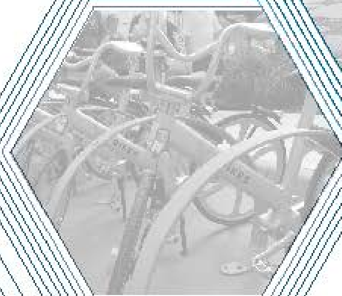

FOOD & FLORA WASTE TO FLEET FUEL: DEVELOPMENT AND APPLICATION OF THE F⁴ FRAMEWORK FINAL PROJECT REPORT

Melanie Sattler, Kate Hyun, Arpita Bhatt, Ardeshir Anjomani, Caroline Krejci, Victoria Chen, Mithila Chakraborty, Nic Raven, Ali Behseresht

FINAL REPORT

Center for Transportation Equity, Decisions & Dollars

FOOD & FLORA WASTE TO FLEET FUEL: DEVELOPMENT AND APPLICATION OF THE F⁴ FRAMEWORK

FINAL PROJECT REPORT

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Co-Principal Investigators: Kate Hyun, Arpita Bhatt, Ardeshir Anjomani, Caroline Krejci, Victoria Chen

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UNIVERSITY OF TEXAS AT ARLINGTON

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As cities strive for more sustainable transportation systems, many are considering renewable fuels for fleets. Biogas has several advantages as an alternative fuel. Composed primarily of methane, it can be cleaned for use in natural gas vehicles, or burned in a turbine/engine to generate electricity for electric vehicles. Biogas can reduce air pollutant emissions from fleet vehicles; in addition, if wastes are used to produce the biogas in digesters, the problem of urban wastes is reduced.
Many cities already have anaerobic digesters that convert sewage sludge at wastewater treatment plants (WWTPs) to biogas. Because of its abundance in landfilled waste (22%), food waste is of current critical concern to the US Environmental Protection Agency. Yard (flora) waste comprises an additional 7.8% of waste going to landfills. Both food and yard waste could be used to boost biogas production in WWTP digesters. If a city/region is considering enhancing existing WWTP infrastructure to accommodate food/yard waste, several critical questions arise:
1. Which existing digesters are the best candidates to produce vehicle fuel from food/yard waste?
2. How much fuel will be produced?
3. What will be the payback time for capital investments?
The overall project goal is to facilitate food/yard waste conversion to vehicle fuel, and help cities/regions answer the questions above, via development of the "Food/Flora Waste to Fleet Fuel" (F4) Framework. The F4 Framework will include: 1) Tools for input data collection, 2) Food/Flora-Waste-to Fleet Fuel Basic Tool, 3) F4 Optimization Extension, 4) Food/Flora Waste Separation Policy Survey and City Guidebook. The Basic F4 Tool estimates fuel produced and emission benefits. To select optimal WWTP digesters for converting food/yard waste to fuel, the Optimization Extension balances trade-offs between food/yard waste transportation costs and capital costs for expanding digesters, cleaning gas/generating electricity, and installing refueling stations. The F4 Framework was used to conduct an example feasibility study for the City of Dallas, TX.</td></tr>
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Abstract

As cities strive for more sustainable transportation systems, many are considering renewable fuels for fleets. One option is biogas, composed primarily of methane (60-70%), which can be cleaned and upgraded for use in natural gas vehicles or burned to generate electricity for electric vehicles. Biogas can reduce air pollutant emissions from fleet vehicles; in addition, if wastes are used to produce the biogas in digesters, the problem of urban wastes is reduced.

Many cities already have anaerobic digesters that convert sewage sludge at wastewater treatment plants (WWTPs) to biogas. Co-digesting food and flora (yard) waste at these digesters can boost biogas production for fleet fuel, as well as free up landfill space. The abundance of food (22%) and yard (7.8%) waste in landfills is of current concern to the US EPA (US EPA, 2018a).

If a city/region is considering enhancing existing WWTP infrastructure to accommodate food/yard waste for the production of fleet fuel, several critical questions arise:

1. Which existing digesters are the best candidates to produce vehicle fuel from food/yard waste?
2. How much fuel will be produced?
3. What will be the payback time for capital investments?

The overall project goal was to facilitate food/yard waste conversion to vehicle fuel, and help cities/regions answer the questions above, via the development of the "Food/Flora Waste to Fleet Fuel" (F^4) Framework. The F^4 Framework includes: 1) Tools for input data collection, 2) F^4 Basic Tool, 3) F^4 Optimization Extension, 4) City guidebook entitled "Anaerobic Digestion of City Food and Yard Waste: Answers to 10 Critical Questions."

To gather data for the Framework, interviews were conducted with personnel from WWTP, fleet services, and solid waste collection services from several cities; relevant literature was reviewed (>150 articles); and information was collected from EPA and other websites. The F^4 Basic Tool was developed using Excel, and the Optimization Extension was developed using Python. To select optimal WWTP digesters for converting food/yard waste to fuel, the Optimization Extension balances trade-offs between costs for food/yard waste transportation and costs for digesters, fuel conversion, and refueling stations. Both capital and operating costs are considered. The city guidebook provides information to cities on why and how to implement food and yard waste collection programs for anaerobic digestion. It is based on information from interviews with officials from 6 US cities with successful food/yard waste collection programs, as well as information from relevant literature. The F^4 Framework was used to conduct an example feasibility study for the City of Dallas, TX.

Chapter 1: Introduction

1.1 Project Goal and Objectives

The **overall project goal** was to facilitate the conversion of food and yard waste to renewable vehicle fuel —compressed natural gas or electricity. To achieve this goal, we developed the Food/Flora Waste to Fleet Fuel (F^4) Framework (Fig. 1.1) that cities/regions can use to make the best use of existing infrastructure (wastewater treatment plant digesters) to convert food/yard waste to biogas fuel or electricity for fleets. F^4 tools can be applied, with appropriate inputs, to any city/region.

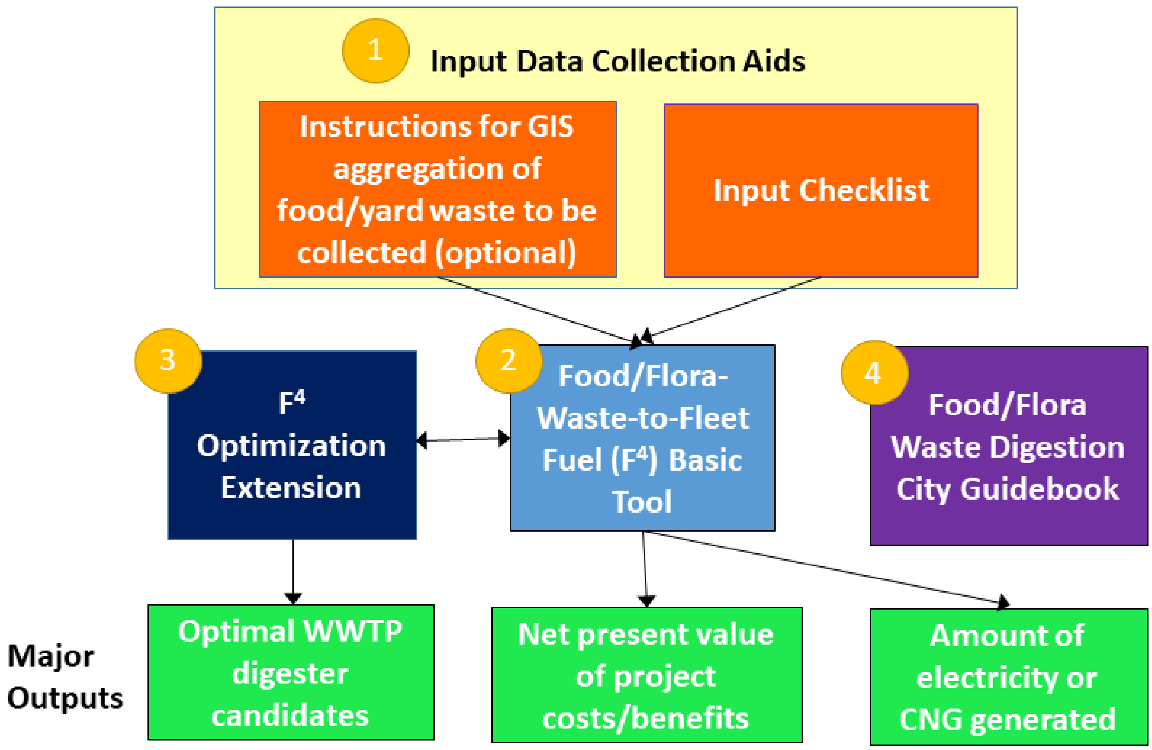

Figure 1.1 Food/Flora Waste to Fleet Fuel (F^4) Framework

Specific project objectives were:

1) To develop tools for F^4 Framework input data collection,
2) To develop the F^4 Basic Tool,
3) To develop the F^4 Optimization Extension,
4) To develop Food/Flora Waste Separation Policy Survey and City Guidebook,
5) To use the F^4 Framework to conduct an example feasibility study for the City of Dallas, TX,
6) To conduct technology transfer with municipal and academic stakeholders.

The project addressed the **CTEDD objective of innovative use of cutting-edge technology** to provide renewable fuel for fleets. It also provided outreach to policy-makers through the collaborations with the North Central Texas Council of Governments and City of Dallas, as well as educated future leaders of the transportation field (4 Ph.D. students, including 2 women).

If the F^4 Framework is utilized to select digesters for food and yard waste diversion, it will have the broader environmental impacts of reducing air pollutants by encouraging cleaner fleet fuels, as well as diverting wastes from landfills.

1.2 Background and literature review

For cities considering renewable fuels for their fleets, biogas offers several benefits. It can be used directly in natural gas-powered vehicles, which reduces emissions, particularly compared to diesel vehicles (NCTCOG, 2019a), or burned to generate electricity for electric vehicles. Reducing vehicle emissions is especially important in regions like Dallas-Fort Worth, which are non-attainment for ozone. Moreover, if wastes are used to make the biogas, the urban waste volume is reduced, freeing up needed landfill space. Fleets are attractive targets for alternative fuels like biogas because many vehicles will collectively be able to take advantage of the installation of a refueling station, which is typically costly.

Many cities already have anaerobic digesters (AD) that convert sewage sludge at wastewater treatment plants (WWTPs) to biogas. Nationwide, 22% of the waste that goes to landfills is food waste, and 7.8% is yard (flora) waste (US EPA, 2018a). In Dallas/Fort Worth, food waste constitutes 28% of what goes to landfills, and yard waste is 3.2% (NCTCOG, 2019b). According to EPA's Food Recovery Hierarchy, if food waste cannot be reduced outright or used to feed hungry people or animals, the next priority is using it to generate energy, rather than composting or sending it to the landfill (US EPA, 2019). Both food and yard waste can be used to supplement biogas production in WWTP digesters.

According to EPA, 78 digesters at WWTPs across the US were co-digesting food waste in 2015 (US EPA, 2018b). Of these, only one generated compressed natural gas (CNG) used as vehicle fuel. Most of the rest used the biogas to produce combined heat and electricity; it is not noted that any of the electricity was used for vehicles. Of the digesters that responded to EPA's survey, 7% were co-digesting source-separated commercial, institutional, or residential organic wastes, which may have included yard waste. With 14,748 WWTPs across the US (Center for Sustainable Systems, 2018), substantial potential exists for expanding the co-digestion of food and yard waste at WWTPs. Digesting the food waste generated by the average American in one year – around 248 pounds (US EPA, 2018a) – could provide enough energy for an electric vehicle (EV) to travel about 41 miles or a CNG vehicle to travel around 22 miles.[1]

Enhancing existing WWTP infrastructure to accommodate food and yard waste, to generate biogas for vehicle fuel, involves determining which WWTP digesters are the best candidates for co-digestion. The best candidates would provide the most biogas for the least cost. Determining this is not straightforward, however, because of the large number of potential WWTPs, waste collection routes, and variables that impact the cost. The 16-county region served by the North Central Texas Council of Governments, for example, has 9 digesters (NCTCOG, 2018). Trade-offs must be balanced between food/yard waste transportation costs and capital costs for expanding digesters, cleaning gas/generating electricity, and installing refueling stations.

Until this project, there was not a model for determining the best use of existing digester infrastructure for food/yard waste to fuel conversion. Galli et al. (2019) provided a qualitative (not quantitative) model of food waste generation and recovery for social purposes for Italy. Several studies have developed food supply network models (Cheshmberah et al., 2011; Mogale et al., 2016), but they do not apply to waste. Lee et al. (2018) developed a system dynamics food waste model for Hong Kong, consisting of sub-models for food waste generation, waste treatment, landfilling, and government expenditure. A similar model, however, is not available for the US. Several general models are available to facilitate municipal solid waste management decisions in the US, including Solid Waste Optimization Lifecycle Framework (SWOLF, NCSU, 2014) and Municipal Solid Waste Decision Support Tool (MSW-DST, RTI International, 2012). However, these models are not specific to food/yard waste and do not address the issue of using existing digester infrastructure to convert food/yard waste to fleet fuel.

In addition, until this project, there was not a user-friendly model for estimating fuel production from food/yard waste and costs/benefits. EPA's Co-Digestion Economic Analysis Tool (Co-EAT, Rock and Ricketts, 2017) is not specific to food/yard waste and requires 78 input values, which are not readily available.

Development of the "Food/Flora Waste to Fleet Fuel (F^4)" Framework helped to fill the gaps mentioned above. The innovation of the F^4 Framework is the combination of various elements –

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[1] These calculations assume a mid-range biogas yield of 0.017 m^3/lb wet food waste (Deublin and Steinhauser, 2008), and biogas with mid-range methane content of 60%, with heating value of 600 Btu/ft^3 (Swedish Gas Technology Centre, 2012). The EV calculation also assumes a mid-range steam turbine efficiency of 42.5% for electricity generation (range 40-45%, Webber, 2007) and electricity consumption of a 2011 Nissan Leaf (3.7 mi/kWh). The CNG calculation assumes that the CNG vehicle gets about the same fuel economy as a conventional gasoline vehicle on a gasoline-gallon-equivalent basis (US DOE, 2019a). The fuel economy of a 2015 CNG Honda Civic (31 MPGe, Compare.com, 2018) is used. Miles traveled for the EV exceeds the CNG vehicle because of the low efficiency (15-25%, Webber, 2007) of the CNG vehicle's internal combustion engine (ICE). Although the steam turbine used to generate the electricity has only a 40-45% efficiency, the efficiency of the electric motor in the EV is 60-75%, which gives an overall efficiency of around 29%, which is greater than the 15-25% range for the ICE.

Geographic Information Systems (GIS), surveys, cost information, digester design information, optimization – in a novel way. The Framework's Optimization Extension determines the optimal use of existing digester infrastructure for food/yard waste to fuel conversion, and the F^4 Basic Tool estimates fuel production volumes and costs/benefits. The F^4 city guidebook, entitled "Anaerobic Digestion of City Food and Yard Waste: Answers to 10 Critical Questions," helps local officials answer questions about why and how to implement food and yard waste collection programs for anaerobic digestion.

