not required, local FWV often needs to be estimated assuming a uniform generation rate per person, per meal served, per employee, per square footage of the establishment, or simply for each average-sized establishment in a specific sector. Table 1 summarizes the reported food waste generation, landfill diversion, and disposal rates in the existing literature by generator type (i.e., residential, commercial, and institutional) in various regions.

Residential FWV is typically estimated on a per-capita or per-household basis, although anecdotal studies suggest that the generation rate does vary by demographic characteristics. For example, studies have found that Hispanic households have lower rates than non-Hispanics; lower income households have lower rates than higher income households (Jones, 2004). Younger people and families with children under 18 reported more food discards (Neff, Spiker, & Truant, 2015). Household size can matter as well; the waste characterization study in Chicago found that a single-family household on average almost doubled the FWV of a multifamily household (CDM, 2010b).

Commercial FWV can be estimated on the basis of employment, establishment size, food products, or sale values (BSR, 2013, 2014; Gustavsson, Cederberg, Sonesson, Otterdijk, &

Table 1. Review on Food Waste Parameters by Generator Type

Generator Type	Generation Rate (Per Unit-Year)	Diversion (DIV), Donation (DON), and/or Recycling (REC) Rates (% or Per Unit-Year)	Disposal Rate (Per Unit-Year)
Commercial			
Supermarket/ Grocery Store/ Food Store	**Employee:** 1,360 kg (DLI, 2002; Mercer, 2013; ReFED, 2016); 240 kg for Retail, and 2,100 kg for Food Store (CCG, 2006); 454 kg for Supercenter, and 10 Tonnes for Wholesale (ReFED, 2016)	DIV 0.5% (11 kg) for Retail, and DIV 35.2% (740 kg) for Food Store (CCG, 2006); DON 17-35% for Grocery Retail, and DIV 42% for Wholesale (ReFED, 2016)	1,360 kg (CCG, 2006)
	Store: 20 Tonnes (Jones, 2004); 40 Tonnes (Griffin, Sobal, & Lyson, 2008); 35-92 Tonnes (Mercer, 2013); 54-490 Tonnes (U.S. EPA, 2009)	DON 26.3% and REC 58.9% (Griffin et al., 2008); DIV 78 Tonnes (LASAN, 2013)	6 Tonnes (Griffin et al., 2008)
	Other: 4.53 kg/Thousand-Dollar-Sales (BSR, 2014); 1.1-3.4 Tonnes/Thousand m² for Shopping Mall (CCG, 2006)	DIV 10-80%, DON 13.2%, and REC 29.3% (BSR 2014); DIV 0-0.2% (CCG, 2006)	
Convenience Store/Small Grocery Store	**Store:** 8,600 kg (Jones, 2004)		621 kg for Convenience Store and 1,539 kg for Small Grocery Store (Griffin et al., 2008)
Lodging and Hotels	**Employee:** 680 kg (Mercer, 2013; ReFED, 2016); 900 kg (CCG, 2006)	DIV 35.2% (CCG, 2006); REC 70-80% (CalRecycle, 2015; LASAN, 2013)	645 kg (CCG, 2006)
	Store: 51 Tonnes (Mercer, 2013; ReFED, 2016); 109-327 Tonnes (U.S. EPA, 2009)	163-218 Tonnes (CalRecycle, 2015; LASAN, 2013)	4 Tonnes (Griffin et al., 2008)
	Other: 0.45-0.68 kg/Meal (U.S. EPA, 2009); 156 kg/Guest-Year (DLI, 2002)		
Special Event	**Visitor-Day:** 0.18-0.20 kg (CCG, 2006; DLI, 2002) **Other:** 0.45 kg/Meal or 0.27 kg/Seat-Day (DLI, 2002, RecyclingWorks, 2015)	DIV 1.7 % (CCG, 2006) DIV 90% (NERC, 2010)	
Full Service Restaurant	**Store:** 5,521 Kg (Griffin et al., 2008); 11-34 Tonnes (EFWN, 2011); 15-30 Tonnes (Mercer, 2013); 23 Tonnes (Jones, 2004); 54-218 Tonnes (U.S. EPA, 2009)	DON 0.32% (Griffin et al., 2008); REC 33 Tonnes (LASAN, 2013)	5,500 Kg (Griffin et al., 2008)
	Other: 0.22-0.68 Kg/Meal (DLI, 2002; Mercer, 2013; ReFED, 2016; U.S. EPA, 2009); 15 Kg/Thousand-Dollar (BSR, 2014)	DIV 10-60%, DON 1.4%, and REC 14.3% (BSR, 2014)	
Quick Service Restaurant/ Cafeteria/ Catering Halls	**Employee:** 1,000 Kg (Mercer, 2013; ReFED, 2016); 1,130 Kg (CCG, 2006);	DIV 13.5% (CCG, 2006)	994 Kg (CCG, 2006)
	Store: 12-18 Tonnes (ReFED, 2016); 69 Tonnes (Jones, 2004); 87-326 Tonnes (U.S. EPA, 2009);		6-7 Tonnes (Griffin et al., 2008)
Large/Corporate Offices	**Store:** 87-152 Tonnes (U.S. EPA, 2009) **Other:** 0.22-0.34 Kg/Meal (U.S. EPA, 2009); 1,668 Kg/ Thousand m² (CCG, 2006)		