1.3 Report Organization

The remaining chapters discuss the development of the various pieces of the F^4 Framework, feasibility study conducted, and outreach as follows:

- Ch. 2 Tools for F^4 Framework for Input Data Collection,
- Ch. 3 F^4 Basic Tool,
- Ch. 4 F^4 Optimization Extension,
- Ch. 5 Food/Flora Waste Separation Policy Survey and City Guidebook,
- Ch. 6 Feasibility Study for City of Dallas,
- Ch. 7 Technology Transfer,
- Ch. 8 Conclusions and Recommendations

Chapter 2: Tools for F^4 Framework Input Data Collection

2.1. Food and yard waste generation estimates

Table 2.1 shows 12 categories contributing to food waste and 4 categories contributing to yard waste. For 7 of the food waste categories (educational institutions (not universities), correctional facilities, food banks, food manufacturers/processors, food wholesale/retail, healthcare facilities, hospitality industry, restaurants & food services), US EPA's Excess Food Opportunities map provides institution-specific food waste values in tons/year. For the remaining food waste categories, as well as the yard waste categories, the following basic equation can be used to estimate waste production:

Waste produced per category per block group (mass/year) = [**Waste generation rate**] (mass/activity/year) * [**Activity level**/block group]

The "Rate" column of Table 2.1 shows **waste generation rate** values obtained from literature. Each rate can then be multiplied by the city- or region-specific **activity level** to obtain waste estimates in tons/year, using the equations given in the "Calculation of waste per block group in tons/year" column in Table 2.1. **Activity levels** can be obtained from GIS information sources given in the "GIS Data Source" column. In the case of parks and commercial lawns, the GIS data sources provided are specific to the Dallas case study, so similar sources will need to be obtained for other regions.

For example, the food **waste generation rate** for universities is listed in the "Rate" column as 0.39 lb/student/ day. This rate can be multiplied by the **activity level** of number of university students per block group to obtain total food waste from universities per block group. The equation for this calculation is given in the "Calculation" column as follows:

Food waste produced by universities per block group (tons/year) = Rate * No. of students per block group * 365 days/year * 1 ton/2000 lbs

It should be noted that F^4 allows the user to specify the fraction of food and yard waste actually collected. This can account for participation rates less than 100% (e.g. not all households participate).

More information on the values reported in the "Rate" column is provided below.

Table 2.1 Waste categories, generation rate, and GIS information

Waste Category		Amount of Waste Generated			
General	**Specific**	**Rate**	**Reference for rate**	**Calculation of waste per block group in tons/year**	**GIS Data Source**
Food Waste	Single-family households	5 lb/ household/ week	SWANA (2016)	Rate * No. of single-family residences per block group * 52 weeks/year * 1 ton/2000 lbs	US Census Bureau - ACS 2019 https://www.census.gov/
	Multi-family households	1 lb/ unit/week	SWANA (2006 and 2016)	Rate * No. of multi-family units per block group * 52 weeks/year * 1 ton/2000 lbs	US Census Bureau - ACS 2018 https://www.census.gov/
	Universities	0.39 lb/student/ day	SWANA (2016)	Rate * No. of students per block group * 365 days/year * 1 ton/2000 lbs	US Department of Education https://nces.ed.gov/collegenavigator/?s=TX
	Educational institutions (not universities), correctional facilities, food banks, food manufacturers/processors, food wholesale/retail, healthcare facilities, hospitality industry, restaurants & food services	Institution-specific, tons/year	EPA Excess Food Opps. Map	Already given in tons/year, waste for different facilities aggregated over the block group	US EPA Excess Food Opportunities Map https://geopub.epa.gov/ExcessFoodMap/
	Special event centers and recreation facilities	150 - 4200 lb/employee/ year	NRDC (2017)	Rate * No. of employees per block group * 1 ton/2000 lbs	ArcGIS Business Analyst https://iuscappa.maps.arcgis.com/home/index.html
Yard Waste	Single-family households	16 lb/ household/ week	SWANA (2016)	Rate * No. of single-family residences per block group * 52 weeks/year * 1 ton/2000 lbs	US Census Bureau - ACS 2019 https://www.census.gov/
	Golf courses	269 lb/acre/week	US EPA, State govern-ment info.	Rate * No. of acres per block group * 52 weeks/yr * 1 ton/2000 lbs	Google Maps, Google Earth, ArcGIS Online Maps https://www.google.com/maps?hl=en&tab=wl1
	Parks	538 lb/acre/week		Rate * No. of acres per census block group * 52 weeks/yr * 1 ton/2000 lbs	NCTCOG's Regional Data Center https://data-nctcoggis.opendata.arcgis.com/
	Commercial lawns	538 lb/acre/week		Rate * No. of acres per census block group * 52 weeks/yr * 1 ton/2000 lbs	NCTCOG's Regional Data Center, City of Dallas GIS Services https://gis.dallascityhall.com/shapefileDownload.aspx ; https://data-nctcoggis.opendata.arcgis.com/

2.1.1 Food waste generation rates

For food waste per **single-family household**, 5 lb/household/week is recommended by SWANA (2016) as a reasonable average for voluntary programs, although mandatory program average collection rates can go as high as 9 lb/household/week.

For food waste for **multi-family households**, food waste collection data is scarce. SWANA reported an average collection rate of 1.6 lb/household/week for San Francisco (2016), and 1.1 lb/household/week for Ontario, Canada (2006). Table 2.1 uses 1 lb/household/week as a conservative estimate.

2.1.2 Yard waste generation rates

For yard waste collection per **single-family household**, 16 lb/household/week represents an average of 6 municipal programs in the US and Canada (SWANA, 2016).

Yard waste for **golf courses** is assumed to be primarily grass clippings (rather than leaves or brush). An extensive search of peer-reviewed literature, government web sites, and other internet sites did not turn up a reliable value for grass clipping yield (mass/golf course area/time) for golf courses. We were able to find several grass clipping yield values, presumably for presumably single-family lawns, from several government websites (e.g. CalRecycle, 2020; Franklin County Solid Waste Management District, 2019). These values were averaged to give 7 tons/acre/year, or 269 lb/acre/week. Although this value was for lawns, it was assumed to apply to golf courses also.

Yard waste for **parks and commercial lawns** was assumed to include leaves and brush, as well as grass. An internet search did not yield any values for grass, leaves or brush from parks or commercial lawns (mass/area/time). We thus assumed that the 269 lb/acre/week value for single-family lawns applied to parks and commercial lawns as well. According to US EPA (non-dated c), yard waste is around 50% grass clippings, 25% brush, and 25% leaves. Doubling the 269 lb/acre/week value for grass, in order to account for brush and leaves, gives an average value of 538 lb/acre/week. Table 2.1 uses this value for parks and commercial lawns. Improved estimates of yard waste generation rates for golf courses, parks, and commercial lawns are recommended for future research.

2.2 GIS procedure for estimating food/yard waste generation per block group and garbage route

The following procedure was developed to estimate food/yard waste using ArcGIS:

- **Step 1:** Georeference waste items
- **Step 2:** Quantify and join all items in block groups
- **Step 3:** Calculate food/yard waste in each block group

- **Step 4:** Aggregate food and yard waste based on "Block Groups" and "Garbage Routes."

Each of these steps is now discussed in more detail.

Step 1: **Georeference waste items**. Georeference waste items as needed.

Step 2: **Quantify and join all items in the census block groups.** Waste production for various categories (e.g. single family households, restaurants, golf courses) is joined by census block group. Block groups are used since activity-level data was available by block group for single-family households and multi-family households.

Step 3: **Calculate waste in block groups**. The amount of waste produced in each block group is calculated using the procedure explained in Section 2.1. Equations used are shown in the "Calculation of waste in tons/year" column in Table 2.1. Additional explanations for some calculations are provided below.

- **Food waste**:
  - **Universities**: Since some universities fall within multiple block groups, the polygon of each university's campus is converted to point (aka polygon centroid) to ensure the number of students is assigned to a single block group. Then the number of university students within each block group is multiplied by 0.39 lb/student/day * 365 days/year * 1 ton/2000 lbs, to estimate waste in tons/year.
  - **Special event centers and recreation facilities:** These facilities are categorized into three groups of low[2], medium[3], and high[4] waste producers based on its NAICS code regarding the assumed amount of waste they produce. Then the number of employees in each category in each block group is multiplied by 150, 2175 (median value), and 4200 lb/employee/year for the low, medium, and high waste producers, respectively. Waste in lb/year is multiplied by 1 ton/2000 lbs to estimate waste in tons/year.
- **Yard waste**:
  - **Parks**: Parks are extracted from the land use Shapefile and intersected by block groups. Then the area is calculated in acres and multiplied by 538 lb/acre/year * 1 ton/2000 lbs to estimate waste in tons/year.
  - **Golf courses**: The golf courses are located/drawn on Google Earth, exported/imported/ to ArcGIS, converted to Shapefiles, intersected by block groups, area calculated, and then multiplied by 269 lb/acre/year * 1 ton/2000 lbs to estimate waste in tons/year.

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[2] i.e., performing arts, dance companies, orchestras & bands, music-entertainment, karaoke, kids entertainment, circus companies, basketball clubs, professional sports clubs & promoters, soccer clubs, race tracks, music & live entertainment, museums, art centers, cultural centers, arboretums, botanical gardens, parks, arcades, bingo games, golf courses, recreation centers, skating rinks, bowling centers, family entertainment centers, and membership sports & recreation clubs.

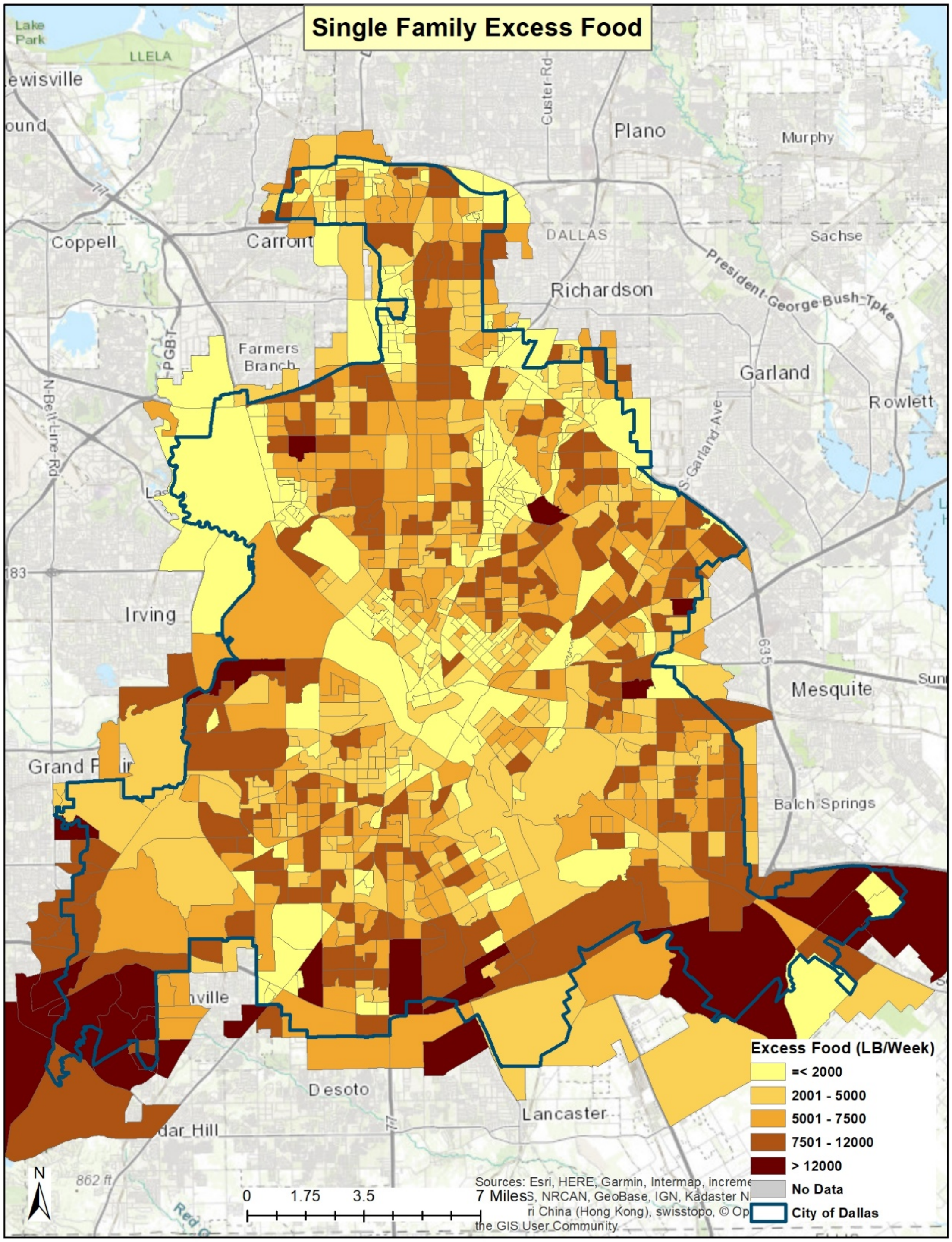
[3] i.e., carnivals, concert venues, stadiums arenas & athletic fields, events-special, event centers, zoos, aquariums-public, picnic grounds, amusement places, water parks.

[4] i.e., concessionaires, fairgrounds

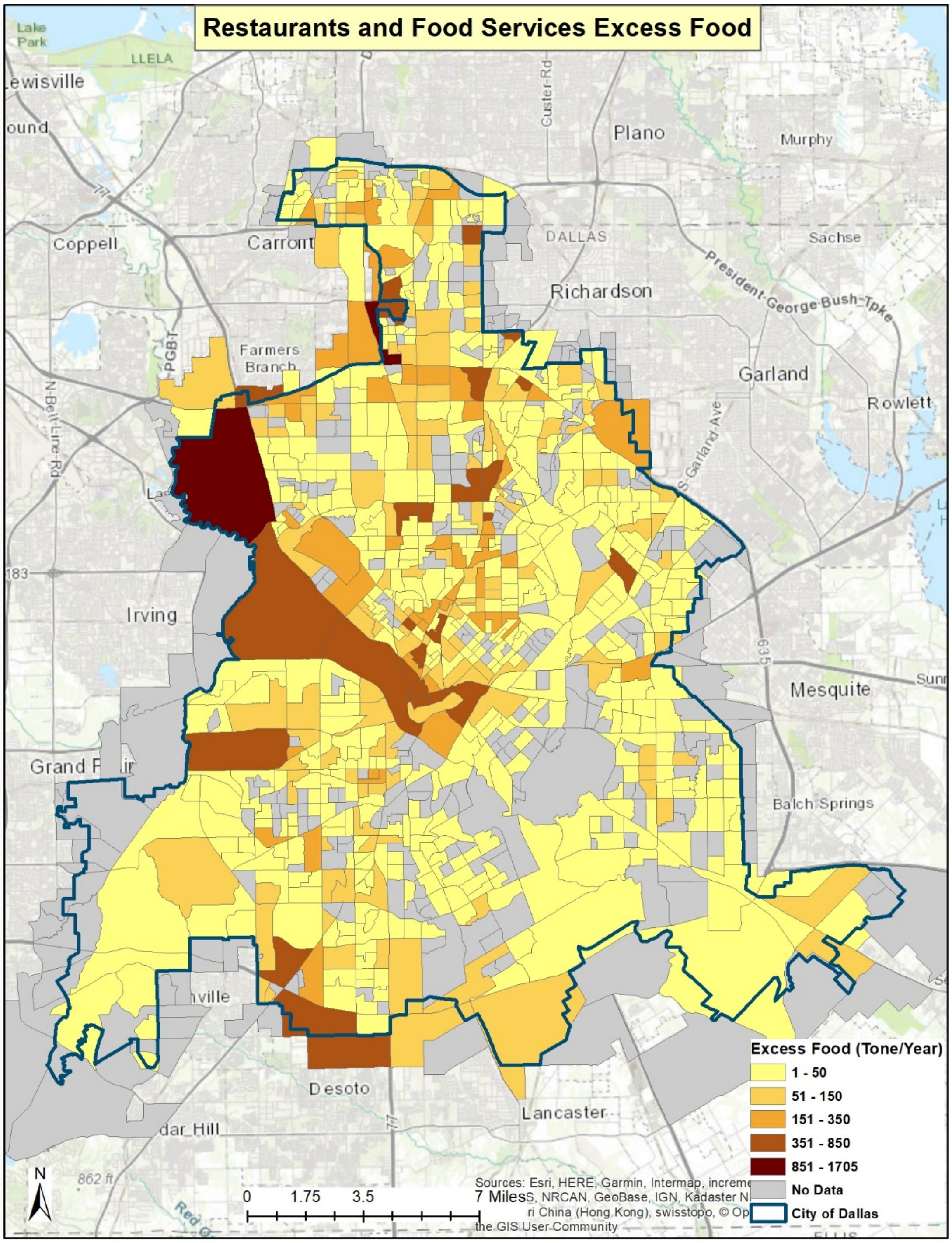
- **Commercial lawns** (Businesses): The commercial land uses (i.e., commercial, hotel/motel, stadium, mixed-use, office, and retail) are extracted from the land use Shapefile, building footprints subtracted, area of lawn calculated in acres, intersected by block groups, and then multiplied by 538 lb/acre/year * 1 ton/2000 lbs to estimate waste in tons/year.

Step 4: **Aggregate food and yard waste based on "Block Groups" and "Garbage Routes."** Once the amount of waste is calculated for each item in the block groups, the total amount of waste in each block group is calculated. By intersecting garbage routes[5] and block groups, the amount of the waste is calculated for each garbage route. Figures 2.1 a) and b) show examples of waste aggregated by garbage route for the City of Dallas. Maps for the other waste categories for the City of Dallas are shown in Appendix A.

[5] Garbage route, in this context, mean parcels (i.e., households) that their garbage is collected within a garbage route/truck.



(a) Food waste for single family homes



(b) Restaurant and food services excess food

Figure 2.1 Waste aggregated by block group, City of Dallas

2.3 Data collection surveys

Surveys for city personnel (Wastewater Treatment Plants, or WWTPS; and Waste Collection/Fleet Managers), shown in Appendix B, were developed to collect data to incorporate into the F^4 Tool. Information collected using these surveys is shown in Table 2.2. In the case of Waste Collection, city services were contracted out to two nationwide solid waste management companies, so the companies were contacted. Truck manufacturers and anaerobic digester manufacturers and vendors were also contacted to obtain the costs of garbage trucks and anaerobic digesters, respectively. Additional lists of questions were developed for the truck and AD manufacturers, and are also included in Appendix B.

Table 2.2 Data collection surveys

Information from	Information about	Contacted	Responded
WWTP's	Anaerobic Digesters	40	17
Waste Collection	All information regarding waste collection, especially about garbage trucks	2	1
Fleet Managers	Relevant fleet information	11	3
AD Manufacturers and Vendors	Price of AD	15	1
Truck Manufacturers	• Price of New Garbage Trucks • Retrofitting Garbage Trucks	28	2

In addition, interviews were conducted with personnel from WWTP, Fleet Services, and Solid Waste Collection Services from several cities, as shown in Table 2.3 below, to clarify responses and gather additional information.

Table 2.3 Data collection interviews conducted

Interview Topic	Interviewee	No. of Interviews
AD operation	Operational manager of the plant, Superintendent of plant	5
Fleets	Facility service director, Fleet manager, etc.	4
Waste management	Sr. public service affair manager and district manager	1

Chapter 3: F^4 Basic Tool

3.1. Collection of cost information

Information was collected for costs of anaerobic digester (AD) expansion and operation, biogas purification, turbines/engines for converting biogas to electricity, CNG refueling stations and electric charging stations, and benefit value of electricity/fuel generated. Information was obtained from surveys and interviews (Obj. 1), government websites, and a review of over 150 articles.

Cost information was collected for vehicles and fuel, as well as information concerning vehicle fuel economy, annual miles traveled, and lifespan. Cost information was also collected for additional categories, including waste shredding, landfill tipping fees, emission reduction health benefits, renewable energy credits, and sale of landfill gas. Alternative methods of estimating digester capital and operating costs were explored by reviewing the literature and talking to UTA construction and structures faculty members, and city personnel. Finally, based on our conversations with a construction faculty member, a consultant who works with digesters, and a geotechnical faculty member (who has expertise in foundations), we were able to devise a reasonable method for estimating digester capital costs.

Sources of information used in the F^4 Basic Tool are documented as references in the tool itself.

3.2 F^4 Spreadsheet Basic Tool

The F^4 Basic Tool enables a city to evaluate the feasibility of using one digester to accommodate food/yard waste for conversion to vehicle fuel. Designed as a user-friendly Excel screening tool, cells are color-coded to help users, as shown in Fig. 3.1. Table 3.1 describes the various spreadsheet tabs within the tool. The user should first read the tabs labeled "**User Guide**," "**Read me**," "**Necessary Information Needed**," and "**Acronyms Used.**"

Color	Color Coding of Cells
	Users Must Input Cell
	Default Cell
	Optional: Cells user can input if they want
	Outputs

Figure 3.1 F^4 Basic Tool cell color coding

Fig. 3.2 shows the inputs and outputs of the F^4 Basic Tool. In the Tool, the "**Quick Overview – Inputs & Outputs**" tab summarizes the main inputs and outputs. The user does not need to input information on any of the other tabs, or access outputs on any other tab. The other tabs perform calculations, with the exception of the last three ("**Unit Conversions**," "**Bibliography**," and "**Help**"), which the user can access for additional information.

A ***user manual and tutorial video*** are available on the project website.

Table 3.1 F^4 Basic Tool spreadsheet tab descriptions

Tab Name	Description
User Guide	General information about the F^4 Spreadsheet as well as the meaning of color-coded cells used in the spreadsheet.
Read Me	A detailed flowchart about the F^4 Spreadsheet showing what tabs contain which information.
Necessary Information Needed	A quick checklist of information that user must input to use the spreadsheet.
Acronyms Used	All the acronyms used and their meanings are listed here.
Quick Overview – Inputs & Outputs	The only tab where user must INPUT values. Overall user INPUT, OUTPUT, benefits, revenues, losses, net benefit/cost, etc. are arranged here. It is the most important part of the F^4 spreadsheet. With very limited INPUTs, the user can have an overview of all the OUTPUTS with overall benefit/cost information in terms of 50 years with 2% interest rate.
Waste Mass Calculations	Calculations for generated Food and Yard waste.
Sludge Mass Calculations	Calculations for currently treated Sludge Mass.
Fleet Information	All information about Fleets (fuel economy, mileage, cost of fuel, average lifespan, etc.) that can be refueled by generated biogas.
AD Calculations	Calculation for Anaerobic Digester (AD), including remaining capacity, volume, number of new digesters to be installed, etc.
Digester Biogas Calculations	Detailed calculations about the amount of biogas generated from food, yard, and sludge; conversion of biogas to energy, electricity; miles per year different vehicles can travel on biogas produced; number of vehicles that can be refueled by generated biogas; etc.
Vehicle Emission Benefit Calculations	Calculation of emission benefits in terms of vehicular emissions by using biogas (electricity & CNG) and comparison with conventional vehicles (diesel & gasoline).
LFG to Energy Emission Benefit Calculations	Calculation of emission benefits in terms of electricity generated using landfill gas, compared to electricity using a conventional mix that includes fossil fuels.
Cost-Benefit Calculations	Detailed calculations for all individual cost and benefits.
Unit Conversions	Used units and their conversions.
Bibliography	List of references used.
Help	Contact information for questions regarding F^4 Tool.

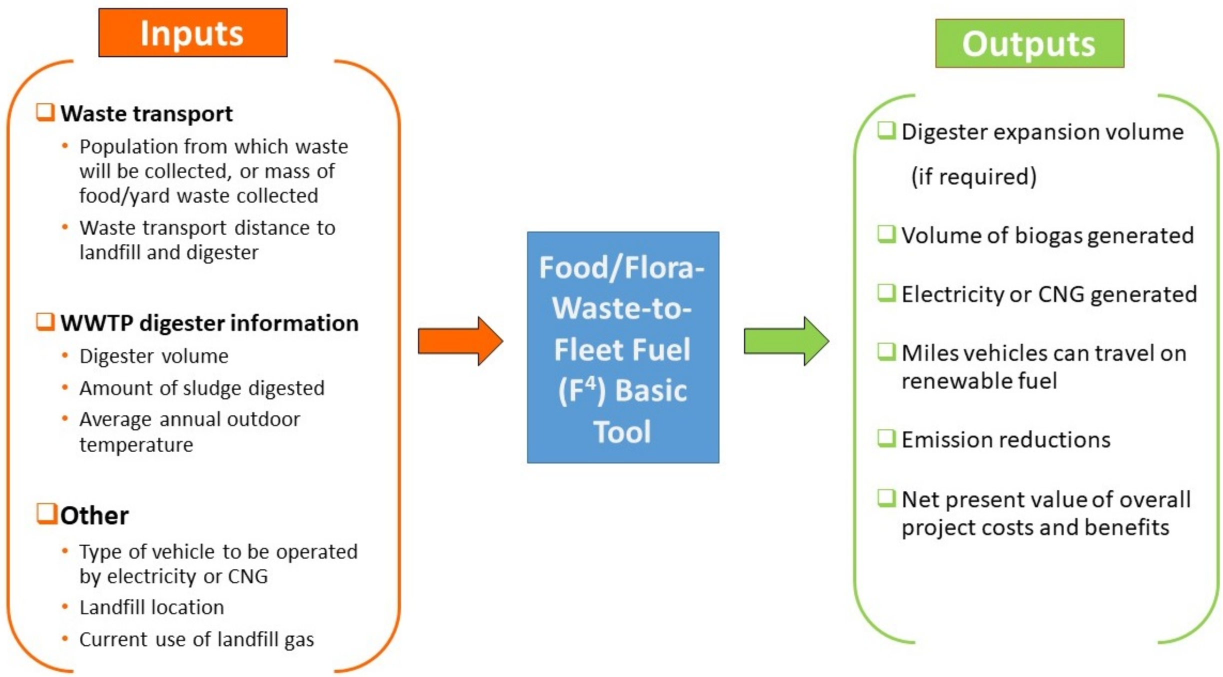


Figure 3.2 F^4 Basic Tool

3.2.1 F^4 Basic Tool Inputs

As shown in Fig. 3.2, limited inputs are required for the Basic Tool (8 inputs), compared to 78 for US EPA's Co-Digestion Economic Analysis Tool, Co-EAT (Rock and Rickets, 2017). The Tool compares the overall cost/benefit of digesting food/yard waste to the current scenario, which is assumed to be landfilling of the food/yard waste. Hence, inputs include information about the current landfill scenario: distance of waste transport to landfill, state where landfill is located (used to estimate tipping fees), and the current use of landfill gas. Costs associated with the landfill scenario are described in more detail in Section 3.2.3.

The input of mass of food and yard waste to be collected can be estimated using GIS, as described in Ch. 2 (preferred, because it is more accurate), or estimated based on the area population (see Appendix C). If the area population is input, then the Tool estimates waste mass to be collected using national estimates of food and yard waste per capita, obtained from US EPA (2018a).

In terms of inputs related to WWTP digester information, the average annual temperature is required in order to estimate the cost of heating for the digester. It is assumed that the digester is heated to a mid-range temperature of 95°F (35°C). The user must also select the type of fleet vehicles to be operated using electricity or CNG: passenger cars, garbage trucks, passenger trucks, or light commercial trucks.

3.2.2 F^4 Basic Tool Outputs Except for Costs

Methods of estimating outputs are summarized below.

3.2.2.1 Digester Expansion Volume

Digester Expansion Volume = [(Volume of food waste to be added per day) + (Volume of yard waste to be added per day] * (Residence time) + (Volume of sludge treating) – (Existing digester volume) ("**AD Calculations**" tab)

Volume of food waste to be added per day = (Mass of food waste collected per day from GIS or population) / (Average density of food waste) ("**Waste Mass Calculations**" tab)

Average density of food waste = 1513 lb/yd^3 (Waste 360)

Waste mass calculations are shown in Appendix C.

Volume of yard waste to be added per day = (Mass of yard waste collected per day from GIS or population) / (Average density of yard waste) ("**Waste Mass Calculations**" tab)

Average density of yard waste = 1568 lb/yd^3 (McNulty and Kennedy, 1982; Gryc et al., 2011)

Default residence time = 40 days (Deublein and Steinhauser, 2008) ("**AD Calculations**" tab)

Number of digesters needed = (Digester volume needed)/(Volume per digester) ("**AD Calculations**" tab)

Volume for 30 m diameter x 30 m tall digester = 5.6 MG (Ripley, 2020)
Number of digesters needed = (Digester volume needed)/5.6

The required carbon/nitrogen ratio and moisture content of the digester feedstock is not considered.

3.2.2.2 Volume of Biogas Generated ("**Digester Biogas Calculations**" tab)

For food and yard waste (Deublein and Steinhauser, 2008):
$Q = q * M * 0.75$

where
Q = Gas production rate for food or yard waste, m^3/day
q = max. specific yield of biogas per lb wet food or yard waste, m^3/lb
= 0.017 for food waste and

= 0.055 for yard waste
M = waste feed rate, lb/day
0.75 = factor to account for practical biogas yield (all of the food/yard waste is is not able to be broken down by microorganisms).

For sludge:

$$Q = q * M * F_{TS} * F_{oTS} * 0.75$$

where
Q = Gas production rate for sludge, m^3/day
q = max. specific yield of biogas per lb of dry organic matter, m^3/lb = 0.216 m^3/lb
M = waste feed rate, lb/day
F_{TS} = Fraction of sludge by weight that is solid = 0.05
F_{oTS} = Fraction of total solids by weight that are organic = 0.68
0.75 = factor to account for practical biogas yield

The current version of F^4 calculates biogas from sludge as well as food and yard waste. A future version will enable users to deselect sludge, in case it is already beneficially reused, to estimate the additional amount of gas to be produced from food and yard waste alone.

3.2.2.3 Energy Generated ("**Digester Biogas Calculations**" tab)

Energy generated by waste (BTUs/year) = (Annual Gas production, m^3/lb) * (Biogas heating value, BTUs/ft^3) * (1 ft/0.3047 m)^3

Biogas heating value = 600 Btu/ft^3 (Swedish Gas Technology Centre, 2012)

3.2.2.4 Electricity Generated ("**Digester Biogas Calculations**" tab)

Electricity Generated (kWh/year) = Energy generated (BTUs/year) * 0.425/(3412 BTUs/kWh)

where 0.425 = average turbine efficiency (Webber, 2007)

3.2.2.5 Miles Vehicles Can Travel on Renewable Fuel ("**Digester Biogas Calculations**" tab)

Electric VMT = (kWh electricity generated) * (miles/gallon gasoline equivalent) / (33.7 kWh/gallon gasoline equivalent)

OR

Electric VMT = (kWh electricity generated) * (miles/gallon diesel equivalent) / (40.7 kWh/gallon diesel equivalent)

CNG VMT = (BTUs energy generated) * (miles/gallon gasoline equivalent) / (115,000 BTUs/gallon gasoline equivalent)

OR

CNG VMT = (BTUs energy generated) * (miles/gallon diesel equivalent) / (139,000 BTUs/gallon diesel equivalent) (EngineeringToolbox.com)

Average fuel economy (miles/gallon) values were from AFLEET (Argonne National Lab), as shown in Table 3.2.

Table 3.2 Fleet information (ANL, AFLEET)

Vehicle Category	Vehicle Fuel	Avg. Fuel Economy*	Fuel Unit	Cost of fuel ($/Fuel unit)	Average vehicle miles travelled per year	Average Lifespan (Years)**
Passenger Car	Gasoline	26.2	Gallon	$2.68	12,400	11.8
	Diesel	31.4	Gallon	$2.92		
	EV	72.0	kWh	$0.11		
	CNG	24.9	GGE	$1.82		
Garbage Trucks	Diesel	1.7	Gallon	$2.92	23,400	12
	Electric	4.4	kWh	$0.11		
	CNG	1.5	GGE	$1.82		
Passenger Trucks	Gasoline	16.4	Gallon	$2.68	11,400	11.8
	Diesel	19.7	Gallon	$2.92		
	EV	44.3	kWh	$0.11		
	CNG	15.6	GGE	$1.82		
Light Commercial Truck	Gasoline	13.0	Gallon	$2.68	24,000	11.8
	Diesel	15.6	Gallon	$2.92		
	EV	33.7	kWh	$0.11		
	CNG	12.3	GGE	$1.82		

*Miles per diesel gallon equivalent (MPDGE) for electric garbage trucks; miles per gallon gasoline equivalent (MPGGE) for other electric vehicles.