continued

Table 1. Review on Food Waste Parameters by Generator Type *(continued)*

Generator Type	Generation Rate (Per Unit-Year)	Diversion (DIV), Donation (DON), and/or Recycling (REC) Rates (% or Per Unit-Year)	Disposal Rate (Per Unit-Year)
Residential			
	Household: 212 Kg (Jones, 2004); 215 Kg (U.S. EPA, 2009); 143 Kg for Multi-Family, and 298 Kg for Single-Family (CDM, 2010b)	REC 41-93 Kg or from 2-5% to 36-46 % (KCI, 2012); REC 46-80 Kg (DSNY, 2015a, 2015b); REC 165-220 Kg (Freeman & Skumatz, 2010)	
	Person: 52 Kg (Griffin et al., 2008); 59 Kg (U.S. EPA, 2014a); 109 Kg (Jones, 2004)	REC 2.4% (Griffin et al., 2008)	
Institutional			
Overall	**Store:** 54-327 Tonnes (U.S. EPA, 2009) **Other:** 0.34-0.45 Kg/Meal (U.S. EPA, 2009)		
Elementary and Secondary Schools	**Student:** 11 Kg (Mercer, 2013); 41 kg (DLI, 2002; Griffin et al., 2008; RecyclingWorks, 2015) **Employee:** 254 Kg (ReFED, 2016; Smith, Shiralipour, & Kessler, 1998) **Other:** 0.23 Kg/Meal (DLI, 2002, Griffin et al., 2008); 0.10 (Off-site) to 0.25 (On-site) Kg/Meal (SERA, 2014)	REC 10-25 Tonnes/School (CalRecycle, 2015; LASAN, 2013; SFRP, 2000) REC from 18%-47% to 56%-75% (DSNY, 2015a, 2015b)	
Colleges and Universities	**Student:** 17-64 Kg (RecyclingWorks, 2015); 34-59 Kg (Griffin et al., 2008) **Employee:** 708 Kg (CCG, 2006) **Other:** 0.16 Kg/Meal (DLI, 2002; RecyclingWorks, 2015)	DON 0.5% and REC 22%-50% (Griffin et al., 2008) DIV 8.16 Kg/Person (LASAN, 2013)	
Correctional Facilities	**Person:** 163 Kg (ReFED, 2016); 166 kg (DLI, 2002; Griffin et al., 2008)		
Hospital	**Bed:** 566 Kg (DLI, 2002; Griffin et al., 2008; RecyclingWorks, 2015); 680-1,225 Kg (Mercer, 2013) **Site:** 9-152 Tonnes (U.S. EPA, 2009) **Other:** 0.23-0.45 Kg/Meal (RecyclingWorks, 2015; U.S. EPA, 2009)		
Nursing Homes	**Bed:** 298-331 Kg (DLI 2002; Griffin et al., 2008; Mercer, 2013; ReFED, 2016) **Site:** 33-98 Tonnes (U.S. EPA, 2009) **Other:** 0.27-0.50 Kg/Meal (Griffin et al., 2008; Mercer, 2013; RecyclingWorks, 2015; ReFED, 2016); 0.34-0.45 Kg/Meal (U.S. EPA, 2009)		

Meybeck, 2011; Parfitt, Barthel, & Macnaughton, 2010). Understandably, the generation rates vary considerably within this broadly defined sector. Thus, some studies separate food retail sale stores (e.g., grocery store, supermarket and convenience stores) from food service establishments (e.g., restaurants or hotels). For special events, FWV can be estimated based on the number of visitors,

seats, or meals (CCG, 2006; DLI, 2002; RecyclingWorks, 2015). In particular, studies have consistently found that the food discard ratio of small generators (e.g., convenience stores) is much higher than generators in supermarkets, mostly due to their limited flows (CCG, 2006; Griffin, Sobal, & Lyson, 2008; Gruber, Holweg, & Teller, 2016). Therefore, alternative approaches to FWM in small

businesses present significant opportunities for food waste diversion from landfills.

Institutional food waste generators include schools, universities and colleges, hospitals, nursing homes, and correctional facilities. FWV from these facilities is often estimated per capita or bed. On a per-capita basis, universities or colleges with on-campus housing are considered to generate more food waste than those without dorms (Griffin et al., 2008; RecyclingWorks, 2015).

Major gaps are present in landfill diversion and recycling statistics, in terms of both definition clarity and data availability. The statistics related to diversion tend to leave out food donation, and focus on food waste reused for human and/or animal consumption, recycled for compost, or recovered for biogas. Existing programs suggest that the food waste diversion rates are generally low, especially for household discards (DSNY, 2015a, 2015b; KCI, 2012). Institutions tend to achieve the highest diversion rates (about 50%) (CalRecycle, 2015; DSNY, 2015a, 2015b; LASAN, 2013; SFRP, 2000). As presented in Table 1, food waste generation and diversion rates vary greatly by sector and region, which demonstrates the need for community-specific and sector-specific estimates.

Existing Tools of FWM
At the facility and regional level, multiple tools have been developed to facilitate FWM, such as the U.S. EPA Food Waste Management Cost Calculator, Food Waste Biogas Economic Model, and the continuously updated Waste Reduction Model (WARM) (U.S. EPA, 2009, 2010, 2016c). These tools can be used by individual waste generators to conduct a cost-benefit analysis or by local government and organizations to quantify the connection between waste management methods and greenhouse gas emissions. However, these tools have focused on a region-wide estimate based on fixed parameters; they have also focused on single facilities in the category of medium or large food waste generators. However, small food waste generators, such as residential or small commercial sites, are typically excluded.