** US DOE (2019b), USF

3.2.2.6 Vehicle Emissions ("**Vehicle Emission Benefit Calculations**" tab)

Emissions (kg/year) = (Emissions/mile) * (Vehicle miles travelled/year)

Vehicle emission factors (emissions/mile) & average fleet vehicle miles traveled/year were taken from Argonne National Lab's GREET Model, as shown in Tables 3.3 and 3.2, respectively. Right now, only emissions associated with passenger cars and garbage trucks are included, not passenger trucks or light commercial trucks, because GREET did not include appropriate emission factors for them. These will be included in an updated version of F^4.

Table 3.3 Vehicle emission factors (ANL, GREET)

	Emission factor, g/mi			
	Passenger Car		Garbage truck	
Pollutant	**EV**	**CNG**	**EV**	**CNG**
Volatile organic compounds (VOCs)	0.0137	0.17	0.224	0.350
Carbon monoxide (CO)	0.0368	2.86	0.602	23.93
Nitrogen oxides (NO_x)	0.0470	0.32	0.768	2.09
Particulate matter 10 (PM 10)	0.00072	0.00927	0.0117	0.0518
8Particulate matter 2.5 (PM 2.5)	0.00064	0.00745	0.0104	0.0418
8Sulfur dioxide (SO_2)	0.0181	0.0795	0.296	0.470
Methane (CH_4)	0.3055	1.28	5.000	17.32
Carbon dioxide (CO_2)	0.00842	310	0.138	1770
Nitrous Oxide (N_2O)	0.00127	0.0149	0.0207	0.0435

Emissions for vehicles fueled with electricity generated using biogas are assumed to be the same as those for electricity generated with natural gas, because GREET does not provide emissions for vehicles fueled with electricity generated using biogas. Since impurities are removed from biogas before it is used to generate electricity, emissions from combusting the cleaned biogas to produce electricity should be similar to those for combusting natural gas. Both biogas and natural gas are predominantly methane.

3.2.2.7 Electricity Generation Emissions ("**LFG to Energy Emission Benefit Calculation**" tab)

Emissions (kg/year) = (Emissions, lb/MWh) * (MWh/year) * (1 kg/2.2 lb)

Emissions (lb/MWh) are shown in Table 3.4 (from Chen & Greene (2003) for electricity generated from landfill gas and Energy Information Administration (2018) for regular electricity power mix).

Table 3.4 Emission factors for electricity production

Pollutant	Emission factor for electricity production, lb/MWh	
	From landfill gas*	**From standard US power mix****
Nitrogen oxides (NO_x)	2.5	0.8
Sulfur dioxide (SO_2)	0.027	0.8
Volatile organic compounds (VOCs)	0.86	0.1
Particulate matter (PM)	0.4	3.6
Carbon dioxide (CO_2)	938	987

*Chen & Greene (2003), **Energy Information Administration (2018)

The electricity generated for landfill gas is based on a 50% landfill gas collection efficiency for food and yard waste, based on average decay rates for food and yard waste (de la Cruz and Barlaz, 2010), and varying landfill gas collection efficiency by year (Levis and Barlaz, 2011).

3.2.3 F^4 Basic Tool Outputs: Costs

Table 3.5 shows costs and benefits included in the F^4 Basic Tool. The time frame is 50 years, which represents a reasonable estimate of the lifespan of a WWTP digester, according to our interviews. Standard engineering economy factor table values are used to convert annual costs to present values as needed, assuming a 50-year project lifetime (average digester lifetime, from interviews with wastewater treatment personnel) and 2% annual interest rate (representative average annual interest rate in US for past 10 years, Macrotrends).

Table 3.5 Costs/benefits included in the F^4 Basic Tool

General Category	Specific Category	Landfill	Digester
Out-of-Pocket Costs for City	**Waste transport** operating costs[1]	To landfill	To digester
	Waste treatment/ disposal capital and operating costs	Landfill, considered via tipping fee	Anaerobic digester, grinder, energy conversion/refueling station
	City fleet vehicles – capital costs	Gasoline or diesel vehicles	CNG or electric vehicles
Out-of-Pocket Benefits to City	Benefits from **renewable fuel**	Revenue from sale of: • **Electricity** plus premium & renewable energy credit • **Direct use/high BTU gas** plus climate credit • **CHP hot water or steam production** plus climate credit • **CNG** plus RIN	**Fleet fuel cost savings** (gasoline or diesel) plus climate credits
Emission/Social Costs/Benefits	Emissions from **city fleet vehicles**	Gasoline or diesel	CNG or electric
	Emissions from **electricity production**	From landfill gas	From standard fuel mix

[1] Includes fuel, driver & helper wages

The following sections discuss the costs and benefits in more detail.

3.2.3.1 Waste Transport Costs

Table 3.6 shows the information used to estimate waste transport costs. It is assumed that no new trucks are needed for pickup of food and yard waste (existing trucks are used). It is assumed that a garbage truck travels at 30 mi/hr (needed to calculate transport time, which is used to calculate driver and helper wages).

Table 3.6 Information to estimate waste transport costs

Category	Cost	Reference
Fuel	$2.92/gallon diesel	AFLEET, Argonne National Lab
Driver salary	$40,000/year	US Dept. of Labor (Gillespie, 2016)
Helper salary	$20,728/year	US Dept. of Labor (ZipRecruiter, 2019)

Gallons of fuel consumed are calculated according to:

Gallons of fuel = (Vehicle miles traveled) / (Miles/gallon)

Average fleet vehicles miles traveled and fuel economy (miles/gallon) were taken from AFLEET, as shown in Table 3.1.

3.2.3.2 Waste Treatment/Disposal Costs: Landfill

The landfill tipping fee is assumed to cover operating and capital costs associated with the landfill (Bolton, 2018). Table 3.7 shows regional landfill tipping fees included in the Tool.

Table 3.7 Regional landfill tipping fees (EREF, 2019)

Area (States)	Tipping Fee ($/ton)
National Average Tipping Fee	55.36
Pacific (AK, AZ, CA, HI, ID, OR, WA)	73.03
Northeast (CT, DE, ME, MD, MA, NH, NJ, NY, PA, RI, VT, VA, WV)	66.53
Midwest (IL, IN, IA, KS, MI, MN, MO, NE, OH, WI)	48.87
Mountains/Plains (CO, MT, ND, SD, UT, WY)	50.71
Southeast (AL, FL, GA, KY, MS, NC, SC, TN)	45.25
South Central (AR, LA, NM, OK, TX)	40.92

Landfill disposal costs ($/year) = (Tipping fee, $/ton) * (tons/year diverted from landfill)

3.2.3.3 Waste Treatment/Disposal Costs: Digester

The digester costs include capital and operating costs for the anaerobic digester itself, the food/yard waste grinder, energy conversion equipment to convert digester gas to CNG or electricity, and the refueling station. Each of these costs is discussed in more detail in the following sections.

3.2.3.3.1 Anaerobic Digester Capital Costs

Dr. Leonard Ripley, Ph.D., P.E., Senior Environmental Engineer, Water/Wastewater Treatment and Reuse, Freese and Nichols, Inc. provided advice concerning methods of estimating anaerobic digester capital and operating costs. Dr. Ripley has decades of experience in digesters at wastewater treatment plants.

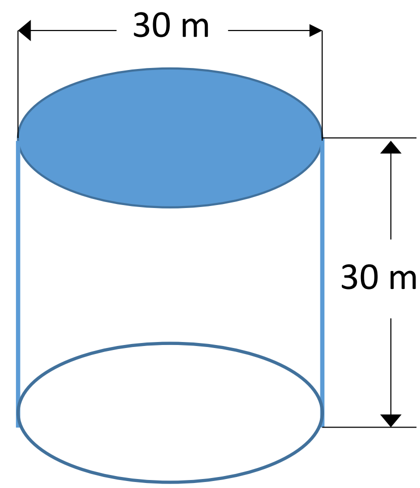


Figure 3.3 5 MG digester

Table 3.8 below estimates capital costs for a 30 m diameter x 30 m tall cylindrical concrete digester (5 million gallons, MG, as shown in Fig. 3.3), which is a common shape and size for new digesters today at wastewater treatment plants. It is assumed that if the waste volume is too large to fit in one digester, a second identical digester will be built. Additional 5.6 MG digesters will be added as needed to achieve the required capacity.

Table 3.8. Capital cost of a 30-meter concrete anerobic digester

Type of Cost	Specific Information	$ value
Concrete for walls and base (yd^3)	2355	$706,556
Steel rebar for walls and base (ft)	168,679	$131,642
Mixer (LM20-20-96 model, Ovivo)	20 hp motor and 96-inch Hydrodisk	$340,000
Cover (Steel Cover, floating, Westech)	For 30 m tank diameter	$400,000
Subtotal Cost 1 ($)		**$1,578,198**
Other Costs	Heating, Pumping, Electrical: 40% of Subtotal Cost [1]	$631,279
Subtotal Cost 2 ($)		**$2,209,477**
Consultants Cost	6% of Subtotal Cost [2]	$132,569
Contractors Cost	12.5% of Subtotal Cost [2]	$276,185
Foundation cost (including contractor)[3]		$500,000
Grand Total Cost ($)		**$3,118,230**

[1] Ripley (2020), [2] Shapoorian (2020), [3] Hossain (2020)

Concrete and steel rebar for a 30 m diameter x 30 m tall cylindrical concrete digester, as shown in Table 3.7, was estimated based on plans of existing digesters at the Village Creek Wastewater Treatment Plant in Fort Worth, Texas, with height adjusted to 30 m tall (the actual digesters are 30 m in diameter but only about 10 m tall). Although additional rebar was added to a height of

30 m in the wall, the rebar diameter was not increased to be able to carry excess load associated with a taller digester wall.

3.2.3.3.2 Anaerobic Digester (AD) Operating Costs

Operating costs are estimated for new digesters only, not for the existing digesters, which are already treating sludge (additional operating costs for adding food and yard waste to the existing digesters are not considered).

AD Operating Cost = **Mixing Cost** + **Pumping Cost** + **Heating Cost**

Mixing Cost ($/day) = Motor hp * (hours of operation/day) * (2545 BTU/hr/hp) / (3412 BTU/kWh) / (Motor efficiency) * $0.11/kWh

where
Motor hp = 20 hp (EBMUD WWTP)
Hours of operation/day = 3-4 (EBMUD WWTP)
Motor efficiency = 80% (Webber, 2007)
$0.11/kWh = average cost of commercial power in the US for 2019 (EIA, 2020)

Mixing Cost ($/ton) = Mixing cost ($/day)/(Sludge feed rate, tons/day)
Sludge feed rate = 15 tons/day (EBMUD WWTP)

Pumping Cost ($/day) = Pump hp * (hours of operation/day) * (2545 BTU/hr/hp) / (3412 BTU/kWh) / (Pump efficiency) * $0.11/kWh

where
Pump hp = 15 hp (EBMUD WWTP)
Hours of operation/day = 3-4 (EBMUD WWTP)
Motor efficiency = 80% (Webber, 2007)
$0.11/kWh = average cost of commercial power in the US for 2019 (EIA, 2020)

Pumping Cost ($/ton) = Pumping cost ($/day)/(Sludge feed rate, tons/day)
Sludge feed rate = 15 tons/day (EBMUD WWTP)

Heating Cost ($/year) = [(**Heat needed to raise temperature of waste**) + (**Heat needed to compensate for losses**)] (hours of operation/day) * / (3412 BTU/kWh) / (Efficiency of electric resistance heating) * $0.11/kWh

Heat needed to raise temperature of waste (BTUs) = (annual waste mass in lb) * (waste heat capacity) * [95°F - (average annual outdoor temp.)]

where
Waste heat capacity (assumed same as water, since food has high water content) = 1 Btu/lb/°F = 2000 Btu/(English ton of waste)/°F (Metcalf and Eddy, 2004)
95°F = 35°C = Mid-range of mesophilic temperatures (30-40°C); mesophilic digesters are most common, from our survey of WWTP with digesters

Heat needed to compensate for losses = (**Heat loss through new digester roof and floor**) + (**Heat loss through new digester walls**)

Heat loss through new digester roof and floor, MMBtus/yr/digester = 17.0 * (95°F - average annual outdoor temp); 17.0 comes from digester dimensions and heat transfer coefficient values for concrete digester base and roof from Metcalf and Eddy (2004).

Heat loss through new digester walls, MMBtus/yr/digester = 30 * (95°F - average annual outdoor temp); 30 comes from digester dimensions and heat transfer coefficient value for concrete digester walls from Metcalf and Eddy (2004).

Heat loss through existing digesters due to addition of food/yard waste is not accounted for.

Hours of operation/day = 24
Efficiency of electric resistance heating = 100% (US DOE)
$0.11/kWh = average cost of commercial power in the US for 2019 (EIA, 2020)

3.2.3.3.3 Grinder Capital and Operating Costs

One WWTP digester site is considered, so only one food/yard waste grinder is added. It is assumed that there is no existing grinder at the WWTP.

Capital cost: $900,000 (Mobark 6600 Grinder), with replacement every 5 years (per manufacturer)

Operating cost: $1/ton (CBI, 2020)

3.2.3.3.4 Energy Conversion/Refueling Station Costs

One WWTP digester site is considered, so only one fuel conversion system/refueling station is added. It is assumed that there is no existing fuel conversion system/refueling station at the WWTP.

Turbine-generator set for conversion to electricity

Capital cost = $1015*kW (US EPA, 2017) (Installed cost of gas compression/treatment, turbine/generator, site work and housing)

Installed Interconnecting Electrical Equipment Capital Cost = $250,000 (US EPA, 2017)

Operating cost = $0.0144*kWh (US EPA, 2017)

Reciprocating engine-generator set for conversion to electricity

Capital cost = $1300*kW +$1,100,000 (US EPA, 2017) (Installed cost of gas compression/treatment, engine/generator, site work and housing)

Installed Interconnecting Electrical Equipment Capital Cost = $250,000 (US EPA, 2017)

Operating cost = $0.025*kWh (US EPA, 2017)

CNG conversion

Capital cost = $95,000*$(ft^3/min)^{0.6}$ (US EPA, 2017) (cleaning, compression, and fueling station equipment)

Installed Interconnecting Electrical Equipment Capital Cost = $250,000 (US EPA, 2017)

Operating cost = $1/(gallon gasoline equivalent) (US EPA, 2017)
3.587 m^3 CNG = 1 gallon gasoline equivalent

3.2.3.4 Vehicle Capital Costs

Table 3.9 shows costs for purchasing city fleet vehicles (electric or CNG, as well as regular gasoline and diesel), taken from AFLEET Model, fleet managers, truck manufacturers, and Google for pickup trucks and car. Vehicles are assumed to be replaced every 13 years, based on the vehicle lifetimes shown in Table 3.2 and conversations with a waste management company. F^4 calculates the additional costs for purchasing electric vehicles with respect to diesel vehicles, and additional costs for CNG vehicles with respect to gasoline vehicles.

Table 3.9 Vehicle capital costs

Category	Sub-Category	Cost
Garbage Truck	Electric	$560,000
	Diesel	$210,000
	CNG	$245,000
Passenger Car	Gasoline	$20,000
	Diesel	$22,500
	Electric	$37,500
	CNG	$27,000
Pickup Truck	Gasoline	$32,000
	Diesel	$39,500
	CNG	$43,500
	Electric	$69,000
Light Commercial Truck	Gasoline	$36,000
	Diesel	$46,500
	CNG	$44,000
	Electric	$69,000

3.2.3.5 Benefits from renewable fuel

Table 3.10 shows benefits that cities gain from use and sale of renewable fuel. The current version of F^4 assumes:

- ***The landfill gas is sold to another party*** in the form of electricity, high BTU gas, CHP hot water or steam production, or CNG, or beneficially used. The option of the city using its own landfill gas for beneficial purposes is not included.
- ***Digester gas is used to fuel city fleet vehicles*** (electric or natural gas). These vehicles will replace vehicles that are gasoline or diesel. Thus, the costs of gasoline or diesel fuel are saved.

Since landfill gas is sold to another party, renewable energy certificates (REC) for electricity and Renewable Information Number (RIN) for CNG are obtained (REC and RIN typically involve a sale to another party). Since CNG and electricity generated from digester gas are not sold to another party, climate credits are obtained, but not Renewable Energy Certificates (REC) or Renewable Information Number (RIN). Credits that expire in 2020 (e.g. Renewable Electricity Production Tax Credit) are not included.

Table 3.10 Benefits from renewable fuel

Category	Sub-category	Selling Price	Kind of Credit	Value of Credit	Reference
Landfill Gas	Electricity	\$0.124 (includes renewable premium)	Renewable energy certificate	\$0.70/MW	US EPA
	Direct use/high BTU gas	\$2.25 per MMBtu	Climate	\$13.86/metric ton CO_2-equiv.	US EPA (2017), Investing.com
	CHP hot water or steam production	\$4 per MMBtu	Climate	\$13.86/metric ton CO_2-equiv.	US EPA (2017), Investing.com
	CNG	\$2/gallon gasoline equivalent	RIN	\$2.85/credit RIN Credits = (BTUs generated)/77,000	US EPA (2017)
Digester Gas	N/A	\$2.68/gallon gasoline, \$2.92/gallon diesel	Climate	\$13.86/metric ton CO_2-equiv.	ANL AFLEET, Investing.com

3.2.3.6 Emission/Social Costs/Benefits

When digester gas is used to produce electricity or CNG for fleet vehicles, emissions associated with current vehicles (gasoline, occurring at the tailpipe; or electric, occurring at the power plant) are avoided. On the other hand, when waste is sent to the digester instead of the landfill, the electricity generated by landfill gas is replaced with electricity generated by the standard US fuel mix (resulting in greater emissions).

Social costs associated with these emission trade-offs are included in the Tool based on information from the Interagency Working Group on Social Cost of Carbon, United States Government (2010) and European Union Environmental Prices Handbook (version EU28, Bruyn et al., 2018) as follows:

- For traditional air pollutants (VOCs, CO, NOx, PM10, PM2.5, SO_2), the value of reduced damage to human health, ecosystem services, buildings and materials, resource availability, and wellbeing
- For climate pollutants (CH_4, CO_2, N_2O), the value of reduced damage to agricultural productivity, human health, property (flood risk), and ecosystem services.

Right now, social costs associated with passenger cars and garbage trucks only are included, not passenger trucks or light commercial trucks, because GREET did not include appropriate emission factors for the passenger trucks or light commercial trucks. These will be included in an updated version of F^4.

Right now, social costs associated with landfill gas conversion to electricity only are included; social costs associated with conversion to high BTU gas, combined heat and power (CHP) hot water or steam production, or CNG will be included in an updated version of F^4.

Chapter 4: F^4 Optimization Extension

4.1 Literature review and cost identification

The research team reviewed literature on cost optimization modeling, focusing on a multi-objective optimization problem that minimizes the total system costs including transportation, capital, and facility operational costs. Transportation (including fuel and employee time) and conversion costs were collected as part of Obj. 1 (surveys) and Obj. 2 (collect additional cost information).

4.2 Model design and implementation within a sample network

The F^4 Optimization Extension was developed, with inputs and outputs shown in Fig. 4.1. The model determines the overall least-cost system of digesters for converting food/yard waste to fleet fuel. When more than one WWTP with digesters is available, the Extension determines the optimum region(s) of waste to send to each.

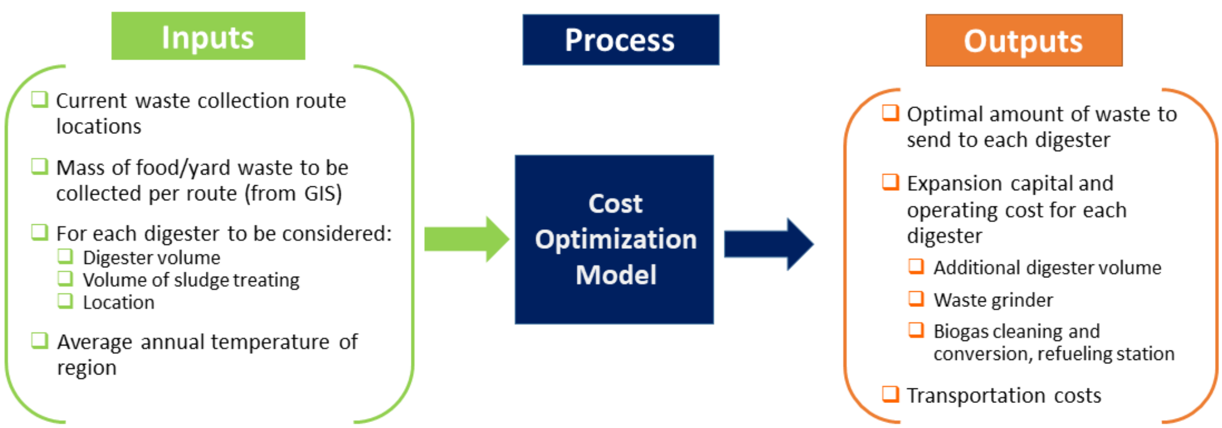


Figure 4.1 F^4 Optimization Extension inputs and outputs

The Extension balances trade-offs between waste transportation costs and capital and operating costs for digesters, waste grinders, biogas cleaning and conversion, and refueling stations. For example, as shown in Fig. 4.2, small capacity digesters in multiple locations may require lower transportation costs due to the shorter distances between waste generators and a digester. However, higher capital costs would be necessary to add additional digester capacity and provide gas upgrading/conversion equipment and refueling stations at these multiple facilities. A large digester could minimize the capital expansion costs (cost per unit of waste digested); however, higher transportation costs are expected since all the waste has to be transported to the central facility.

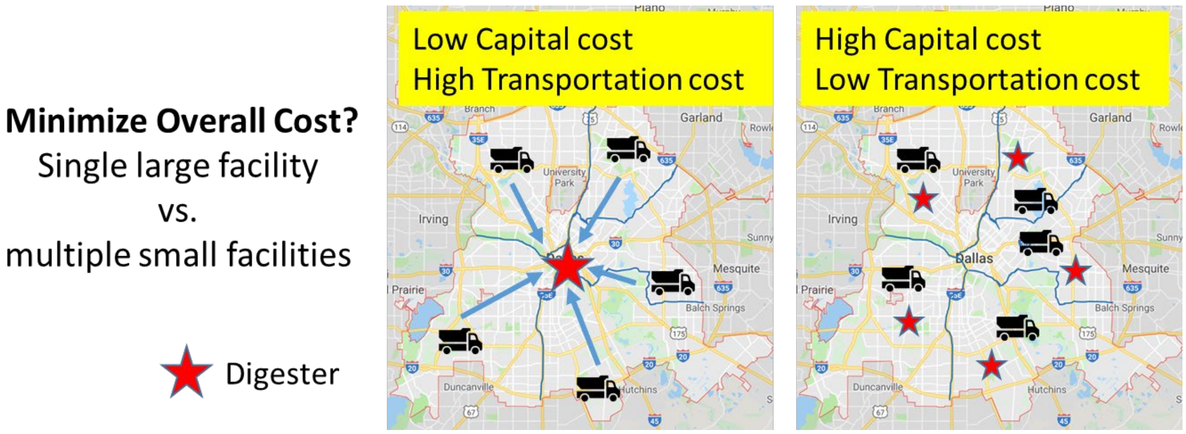


Figure 4.2 Optimization Extension balancing of transportation costs with digester facility capital costs

The team formulated an objective function and system constraints, as shown in Fig. 4.3. The objective function identifies minimum total costs for selected facility locations considering various capacities and expansion of digesters. Constraints ensure additional logistic requirements such that the total waste amount meets total facility capacity. Transportation costs are determined using the shortest path algorithm in ArcGIS.

i : zone, l: facility, S: facility cost, c: transportation cost

$y_l \in \{0,1\}, z_{il} \in \{0,1\}$ (Binary decision variable)

Facility cost | Transp. cost

Min $\sum_l s_l y_l + \sum_i \sum_l c_{il} z_{il}$

Subject to

$\sum_l z_{il} = 1 \; for \; all \; i$ (one zone transport to one facility)

$\sum_l y_l = 1 \; for \; all \; i$ (one facility has only one size)

$\sum_i x_{il} z_{il} <= f_l y_l \; for \; all \; l$ (Supply <= Capacity)

$\sum_{l=1} x_{il} z_{il} = d_i \; for \; all \; i$ (Supply = Demand)

$\sum_l x_{il} <= \sum_l d_i y_l \; for \; all \; i$ (Supply = Demand & Supply <= Capacity)

$\sum_l s_l = C$ **(facility costs from Cost Spreadsheet)**

Figure 4.3 Objective function

The research team investigated a sample network for implementation of the objective function and chose the widely-used Nguyen-Dupuis network. The research team developed two optimization frameworks (uncapacitated and capacitated) using the sample network using solver from optimization software Gurobi (Python API). A second spreadsheet, “Input-Output for Optimization Extension,” was developed to summarize inputs needed for the Optimization Extension, as well as outputs from the Optimization Extension.

Chapter 5: Food/Flora Waste Separation Policy Survey and City Guidebook

5.1 Policy Survey

5.1.1 Literature search

Information was collected from the web and various literature sources on US (Table 5.1) and international (Table 5.2) food waste diversion programs, including year enacted, applicability to residential and/or commercial food waste, whether donation is encouraged or required, incentives/penalties, and impact. The US programs for which interviews were not conducted, as well as international programs, are discussed in more detail in 5.1.1.1 through 5.1.1.6. US programs for which interviews were conducted are discussed in Section 5.1.2.

Table 5.1 Selected US food diversion programs

Location	Year Enacted	Commercial/ Residential	Food Donation	Goal/Impact
Connecticut	2010	Commercial Only	No	Reduction of 1 ton per week by 2020
Massachusetts	2014	Commercial Only	No	35% diversion by 2020
New York	2022	Commercial Only	Yes	50,000 tons per year targeted
Portland	2018	Commercial/ Residential	Yes	50% by 2050
San Francisco	2009	Commercial Only	Yes	80% diversion (2012 data)
Seattle	1988	Commercial Only	No	Diverted 38,000 tons or 60%

Table 5.2 Selected international food diversion programs

Location	Year Enacted	Commercial/ Residential	Food Donation	Impact
Australia	2018	Commercial Only	Not Required	Reduction of 50% per week by 2030
Denmark	2016	Commercial Only	Not Required	25% diversion by 2021
France	2012	Commercial/Residential	Required	Reduction of 120 tons/yr
Italy	2016	Commercial Only	Required	25% reduction in 5 years
South Korea	2013	Commercial/ Residential[1]	Required	10% reduction per day
UK	2013	Commercial/ Residential	Required	Reduction of 1.5Mt by 2025

5.1.1.1 New York City, NY, US

New York City, NY, passed an ordinance in 2019, which takes effect in 2022 and bans landfills from accepting food waste. Regulatory compliance is limited to commercial producers of food and vegetative waste. Yard waste is excluded. Donation is mandatory 1 week prior to the use-by date, and for pre-line food (not served to the public). Fines are imposed for non-compliance.

5.1.1.2 Seattle, Washington, US

In 1988, Seattle prohibited yard waste from the garbage. In 2005, Seattle prohibited recyclables from the garbage and also began curbside food waste collection. In 2009, Seattle required all residential properties to either subscribe to food and yard waste collection or participate in backyard composting. Since late 2011, multi-family buildings in Seattle have been required to provide compost collection service for their residents. In 2015, Seattle prohibited food waste from the garbage.

5.1.1.3 Denmark

Denmark adopted a program in 2010 and the EU Parliament passed a resolution to target the reduction of food waste by 50% before 2025. Denmark has limited space for landfills; therefore, biological treatment for food waste is available in a few locations. Regulatory compliance is limited in Denmark to limited to commercial producers. Landfills are restricted from accepting food and yard waste. Landfill permits may be revoked for non-compliance.

5.1.1.4 France

Landfills are banned from accepting food and yard waste. Commercial producers are required to donate food, with fines for violations. Food donation is required prior to the expiration date; it may also be donated after the expiration date if not spoiled.

5.1.1.5 South Korea

Regulatory compliance for commercial/residential producers of food and vegetative waste. Yard waste is also collected. Food donation is required. The weight of food waste collected is measured for each household. Fines are imposed for violations. Incentives are provided for compliance.

5.1.1.6 UK

Regulatory compliance for commercial/residential producers of food and vegetative waste. Food waste collection and donation are required. Funding is provided for waste reduction programs. Reworking/repackaging of edible food is used to minimize waste. Incentives are provided for compliance.

5.1.2 Questionnaires and Phone interviews

Based on the review of the literature, programs were short-listed based on the following factors: 1. The inclusiveness of the program, 2. The projected amount of food diversion, 3. Access to information on their program website, 4. Existence of state-level tax incentives. Questionnaires were sent to 11 programs, with responses from the 7 programs shown in Table 5.3. Once the questionnaires were returned, follow-up telephone interviews were conducted, using the questions shown in Figure 5.1. Information from the literature review, questionnaires, and phone interviews is summarized for the 7 programs in the next section. Additional information is provided in the city guidebook on the project website.

Table 5.3 Food waste diversion programs for which phone interviews were conducted

STATE	MUNICIPALITY	Materials Collected
California	San Francisco	Yard Waste; Food Scraps; Food Soiled Paper
Connecticut	Statewide Program	Yard Waste; Food Waste; Compostable Material
Massachusetts	Statewide Program	Yard Waste; Food Scraps; Food Soiled Paper
Nevada, Southern	Las Vegas	Food Waste only
Texas	Austin	
Vermont	Statewide Program	Compostable products only.
Washington	Statewide Program	Yard Waste; Food Scraps; Food Soiled Paper

- What sticks/carrots were established?
  - Are they directed to the producer/grower/individual?
  - Are there any consequences for the landfill if food/yard waste is deposited?
  - Tax incentives for participation
  - Subsidies for residential homes
  - Availability of digestate for fertilizer
  - Renewable energy credits
  - Carbon offset credits
- Was the anticipated participation rate met?
- How much biomethane was captured?
- Cost/Benefit of the program
- How was cost offset accomplished?
  - Capital bonds?
  - Public private partnership grants?
  - Federal Subsidies?
- How was community engagement accomplished?
  - What was effective?
  - What was not effective?
- Are you diverting biomass from the landfill?
  - If so, how much is being diverted?
  - What materials are you diverting?
    - Organic (food) waste?
    - Organic (non-food) materials?
    - Construction materials?
- For residential collection
  - Is there in-home collection?
  - On-street collection?
  - How are you controlling the smell?
  - How are you controlling the vector/vermin?
- What did you wish you knew before you started?

Figure 5.1 Phone interview questions for municipal food/yard waste diversion programs

5.1.2.1 California: San Francisco

Program Manager/contact: Alex Dmitriew, Commercial Zero Waste Coordinator, San Francisco Department of the Environment
Website: https://sfenvironment.org/zero-waste-in-SF-is-recycling-composting-and-reuse

San Francisco's program is city-wide as they are both a city and a county. They rolled out original programs back in 1998 with some commercial pilots and then expanded to the residential sector in subsequent years. Currently, all sectors (multi-family, commercial and residential) have three stream service: recycling, composting and trash.