There has also been some limited use of geographic information systems (GIS) to map the spatial distribution of food waste generators, such

as those in the states of Connecticut, Massachusetts, Pennsylvania, and Virginia (DLI, 2002; DLI & AGC, 2001; DuPage County, 2012; VANR, 2014). Those tools, however, are also limited to medium and large generators. Moreover, those tools typically rely on self-reported data from businesses or from private consulting firms, such as Dun and Bradstreet. Therefore, the public has limited access to data sources for regular updates (U.S. EPA, 2012c).

By excluding small generators, the existing tools do not seem to address the full scope of food waste. This limitation hinders potential collaborations among generators within their surrounding communities. Robust references at refined geographical scales are largely lacking, which presents a major challenge for food scrap collection and recovery. More importantly, food waste generators and food banks (as an example of potential users) are often examined separately. To achieve efficient and effective FWM through economies of scale, it is important to set up various levels of collaboration among different waste generators in a community.

Integrated Model of Community-Level Food Waste Management
To help fill the data gap and planning references for local FWM, we propose a scalable model for FWV estimates and FWM program development. The model is designed to be adaptable in specific communities (e.g., ZIP Codes or city neighborhoods) as well as cities and counties. The quantitative analysis in this study will adopt the material flow analysis approach and focus on retail and consumer food discards—i.e., "food waste" as defined above. For the aforementioned reasons explained in the first section, industrial generators are not included in the numerical analysis. The generic model entails the eight steps as follows.

(1) Characterize Waste Generators. The categorization of waste generators can be contingent upon local and regional FWM practices, pertinent programs and regulations, and data availability. It is common to adopt three general categories—e.g., residential, commercial, and institutional. Specific subcategories (as shown in Table 1) may vary by

community and region. They need to be identified, differentiated, and modeled, especially when large variations of FWV within the subcategory are expected. The adoption of publicly accessible data sets, such as those from national statistical institutions (e.g., the American Community Survey or ZIP Code Business Pattern from the U.S. Census Bureau), state and county agencies (e.g., department of health), and municipalities (e.g., the city of Chicago data portal), enables the model implementation of FWV modeling over time and comparison across communities.

(2) Determining a Geographic Unit of Analysis. The choice of the unit of analysis of FWM can depend on both the research purpose and data availability, although the results from disaggregated results can always be aggregated. FWV estimates of individual buildings, businesses, or households allows for advanced programming, such as routing optimization for collection and donation pick-ups. However, existing data may not always support such a detailed analysis. In addition, FWV from individual generators may vary over time (e.g., weekdays vs. weekends). Aggregated results at an intermediate level (e.g., communities or ZIP Codes) as a lump sum can help control the relative uncertainties in individual behaviors and still be appropriate for logistics planning.

(3) Select a Causal Parameter for Generation Rates Estimates. The unit generation rates (e.g., per capita, household, or employee), when coupled with local characteristics, provide a potential opportunity to refine estimates of discarded materials (Leigh et al., 2007). Theoretically, the parameter should be the primary factor that minimizes the variation in FWV estimates within the specific generator group (e.g., meals served for fast food restaurants; number of people for residential discards). In practice, the determination of a unit can be largely constrained by data availability. For example, data about employment and establishment size can be more commonly available than meals served or sale receipts at each establishment.

(4) Model Total FWV. With food discard rates and generator information in each subcategory, the total volume of food discards can be modeled mathematically as illustrated in Equation (1). When local or regional waste characterization data are available, the estimates can potentially be validated. Given uncertainties in FWV, a sensitivity analysis is also needed. Examples of data validation and sensitivity analysis will be provided in Section 4.

$$V_{Waste} = \sum_{i=1}^{3} \sum_{j=1}^{C_i} f_{ij} (V_1, V_2, ..., V_m) \times N_{ij} \quad (1)$$

Where,

V_{waste}: *Food waste generation (by weight);*
i: Generator type (i=1 Residential; i=2 Commercial; i=3 Institutional);
j: Sub-categories of each generator type, such as SF and MF of residential generators (detailed categories in Table 1);
C_i: *Number of sub-categories of generator type i;*
f_{ij} (): *Food waste generation rate for sub-category j of generator type i;*
N_{ij}: *Number of units (e.g., employees or establishments) in sub-category j of category i;*
$V_1, V_2, ..., V_m$: *causal factors of food waste generation;*

(5) Estimate Recoverable FWV. Building upon Equation (1), Equation (2) calculates the FWV that is potentially recoverable or reusable by waste generator type. Adopting a recovery rate based on the reported data of existing and emerging practices (as in Table 1) can lead to a benchmark of recovery potential. A region may also have set its diversion goals that include a targeting recovery rate.

$$V_{Potential} = \sum_{i=1}^{3} \sum_{j=1}^{C_i} g_{ij} (R_1, R_2, ..., R_m) \times V_{waste\ ij} \quad (2)$$

Where,

$V_{potential}$: *Food waste recovery potential volume (by weight);*
i: Generator type (i=1 Residential; i=2 Commercial; i=3 Institutional);
j: Sub-categories of each generator type, such as SF and MF of residential generators (detailed categories in Table 1);
C_i: *Number of sub-categories of generator type i;*
g_{ij} (): *Food waste recovery rate for sub-category j of*

business category i;
$R_1, R_2, \ldots, R_m$: *causal factors of food waste recovery;*
V_{waste}: *Food waste generation (by weight).*

(6) Identify Potential Demand for Recoverable Food Discards. An inventory of potential demand for food discards, corresponding to the FWM hierarchy (e.g., food banks, soup kitchens, farms, and composting facilities), should be investigated in the proximity of food waste generation. Data can be typically obtained from public agencies and nonprofit organizations, such as Feeding America (a national network of food banks). When food recovery networks are further developed, the inventory of potential demand can also include food processing facilities and other commercial enterprises. These are enterprises that can process recoverable food into value-added products through creative recipe research and development, as demonstrated in the pilot program in Philadelphia (O'Donnell, Deutsch, Yungmann, Zeitz, & Katz, 2015).

(7) Spatially Match Food Discards and FW Recovery Options. Communities are likely to either have high donation potential or desire more supply at the food banks. Pairing up the surplus and shortage areas that are in closest proximity to each other provides a local solution that reduces the transportation distance while helping to address the community's disparities in food security. This final step employs a GIS analysis to connect the potential "demand" in response to the "supply" derived from Equation (2). Subsequently, planners can identify areas that tend to generate a large FWV but do not have food diversion facilities. Such areas may need new infrastructure for food donation, composting, drop off, or mobile services for food scrap collection. Likewise, existing locations of food recovery centers (e.g., food banks) can identify potential partners (e.g., institutions and community centers) for food pick-ups.

To identify such a mismatch, this study proposes a food waste Supply-Demand Index (SDI), which is calculated as the difference between the Food Supply Index and the Food Demand Index. The Food Supply Index is calculated by the percentile value (0 to 1) of food donation potential

density in a given community. The Food Demand Index is calculated by the percentile value of food bank density in a given community. The frequency distribution of SDI values across neighborhoods or communities can provide references for the determination of SDI threshold values. For example, by referring to the histogram (Appendix), it would make sense to determine the SDI threshold values to be ±0.25. In other words, if the SDI is larger than 0.25, we assume that food discard volume is higher than the demand from food banks, and so the area is categorized as the "Surplus." Likewise, if the SDI is lower than -0.25, we assume that the area needs more food donations and thus it is categorize as the "Shortage."

Case Implementation in Chicago
The city of Chicago hosts 2.7 million residents, 1.45 million jobs, and 78,000 business establishments (U.S. Census Bureau, 2012) that all contribute to food waste generation. According to the Chicago Waste Characterization and Diversion study, only 2% of food waste is currently recovered; 498,800 tonnes of food waste end up in landfills each year (CDM, 2010a). The Illinois Food Scrap Coalition (IFSC) found several challenges to food waste diversion from landfills in the Chicago area, including insufficient education, the cheap landfill cost, missing demand and end market, a lack of infrastructure, and the unstable quality of food waste (IFSC, 2015). Meanwhile, the enactment of Illinois Senate Bill 99 in 2009 has simplified permit applications for composting facilities, which are not licensed currently to accept food waste. Small start-up programs for alternative FWM have been rapidly developing within the region, including vertical farms and biogas production that utilize food waste. There are also more than 300 food banks within the city boundaries. Therefore, we determined that implementing our FWM model in Chicago may lead to a timely and relevant reference for planning.

Data Inputs
To determine the quantity and spatial distribution of FWV, we first developed an inventory for all buildings that may generate food waste. Table 2 below shows the citywide summary statistics for

each generator or building type. Table 2 also shows the data parameters that were adopted for FWV estimates, which are intended to be relatively lower compared to existing and emerging practices. Conservative estimates were developed to make sure potential environmental benefits from landfill diversion and food recovery would not be exaggerated. We used the parameters in Table 2 for estimating FWV at the establishment and

household level and then aggregated the results for community- and city-level discussions.

Results of FWV Estimates
As a conservative estimate derived from Equation (1), the city of Chicago generates 409,400 tonnes of food scraps a year. About 242,700 tonnes of food discards come from residences, 133,000 tonnes from businesses, and 33,700 tonnes from

Table 2. Chicago FW Generator Summary and Modeling Parameters

	No. of Establish-ments	Unit of Analysis for FWV Estimates	Total No. of Units	Generation Rate	Donation Potential
Residential [a]					
Single Family	—	Housing Unit	618,361	298 Kg/Unit-Year	DON: 1.4%
Multifamily	—	Housing Unit	408,988	143 Kg/Unit-Year	
Commercial [b]					
Supermarkets, department stores and large food retail sales (FOSAL1)	622	Employee	25,773	1,360 Kg/Employee-Year	DON: 18%
Convenience stores, small grocery stores, gas stations, and other food retail sales (FOSAL2)	1,595	Employee	4,253	1,360 Kg/Employee-Year	
Hotels (FOSVC1)	97	Employee	776	1,020 Kg/Employee-Year	DON: 1.4%
Full service restaurants, fine dining places and similar food service retailers (FOSVC2)	2,135	Employee	37,171	1,020 Kg/Employee-Year	
Limit service restaurants, fast food restaurants, and similar food service retails (FOSVC3)	2,363	Employee	19,369	1,020 Kg/Employee-Year	
Cafeteria, coffee shop and other food service retails (FOSVC4)	1,582	Employee	11,810	1020 Kg/Employee-Year	
Office building (OFFICE)	157	Thousand m²	12,983	1,668 Kg/Thousand m²-Year	
Institution					
Private/public primary/secondary schools (SCH) [c]	1,033	Student	478,247	28.6 Kg/Student-Year	DON: 1.4%
University with on-campus housing (UNIV1) [d]	23	Student	137,461	52.2 Kg/Student-Year	
University without on-campus housing (UNIV2) [d]	59	Student	113,693	17.2 Kg/Student-Year	
Hospitals (HOSP) [e]	38	Bed	10,080	566 Kg/Bed-Year	
Nursing Facilities (NSG) [f]	120	Bed	17,321	298 Kg/Bed-Year	