As a means to ensure compliance, the program established a "pay as you throw" program to incentivize generators to participate, which applies to all generators/sectors. San Francisco's landfills are privately owned and are not directly affected by the policies. Additionally, due to the nature of the program there are no tax incentives. However, the pay as you throw for residential and discounts for commercial based on the total volume recycled and composted. Furthermore, the organics processor makes finished compost available to the community at no charge during community events.

Since the inception of the program, San Francisco has met their anticipated participation. Virtually all sectors have access to three-stream collection. The entire program is funded by rate payers (generators). Because of this, the department is not funded through the general fund and as such receives no tax funds.

A community outreach department was created and works closely with the sole service provider, Recology, to communicate program parameters and supporting messages to all sectors. The messaging is target-specific, that is, different for the residential vs. commercial sectors. It is further targeted to actual demographics and is language-specific, since San Francisco has a large English as a 2nd language (or no English at all) population.

Currently, this program includes is diverting approximately 700 tons per day. At-home collection is provided only for disabled persons or special circumstances; other collection is curbside. Single-family homes are collected weekly; multi-family and commercial are as needed up to 7 days per week, maintaining adequate service levels to mitigate vector/vermin invasion.

San Francisco adopted a Mandatory Recycling and Composting Ordinance in 2009, targeting an 80% reduction in food waste to landfills by 2020. Landfills are banned from accepting food waste. Fines are imposed for non-compliance. This program is not exclusive to food waste; all recyclable materials must be recycled. The program applies to businesses, residential owners, and renters.

San Francisco offers rewards to food waste generators and service providers for reducing waste. Businesses receive a rate discount based on actual diversion. Residents receive reduced cost for recycle collection bins. (SFDE a, b)

5.1.2.2 Connecticut

Program Manager/contact: Chris Nelson, CT Department of Energy and Environmental Protection
Website: www.ct.gov/deep/recycle. www.RecycleCT.com

Connecticut creates approximately 520,000 tons of food waste and predicts a reduction of 60% in food waste by the target date of 2024. The law requires any business with food waste generation of ≥104 tons per year to divert from the landfill to a recycling facility. This law only affects those producers that are within a 20-mile radius of a recycling facility. Currently, an AD is being built to handle 40,000 tons of food waste per year and produce 1.1 megawatts of electricity.

Landfills are restricted from accepting food waste. The Department of Energy and Environmental Protection (DEEP) may impose fines of $2,500 per violation, but not more than $10,000. It may also revoke permits for non-compliance.

Connecticut does not have a food donation program with incentives; all donations are covered by the Federal Government Tax Incentive Program section 170 of the Internal revenue Code (IRC), which provides for enhanced tax deductions for food donation. Furthermore, corporations that are donating food in accordance with state and federal regulations are protected from legal action according to the 42 United States Code (USC) subsection 1791.

The goal is the diversion of organic materials to anaerobic digesters. Anaerobic digester facilities that generate electricity onsite are eligible for Class I Renewable Energy Certificates (RECs). The program does permit traditional composting operations to benefit from the materials diverted to them for processing. Furthermore, some companies that offer curbside collection of food scraps to paying customers will periodically offer their customers finished compost (which includes digestate from food scraps). (CDEEP, 2019, 2020)

5.1.2.3 Massachusetts

Program Manager/contact: Mr. John Fischer, Department of Environmental Protection
Website: https://www.mass.gov/guides/commercial-food-material-disposal-ban

Massachusetts' program, approved in 2014, bans commercial food and vegetative waste generators greater than 1 ton from disposal in incinerators or landfills. This includes food manufacturers and distributors, restaurants, and universities/colleges. This program also includes yard waste; however, it does not apply to residential food waste. In 2014, 1350 businesses participated in the program, diverting 100,000 tons of organic waste annually. By 2018, 2300 participated, diverting 280,000 tons a year. Massachusetts' program is expected to achieve a 35% food waste diversion statewide by 2020.

This program is regulated by 310 CMR 19.000 and bans disposal of leaves, yard waste, wood, and commercial organic material from being delivered to a landfill. 310 CMR 19.000 (3) (b) states, "No landfill, transfer facility or combustion facility shall accept the restricted material except to handle, recycle or compost the material in accordance with a plan submitted pursuant to 310 CMR 19.017(6), and approved by the Department." The landfill is charged a 3% fee for each violation. Failure to comply may result in the loss of a landfill permit.

In order to ensure compliance, landfills monitor loads. For initial non-compliance, an infraction enforcement notice of non-compliance is issued. Subsequent violations incur the next level of enforcement: a penalty (directed at the producer) of $860 to $1000 per violation.

As a program outreach to assist businesses and institutions with compliance with the ban, a compliance assistance recycling program called RecyclingWorks was developed. There are no tax incentives for participation. All donations are covered by the Federal Government Tax Incentive Program section 170 of the Internal revenue Code (IRC), which provides for enhanced tax deductions for food donation. Furthermore, corporations that are donating food in accordance with state and federal regulations are protected from legal action according to the 42 USC subsection 1791.

The cost of standard landfilling is higher than self-sorting biomass; the assistance programs allow generators to save the cost of landfilling per ton. The cost offset is accomplished by funding through waste to energy grants and qualification for renewable energy credit. There are certain retain 50% into a fund to be returned to the program from the biomass that is sold. (MDEP 2014a, 2014b, 2017)

5.1.2.4 Nevada, Southern

Program Manager/contact: Rachel Lewison, State of Nevada Environmental Waste Management
Jeremy Walters, Republic Services Waste Management
Website: https://ndep.nv.gov/nevada-recycles/recycle/waste-reduction

Southern Nevada's program encompasses the Las Vegas area. The casinos are the largest producer of food waste, due to the regulatory constraints surrounding food safety. Food that is on-line, being available for self-service, is deemed non-edible if it is out and hot after 4 hours and thereby becomes food waste.

Presently, the food waste is diverted from the landfill to livestock agriculture feed and compost, although there are tipping fees if the organic waste is over 2 tons (a minimum of 35 dollars a ton).

Aside from this program, Southern Nevada is participating in waste to energy through the capture of landfill gas. Republic Services captures methane off the landfill utilizing a large number of gas wells, scrubs the methane with the assistance of bacteria, and then pumps the biomethane to the power plant's combustion turbines, which are rated at a combined capacity of approximately 11 megawatts. Nitrogen oxide emissions are removed using selective catalytic reduction. The generated power is sent back to the municipal power grid.

Southern Nevada does not use an anaerobic digester. The Wastewater Treatment Facility does have the capacity to do anaerobic digestion but has not explored the opportunity. (Republic Services, 2011)

5.1.2.5 Texas: Austin

Program Manager/contact: Tyler Markham Planner III - Business Outreach Team
Website: http://www.austintexas.gov/department/austin-resource-recovery

Since its inception in 2018, the City of Austin's Zero Waste goal aims to divert at least 90% of discarded materials from area landfills by 2040 (City of Austin, 2020). A study released by Austin Resource Recovery found that nearly 20% of what ends up in landfills from private waste streams is food that could have been recovered to feed people, converted to animal feed, or composted. Eliminating food waste will also help to meet the City's goal of net-zero community-wide greenhouse gas emissions by 2050, since landfilled food waste generates methane. This program unfortunately does not utilize anaerobic digestion for methane capture. AD is preferable to composting from an environmental perspective because it produces a renewable source of energy in the form of biogas, and composting wastes this energy as heat.

Austin's organics diversion program is directed at both residential and commercial customers and maintained by a contracted company. Although the city encourages donation of food prior to the use-by date, no city tax incentives are available for food donation, only those available from the federal government. As a means of vector/vermin control, residents are provided outside storage bins with covers for organic materials, which are picked up weekly.

Yard trimmings collected curbside are composted to create mulch. The mulch is made available to the public for free. (Austin, 2016)

5.1.2.6 Vermont

Program Manager/contact: Emma Stuhl, Department of Environmental Conservation
Website: https://dec.vermont.gov/waste-management/solid/materials-mgmt/organic-materials

Vermont's food waste ban took effect on July 1, 2020, banning the disposal of food scraps in the trash or landfills. Due to the regulatory nature of the program, no incentives are provided for participation.

Vermont is predominantly a rural community state and as such, the program is focused on residential collection by offering different services. Vermont residents are encouraged to conduct at home composting. Residents that participate in the at-home composting are allowed to dispose of meat and bones after the ban takes effect. For residents that choose not to participate in at-home composting, food waste drop-off facilities are available to receive organic waste. This ban provides unique solutions for business/institutions: if the businesses have edible food, they are encouraged to and have begun donating edible food to food banks. (VDEC 2020a, b)

5.1.2.7 Washington State

Program manager/contact: Jade Monroe, Department of Ecology
Website: https://ecology.wa.gov/Waste-Toxics/Reducing-recycling-waste/Organic-materials/Food-waste-prevention/Food-waste-plan

Food waste makes up over 28% of the overall statewide waste stream. The food diversion program was enacted in 2019, in conjunction with the Departments of Health, Agriculture, and the Office of Public Instruction, in order to divert 50% of the organic waste by 2030. This program is regulatory; therefore, no incentives are provided for compliance. (WDOE, 2019)

5.1.3 Summary

San Francisco and Vermont are the only programs that include residential food waste as part of their food waste ban; the remainder of the bans targeted commercial growers/producers. Due to the amount of residential annual food waste per person, all programs would benefit from the added residential food waste.

Although these programs have considered anaerobic digestion, few programs have explored that avenue as a means of energy production. The Las Vegas program, through Republic Services, Inc., captures methane off the landfill and transports it to a power plant; the energy generated is sent to the municipal power grid. This program would benefit from the development of anaerobic digestion strategy due to the amount of food waste generated by Las Vegas' 51 casinos.

5.2 City Guidebook

The literature review and interviews described above were used as material for the city guidebook, "Anaerobic Digestion of City Food and Yard Waste: Answers to 10 Critical Questions." The guidebook addresses common questions that cities may face when considering diversion of food and yard waste from landfills. The guidebook is available on the project website.

Chapter 6: Feasibility Study for City of Dallas

6.1 Scenarios Evaluated

Dallas has two WWTPs, Central and Southside. Sludge from Central (where there is no digester) is currently pumped to Southside, where the AD is located. Accordingly, the following scenarios were evaluated:

(1) Add new AD (5.6 MG) at Dallas Central and use existing AD at Southside,

(2) Expand AD capacity at Southside by adding a 5.6 MG digester.

These scenarios were hypothetical, run as a proof-of-concept of the GIS procedure for estimating food/yard waste generation, F^4 Basic Tool, and Optimization Extension. In actuality, barriers exist to the addition of digesters at Dallas Central. The City of Dallas previously had digesters at Dallas Central, which were closed due to limited land availability and odor issues in the surrounding community.

6.2 Methods

Spatial locations of food waste sources and yard waste sources were identified and food/yard waste generation was estimated using the GIS procedure developed in Obj. 1. Waste collection route information was obtained from the City of Dallas, and food/yard waste were aggregated by block group and garbage route. It was assumed that 33% of Dallas food waste and 31% of yard waste is sent to an AD. 67%, or 2/3 of food waste, is assumed to be fed to the hungry (Hoover, 2007). 31% is the national average amount of yard waste currently landfilled (EPA, 2018a). Fig. 6.1 shows the total food and yard waste for the City of Dallas aggregated by block group.

Next, the Optimization Extension was utilized to determine whether Scenario 1 or 2 had the lowest total capital plus operating costs for waste transportation plus digestion. The following assumptions were made in running the Optimization Extension:

- Diesel garbage trucks are used to transport food and yard waste (not electric or CNG).
- AD operating costs are considered only for food & yard waste (not sludge).
- Biogas from AD digestion of food and yard waste only (not sludge) is used to generate electricity (for other garbage trucks).

6.3 Results

Table 6.1 shows the optimization results.

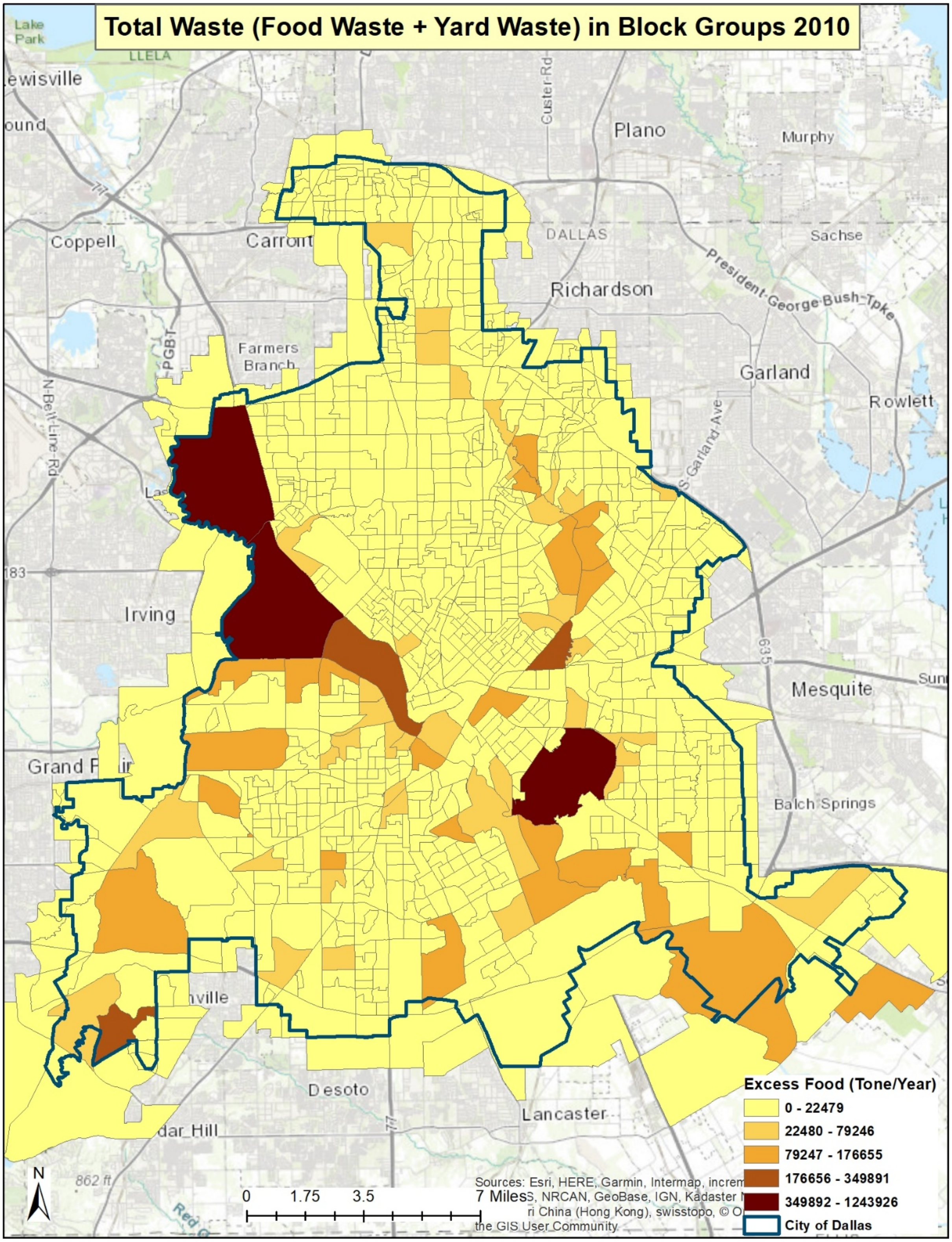


Figure 6.1 Total food/yard waste for the City of Dallas aggregated by block group

Table 6.1 City of Dallas feasibility study optimization results

		Scenario 1			Scenario 2
		Southside	Dallas Central	Total	Southside
Food/Yard Waste	# of routes	31	251	**282**	**282**
	Food waste (tons/year)	4,847	51,974	**56,821**	**56,039**
	Yard waste (tons/year)	125,153	1,724,064	**1,849,217**	**1,849,999**
	Total Mass (tons/year)	130,000	1,776,037	**1,906,037**	**1,906,038**
Facility Costs - Capital and Operation	Digester	$ 11,061,524	$ 155,619,571	**$166,681,095**	**$ 166,681,180**
	Grinder	$ 10,151,765	$ 61,876,173	**$72,027,938**	**$ 65,961,273**
	Biogas conversion	$ 9,778,009	$ 127,250,547	**$137,028,555**	**$ 136,528,314**
	Total (for 50 years)	$ 30,991,297	$ 344,746,291	**$375,737,589**	**$ 369,170,767**
Transportation cost	Total (for 50 years)	$ 2,651,882,303	$ 57,057,200,025	**$59,709,082,328**	**$ 101,675,109,264**
Total Cost (for 50 years)		**$**		**60,084,819,917**	**$ 102,044,280,031**

The following can be observed in Table 6.1:

- For Scenario 2, the existing digesters at Southside are not large enough to accommodate the food and yard waste, so an additional digester must be added.
- Since a digester must be added for both scenarios, the digester capital and operating costs are approximately equal for both scenarios.
- Grinder costs are higher for Scenario 1 (Southside & Central), because a grinder must be provided at each location, vs. only one at Southside for Scenario 2.
- Biogas conversion costs are slightly higher for Scenario 1. Although conversion costs are largely a function of the biogas processed, which is the same for both scenarios, there is a small fixed cost that must be paid twice for Scenario 1, once for each digester.
- Overall facility costs are higher for Scenario 1 due primarily to the grinder.
- Transportation costs are higher for Scenario 2 (Southside alone).
- Overall, costs are higher for Scenario 2 (Southside alone), because the greater transportation costs for Scenario 2 outweigh the greater facility costs for Scenario 1.