Data sources: [a] The numbers of single- and multifamily households are from U.S. Census Bureau American Community Survey (ACS) 5-year estimates (2008–2013); [b] the data for commercial subcategories are from business license database and food inspection database provided by the city of Chicago; subcontract services are excluded due to data constraints; [c] the data for K-12 schools, including private and public primary schools and secondary schools in Chicago, are from the city of Chicago data portal; [d] the data for universities and colleges are from National Center for Education Statistics, including location, student enrollment, and campus housing; [e] the data for hospitals (e.g. location and number of licensed beds) are from Illinois Health Facilities and Services Review Board; [f] the data for nursing facilities (e.g., location and number of licensed beds) are from the Illinois Department of Public Health (IDPH).

institutions. The FWV from residents is nearly double that of businesses, demonstrating the need to include households in food waste reduction efforts.

There are 77 communities in Chicago; on average, a community hosts 35,200 people (CMAP, 2017). At the community level, FWV ranges widely from 252 tonnes to 32,120 tonnes. Three communities (the Loop, Near North Side, and Near West Side) generated 20,000 tonnes or greater of food waste annually. Five additional communities generate more than 10,000 tonnes and are clustered in the north and center of the city. Overall, the communities in the north of the city generate greater FWV than the communities in the south, which corresponds to the spatial disparities of economic conditions (Figure 2, left). In total, 27 out of 77 communities generate more than 5,000 tonnes per year, which would require one truck every day to separately collect all the food scraps. Notably, the waste composition from the three types of generators varies, even when communities generate similar FWV. Because the recovery potential varies by sector (e.g., higher in businesses than residence),

preferable FWM methods may vary across communities.

In terms of density, the central business district (CBD), not surprisingly, shows the highest FWV, at over 7,500 kg/ km² (Figure 2). Areas along the northern coast and the Chicago O'Hare international airport also present a high density of FWV. The north side of the city includes more communities with high-density FWV than the south. But the south does have a few "hot spots," which could be preferable locations for drop-off centers or arranged pick-up service, especially when an extensive curbside program is not available. FWV Result Validation

There are no other studies or statistics of FWV available at the community level. When aggregated to the city level, our results can be validated by the waste audit data documented in the Chicago Waste Characterization and Diversion study (CDM, 2010a; 2010b). Comparison by each sector and generator type is not straightforward, however, due to inconsistencies in the sector and generator classification. Table 3 presents a cross-walk of the generator categories. Generally speaking, the FWV

Figure 2. Food Waste Generation in Chicago Communities
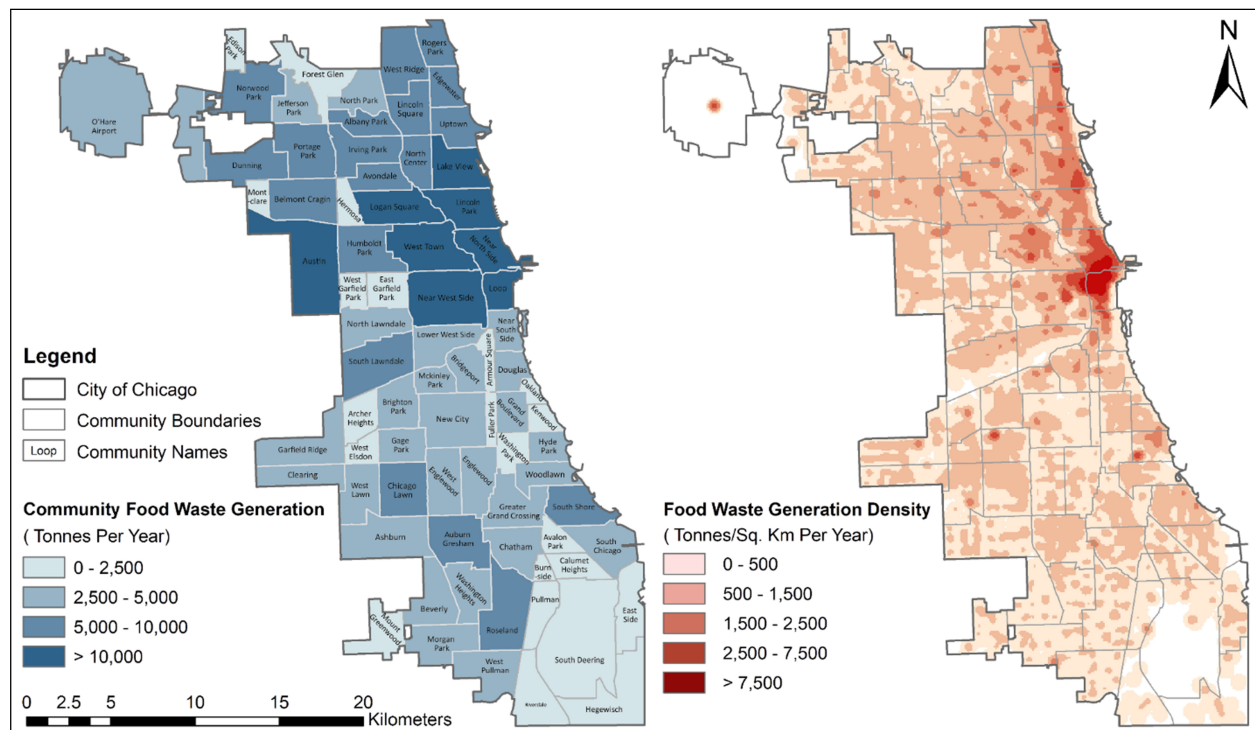
estimates resulting from our study show a comparable magnitude at the city level in comparison to the city's reported findings. As expected, our study presents slightly lower estimates, given that we have adopted a conservative generation rate.

Sensitivity Analysis
To address uncertainties in food waste generation rates of individual generators (e.g., weekdays vs. weekends), we have employed the Monte Carlo (MC) simulation method for a sensitivity analysis. In total, 200 interactions of MC simulation were computed to obtain the statistics at three uncertainty levels and for three FWV rates—i.e., ±20%, ±30%, and ±50% of average generation rates and donation potential. For example, at ±20% variation of the generation rate, input parameters vary randomly from 80% to 120% of the average generation rates in the MC simulation. The coefficient of variance (CV), the ratio of standard deviation (σ) to the mean (μ), is calculated to measure the impact of uncertainties on total FWV (Equation 3). The greater the uncertainty level is, the greater the CVs can be.

$$CV = \frac{\sigma}{\mu} \qquad (3)$$

At ±20% variation of citywide generation rates, the CV is 0.18%. At ±50% variation on individual generation rates—that is, if individuals generate from 50% to 150% of the average rate—it yields 2.47% variance in citywide food waste generation. The CVs for donation volume seem to be even smaller than that of the total generation volume. The MC simulation suggests that variations among individual generation rates have negligible impacts on the total FWV at the city level, and thus they also have negligible impact on the donation potential.

Similar MC simulations were also run at the community level. The CVs can be up to 18.88% at the uncertainty level of ±50% of the average generation rates. Understandably, communities with fewer generators or smaller FWV yield higher CVs. But in general, the average CVs are 1.99% at ±20% variation, 2.98% at ±30% variation, and 5.09% at ±50% variation. These findings suggest that a community could be an appropriate unit for FWM,

where the uncertainties in FWV are manageable and economies of scale of FWM are attainable.

Matching Demand and Supply
The FWM hierarchy suggests reuse as the most desirable approach. Therefore, this study focuses on food donations and food banks as examples of "supply" and "demand," respectively. Additionally, this study takes advantage of point-level FWV estimates when mapping the spatial pattern of supply and demand. The same approach can be applied for other linkages, such as food scrap clusters with local composting facilities or urban community gardens.

Derived from Equation (2), at least 12,900 tonnes of food discards by Chicagoans are recoverable for human use per year. Understandably, the majority of recoverable food (69.45%) is derived from the commercial sector. Households, while individually showing a relatively low recovery rate, in aggregated terms account for about one-fourth of total donation potential. Institutions account for 3.62% of total food waste donation. For individual communities, the donation potential ranges widely from 6 tonnes to 790 tonnes annually, with an average volume of 160 tonnes.

Given that the geographic size of any individual community is rather large and varies across the city, understanding the absolute tonnage of FWV is not enough. The density map shown in Figure 3 can help identify specific locations for efficient pick-ups of recoverable food, such as those with the highest potential donation density at over 250 tonnes per km².

Clearly the locations with a high density of recoverable food do not match the demand for food donation—e.g., food banks (indicated by yellow dots in Figure 3). The results of the SDI in Chicago are presented in Figure 4. Generally, the food surplus communities cluster in the central and northern part of city, as well as along the south branch of the Chicago River. The food shortage communities cluster in the west side of the city and the northern part. The map provides empirical evidence of community disparities, which can be addressed by citywide coordination efforts. For example, once the generation origin and volume of food discards are identified, an appropriate

collection method can be implemented to facilitate food scrap recycling from small generators, such as curbside programs, co-collection of food waste and yard waste, drop-off centers, or kitchen pails.

Conclusion and Discussions

Despite the increasing attention to the food waste challenge, quantitative studies of FWM are still limited, especially at the community level. This study proposes an FWM modeling and planning framework that aims to provide data references and policy insights into community-level FWM. The case implementation in Chicago demonstrates