Table 6.2 shows the energy and emission results for Scenario 1. As shown, digestion of 33% of Dallas' food waste and 31% of its yard was provided enough electricity to continually operate 2507 garbage trucks.

Table 6.2 Energy and emission results for Scenario 1 (Southside and Dallas Central)

Result Category		**Value for Electric Vehicles**
Volume of biogas generated*		422,000 m^3/day
Electricity generated		540 GWh/year
Miles travelled on electricity – **garbage trucks**		980,000 miles/year
Number of **garbage trucks** that can operate continuously on electricity		2507
Emission reductions (over diesel), metric tons/year	CO_2-eq.	120,240 t/yr
	VOCs	0.35 t/yr
	CO	19.2 t/yr
	NO_x	69.3 t/yr
	PM 2.5	3.1 t/yr
	SO_2	3.1 t/yr

*Food & yard waste alone, not sludge

Table 6.3 shows the overall costs/benefits for Scenario 1, in addition to digester and transportation costs. Benefits are shown as negative (-) numbers. The following can be observed in Table 6.3:

- Waste transport costs are higher to take food and yard waste to the landfill because the landfill is farther away.
- Waste treatment/ disposal capital and operating costs are almost five times greater for the landfill compared to the AD. A local landfill tipping fee of $30.50/ton (commercial fee for McComas Bluff) was used to estimate the landfilling cost.
- The purchase of electric garbage trucks costs over twice as much as diesel.
- Greater benefits accrue in terms of renewable fuel from the digester compared to the landfill. This is due in part to the fact that twice as much gas is captured from the digester (an enclosed system) compared to the landfill, where 50% of the gas generated escapes before capture.
- Over a 50-year timeframe, the current landfilling scenario costs almost $28 billion more than digestion.

Table 6.3. Overall costs for Scenario 1

General Category	Specific Category	Landfill: Current Scenario	Digester: Scenario 1
Out-of-Pocket Costs for City	**Waste transport** operating costs	$86,158,383,131	$59,709,082,328
	Waste treatment/ disposal capital and operating costs	$1,826,784,559	$375,737,589
	Garbage trucks – capital costs (2507 vehicles)	Diesel $1,491,272,077	Electric $3,976,725,539
Out-of-Pocket Benefits to City*	Benefits from **renewable fuel**	Sale of electricity from landfill gas plus premium & renewable energy certificate -$1,064,911,810	Diesel fuel cost savings plus climate credits -$2,893,122,563
Emission/Social Costs	Emissions from garbage trucks	Diesel garbage trucks compared to electric $717,295,537	N/A
	Emissions from **electricity production**	N/A	Electricity from standard fuel mix compared to landfill gas $170,537,159
TOTAL COSTS		**$89,128,823,494**	**$61,338,960,052**

*Twice as much electricity is generated from a digester because collection of landfill gas from food and yard waste is only 50% efficient.

Chapter 7: Technology Transfer

The project website contains the following materials available for access/download:

- F^4 Basic Tool, User Manual, and video tutorial,
- City guidebook "Anaerobic Digestion of City Food and Yard Waste: Answers to 10 Critical Questions,"
- This report,
- A video of an American Society of Civil Engineers meeting presentation about F^4.

In terms of technology transfer to municipal officials and policy makers, we conducted three formal meetings with NCTCOG and two formal meetings with the City of Dallas staff, our stakeholders, on development of the F^4 Framework. We also communicated with them informally throughout the project as needed to acquire data.

To reach other practitioners, we presented at the July 2019 Dallas-Fort Worth branch meeting of the American Society of Civil Engineers. We also made presentations at two national conferences: the 2020 Air & Waste Management Association (AWMA) Annual Conference (June 2020) and the Scientific Online Green Energy Conference (July 2020). In addition, a presentation was accepted for the 2020 INFORMS (Institute for Operations Research and the Management Sciences) Annual Meeting to be held in National Harbor, MD, November 2020. Furthermore, the PI has volunteered to write an article for the March 2021 issue of AWMA's *EM (Environmental Manager)*, which reaches a broad audience in government, industry, consulting, academia.

In upcoming months, we will volunteer to make presentations at NCTCOG committees of municipal officials, including the Resource Conservation Council (RCC). Students involved in the project will make presentations at the College of Engineering Research Day and Innovation Day. We will also volunteer to make presentations at meetings of other local organizations. We will present a CTEDD webinar, and to reach academic stakeholders, we will submit articles to journals (e.g. *Transportation Research Record and Practice*, *Clean Technologies and Environmental Policy)*.

UTA is working with NCTCOG on a plan to reach early adopters throughout the DFW Metroplex. NCTCOG and UTA recently collaborated on a proposal to US EPA, in which the two entities will coordinate with stakeholders in the North Central Texas (NCT) region to complete a North Central Texas Food Waste to Fuel Feasibility Study. If funded, the study will advance regional efforts to divert food waste, and other organics, from landfills to preserve landfill capacity; increase regional renewable energy opportunities; and evaluate the potential to reduce fleet emissions. A major task element will be identifying regional anaerobic digestion locations using the F^4 Framework.

Chapter 8: Conclusions and Recommendations

8.1 Conclusions

- The F^4 Framework serves as a method to assess the feasibility of co-digesting food and yard waste in existing wastewater treatment plant (WWTP) digesters.
    - The GIS procedure provides a method for estimating food and yard waste to be collected for digestion.
    - F^4 Basic Tool provides information about anaerobic digestion cost, reduced pollutants emissions, and fuel produced.
    - The Optimization Extension can help select the optimal digesters.
    - The city guidebook addresses common questions that cities may face when considering diversion of food and yard waste from landfills.
- The optimal scenario for digesting food & yard waste for Dallas is to build a new digester at Dallas Central and also use the existing digesters at Southside.
- The City of Dallas could save almost $28 billion over 50 years by sending 33% of its food waste to these digesters, along with the yard waste that is currently landfilled (31%).
- Cost savings are primarily driven by savings in transport costs (the landfill is farther away than the digesters), along with savings in landfill space and diesel fuel (due to use of electricity from digester gas).

8.2 Recommendations for future work

Improvements to incorporate into the next version of F^4 (F^4 2.0) include:

- Additional options for cities to select:
    - End-use of digester gas (non-vehicle fuel, especially if more energy is produced than can be used for fleet vehicles; city sells digester gas rather than using it itself),
    - City use of landfill gas rather than selling it,
    - Refueling station already available,
    - Reference vehicle for electric and CNG vehicle (currently the electric vehicle cost is compared to diesel, and the CNG vehicle cost is compared to gasoline)
    - Deselect sludge, in case it is already beneficially reused, to estimate the additional amount of gas to be produced from food and yard waste alone,
- Emission benefits for passenger and commercial trucks, as well as landfill gas direct use, boiler, and CNG,

- Cost of digestate processing (digester liquid and solid residual),
- Estimation of payback time/internal rate of return,
- A graphical user interface for the Optimization Extension.

An additional recommendation is to conduct a sensitivity analysis to determine the extent to which results depend on fuel costs.

Furthermore, future projects should collect improved data on food-waste generation rates for multi-family housing, as well as yard-waste generation for golf courses, parks, and commercial lawns.