Figure 3. Spatial Distribution of Food Waste Donation Potential and Its Potential Users
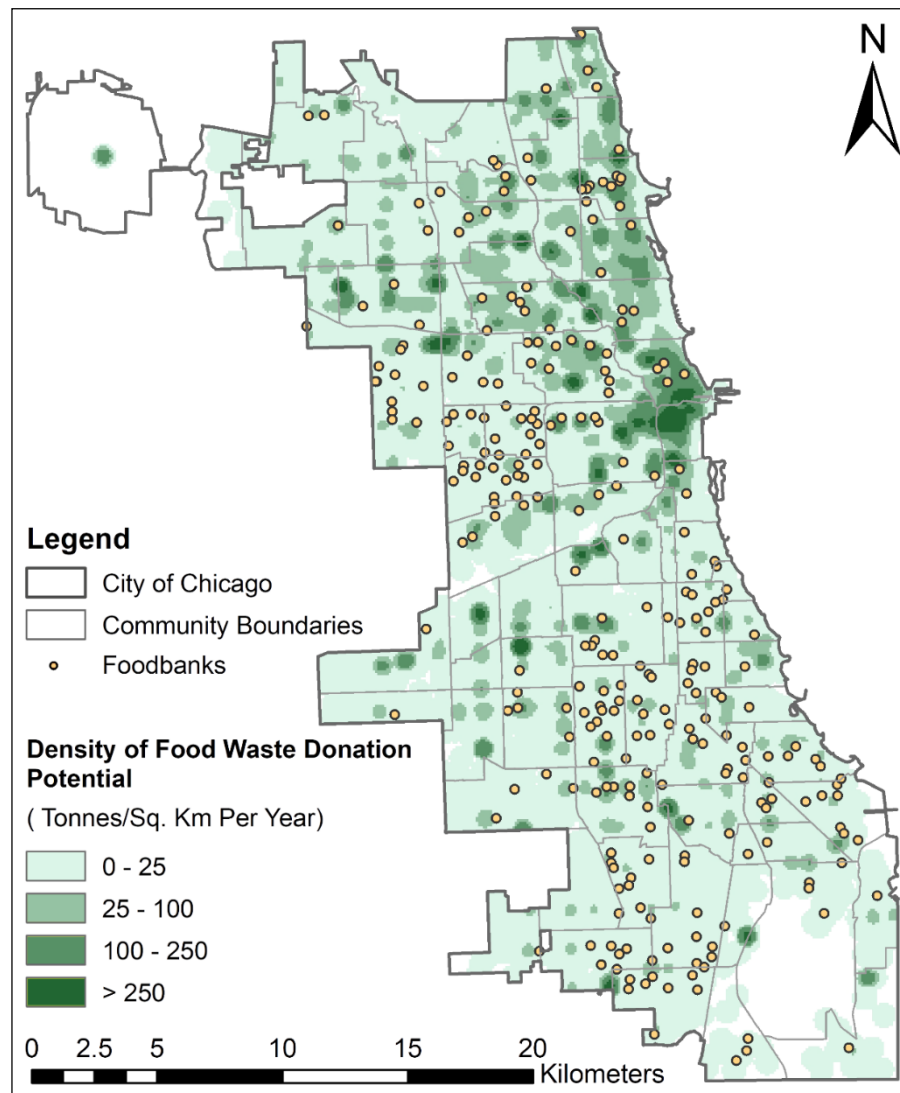

the potential opportunities for urban planners to promote the efficiency, effectiveness, and equity goals surrounding FWM. Notably, in regards to food waste, and waste in general, people tend to adhere to an "out of sight, out of mind" mentality. The system modeling and planning framework in this study could increase the visibility of food waste challenges that could be integrated with other food system planning programs (e.g., those related to food insecurity, food dessert, and nutrient loss), and helping to close the loop of food systems.

FWM necessitates a thorough understanding of waste origin and volume, which is only periodically recorded through the waste auditing process in some regions. This study demonstrated the feasibility of producing reasonably accurate estimates of FWV by employing publicly accessible data sets. The FWV model also allows communities to incorporate their unique characteristics and enables comparison across different regions with a relatively consistent approach.

Further, the sensitivity analysis in the Chicago case implementation suggests that the uncertainties of FWV estimates can be manageable at a relatively small geographical scale. The refined volume estimates, as discussed in this study, can provide critical information to help improve the performance of FWM. For example, planning can focus on the communities that present the highest food donation potential as pilot locations. Planning can also

design food scrap collection infrastructure strate-
gically based on the FWV and composition of
waste generators in order to facilitate reuse and
recycling programs at the community level. "Hot
spots" of FWV could serve as the anchors of food
recovery locations, instead of contributing to
environmental injustice.

    This study has demonstrated the importance of
engaging small food waste generators in alternative
FWM programs. As concluded in the case study,
residences generate nearly twice as much FWV as
businesses and contribute to more than one-third
of the total recoverable food in Chicago. An inclu-
sive approach of FWM
will not only improve the
accuracy in inventory
modeling, but also present
potential opportunities for
community-specific
implementation. Adopting
an inclusive FWM frame-
work can foster a bottom-
up approach for FWM.
Participatory approaches
to FWM also present
potential opportunities for
educating communities,
enhancing FW data accu-
racy, fostering organized
networks, and implement-
ing a preferred hierarchy
of FWM efficiently.

    Most importantly, our
proposed FWM modeling
and planning framework
promote local solutions to
FWM by connecting food
waste generators and
potential users. The infor-
mation derived from our
proposed model aims to
facilitate collaboration
among residents, busi-
nesses, and institutions as
community consortia in
minimizing food waste
disposal. By connecting
food scrap generation

with reuse and recovery options, this study demon-
strates empirical evidence of spatial mismatch.
FWM efficiencies and social equity goals can be
further improved if planning can pair up food
surplus and shortage communities strategically,
although further analysis is still needed to examine
collection and transportation strategies as well as
their ensuing impacts.

    We anticipate that developing community-
specific FWM models, involving local stakeholders,
and disseminating the results would also increase
the awareness of food waste problems and provide
valuable references for public education, which

Figure 4. Spatial Matching of Food Waste Donation Potential and Food Banks by Chicago Community Areas
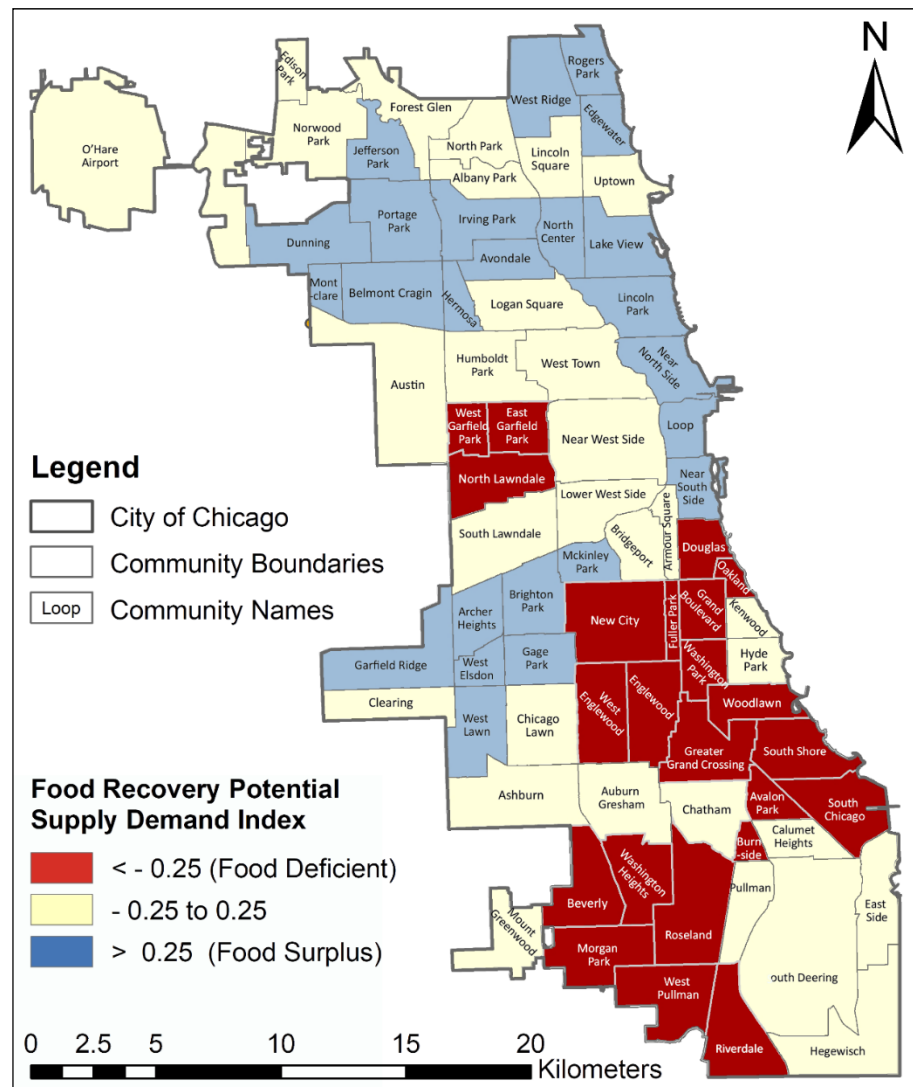
have been identified as key solutions to address barriers of food waste diversions and to promote best-practice programs (Freeman & Skumatz, 2010; Neff et al., 2015). Improving and/or increasing communication between local communities and food recovery networks would also provide valuable opportunities for data validation, which currently has limited options, as previously discussed above. In particular, additional information from residents and business owners in the planning process can help refine the estimates for small food waste generators. Besides quantity, the quality of food scraps is crucial for determining the range of options for food scrap recovery and reuse. Uncertainties about the quality over time and across seasons make food scraps particularly difficult to model compared to products with longer life spans (e.g., e-waste and automobile tires). Sharing data by the community on food purchasing and consumption behaviors is key to addressing constraints and uncertainties on food data.

Future work and greater data availability could help expand the proposed FWM modeling and planning framework. Our numerical models can be adapted to market dynamics and technology advancement by, for example, adjusting the generation rate and recovery rate. After the modeling results are validated, the data references that we have developed could enable transportation logistics analyses that explore efficient strategies to match food shortage and surplus. In addition, testing the model in other regions could reveal the heterogeneities in food flows and correspondingly provide empirical references for region-specific hierarchy solutions for FWM.

To conclude, it is important to further clarify that food waste prevention necessitates both food discard recovery and source reduction. Essentially, our hypothesis is that better measurement of the location and volume of excess food helps prevent food waste. Our numerical analysis and planning framework have focused on food recovery, or "recoverable food," in addition to addressing food waste in general. Strategies for source reduction involve many more complex factors (e.g., technology, economic incentives and/or disincentives, behavioral issues related to culture, religion, and diet). Although not the focus of this study, source reduction would make economic sense as the first step of sustainable FWM, instead of managing food already produced, distributed, purchased, and discarded. Compared to the logistics planning of food recovery trips, however, food purchasing and consumption behaviors may not be easily influenced by public policies in the short term. This suggests that the cost effectiveness of FWM strategies may vary by temporal as well as geographic scopes. While the benefits of community-based planning strategies discussed here may be more predictable, and we may be able to see those benefits sooner than those of source reduction programs, source reduction should be a continuous and long-term planning goal.

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Appendix. Histogram of Supply-Demand-Index for Chicago Communities