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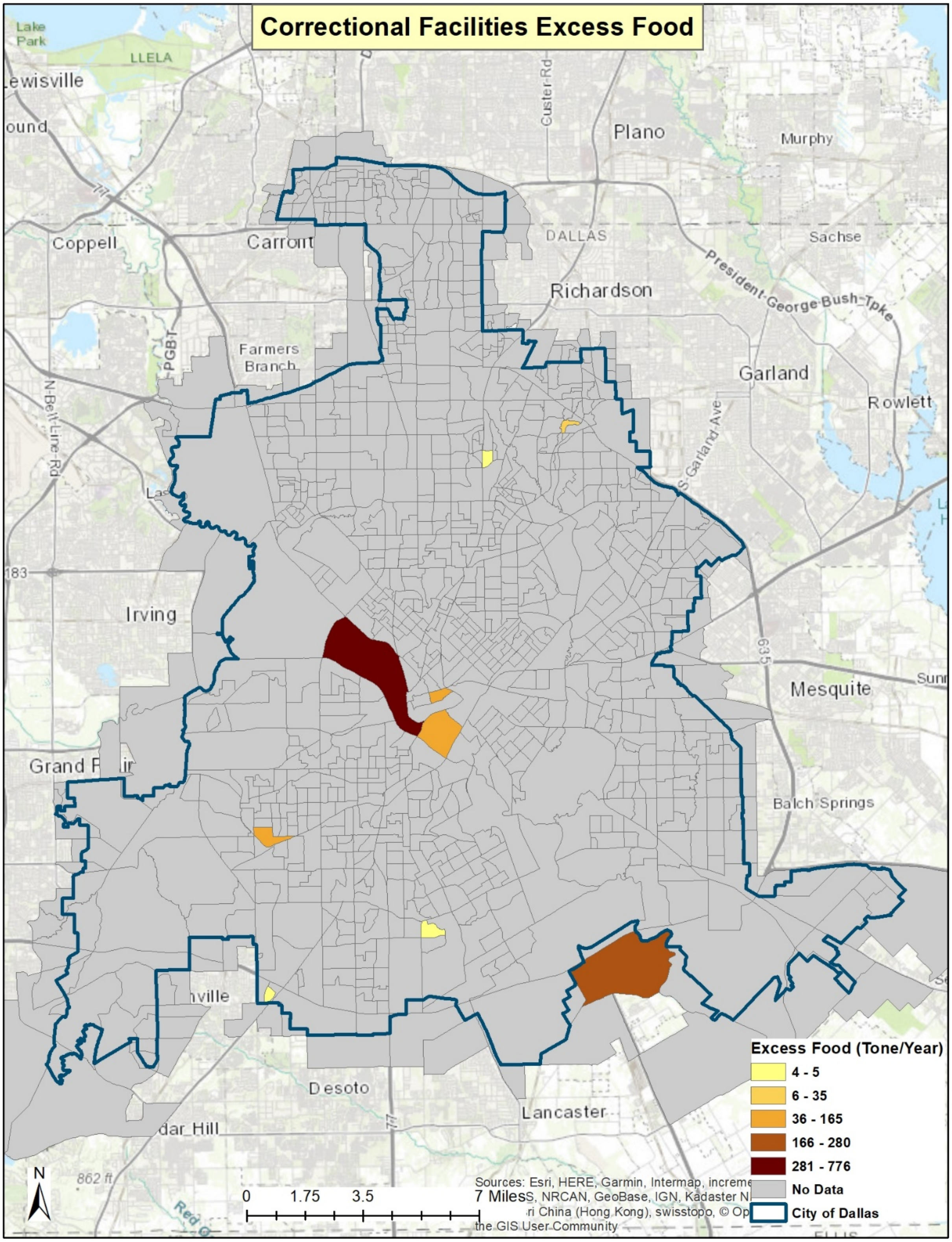
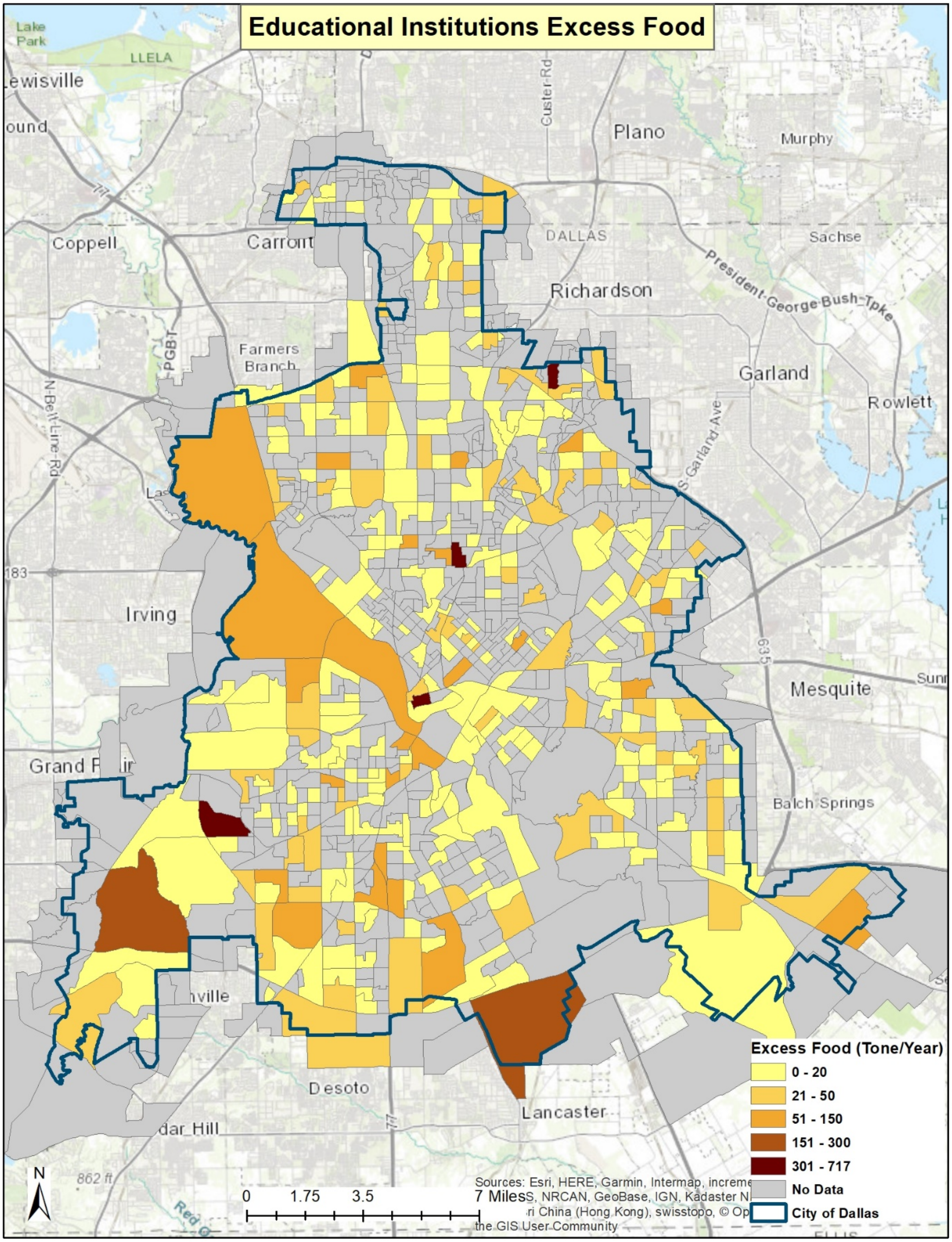
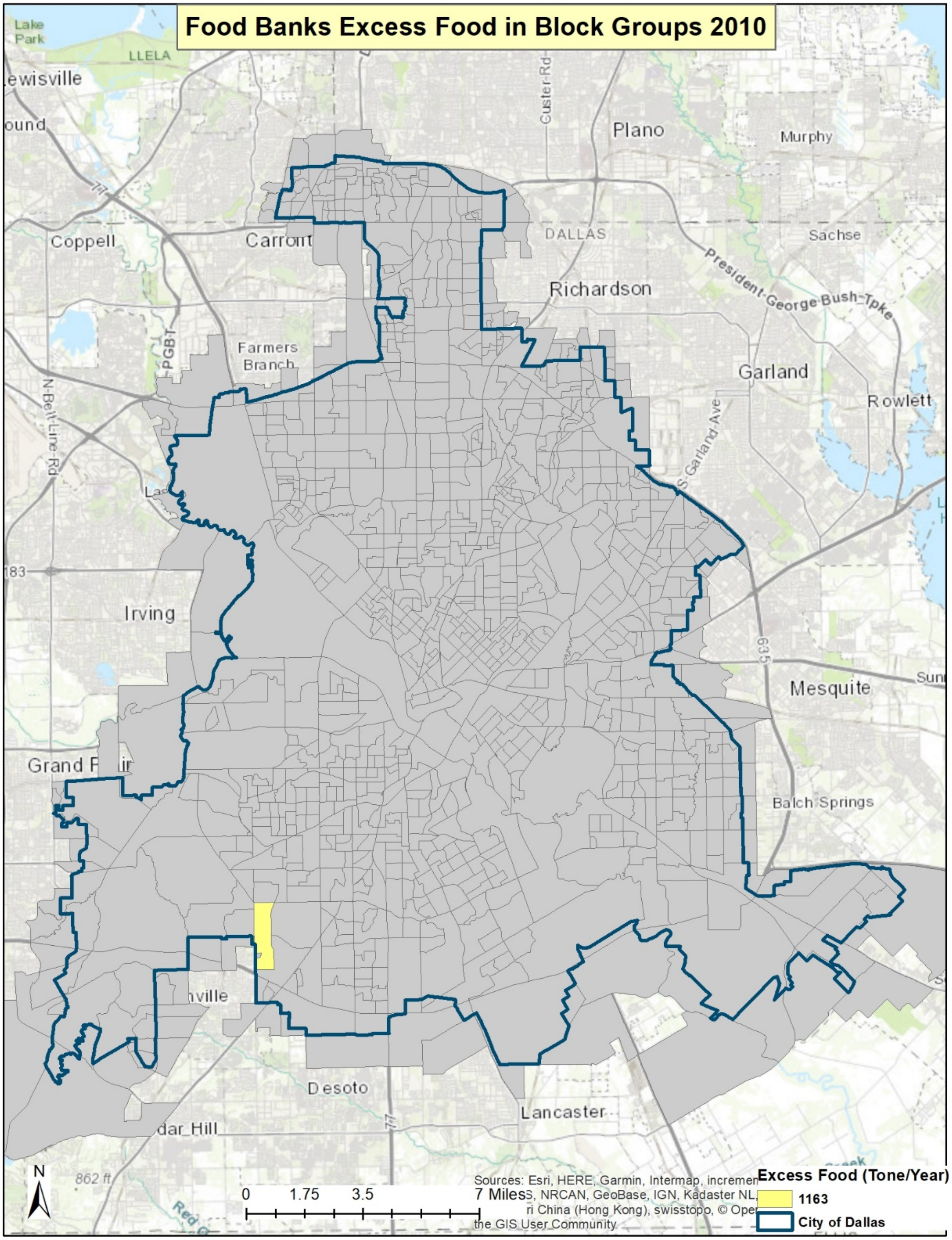
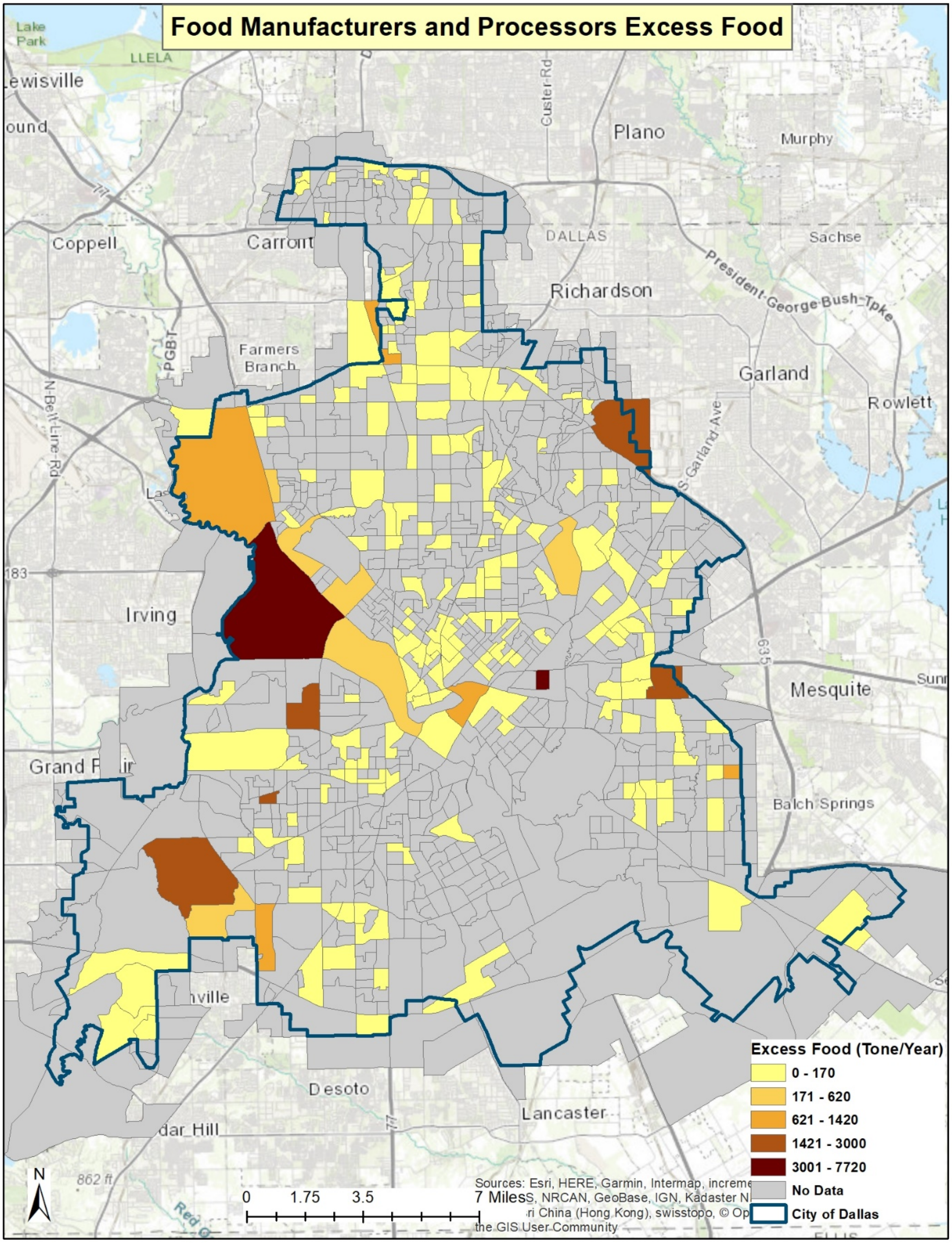
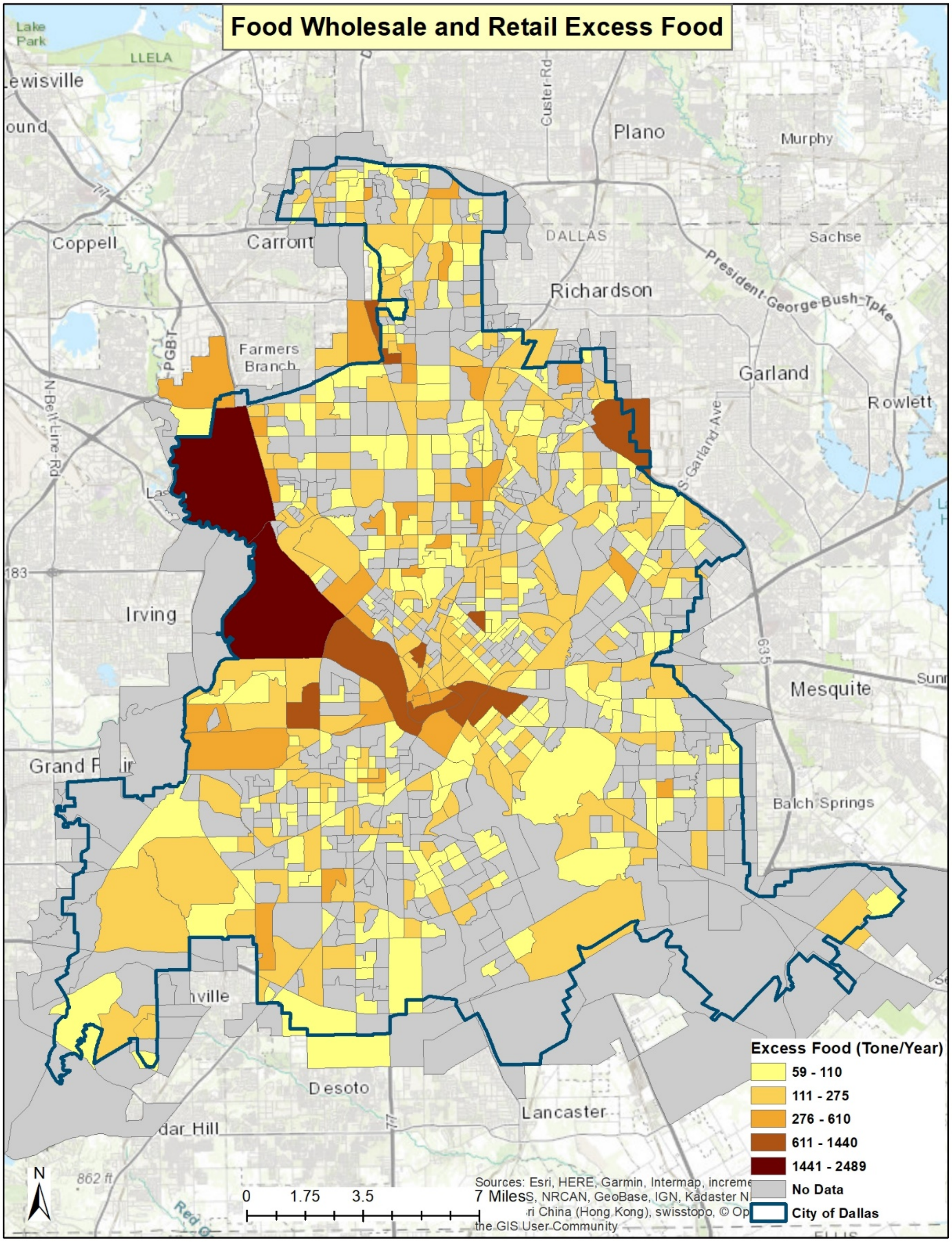
Appendix A: Food and Yard Waste Aggregation Maps

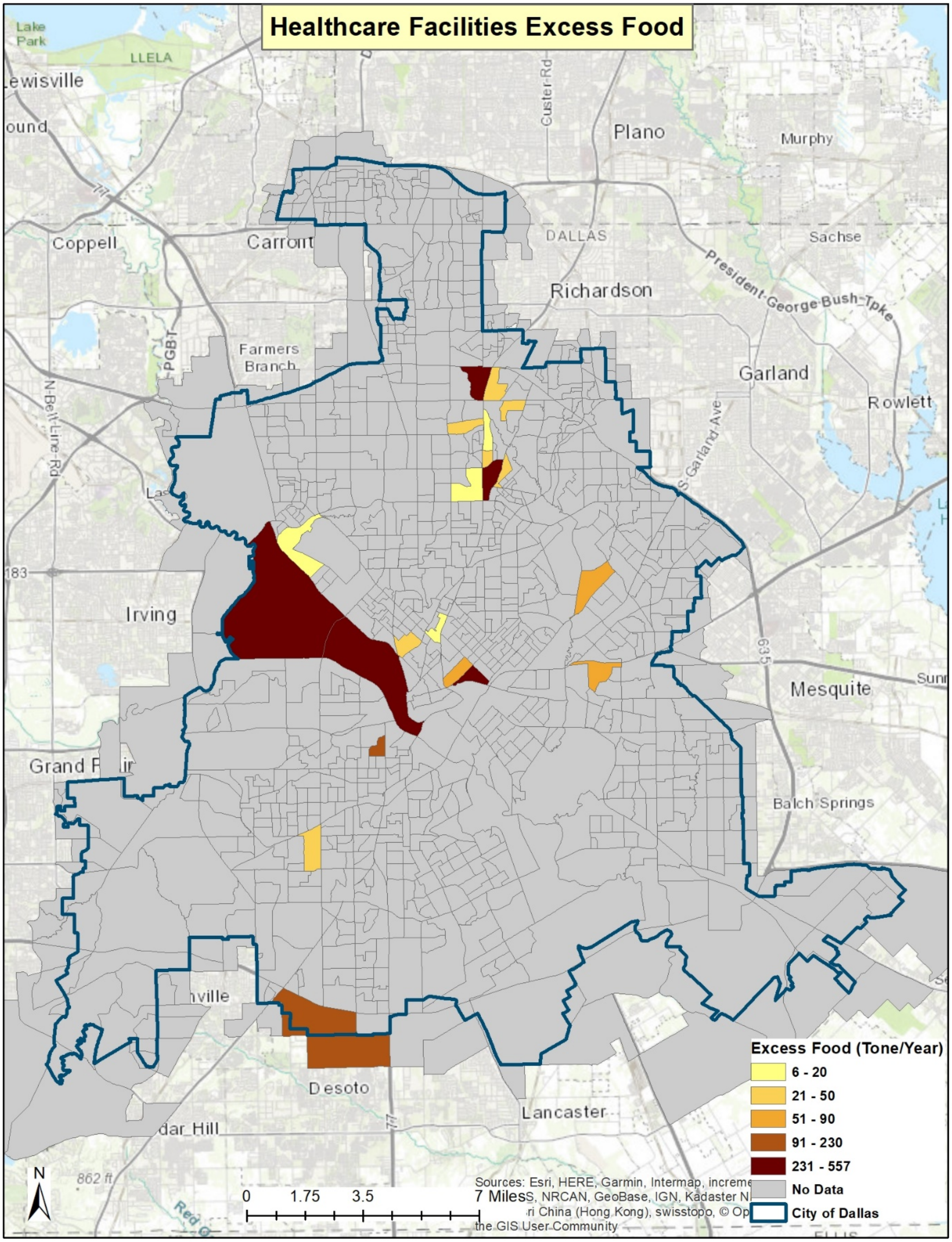


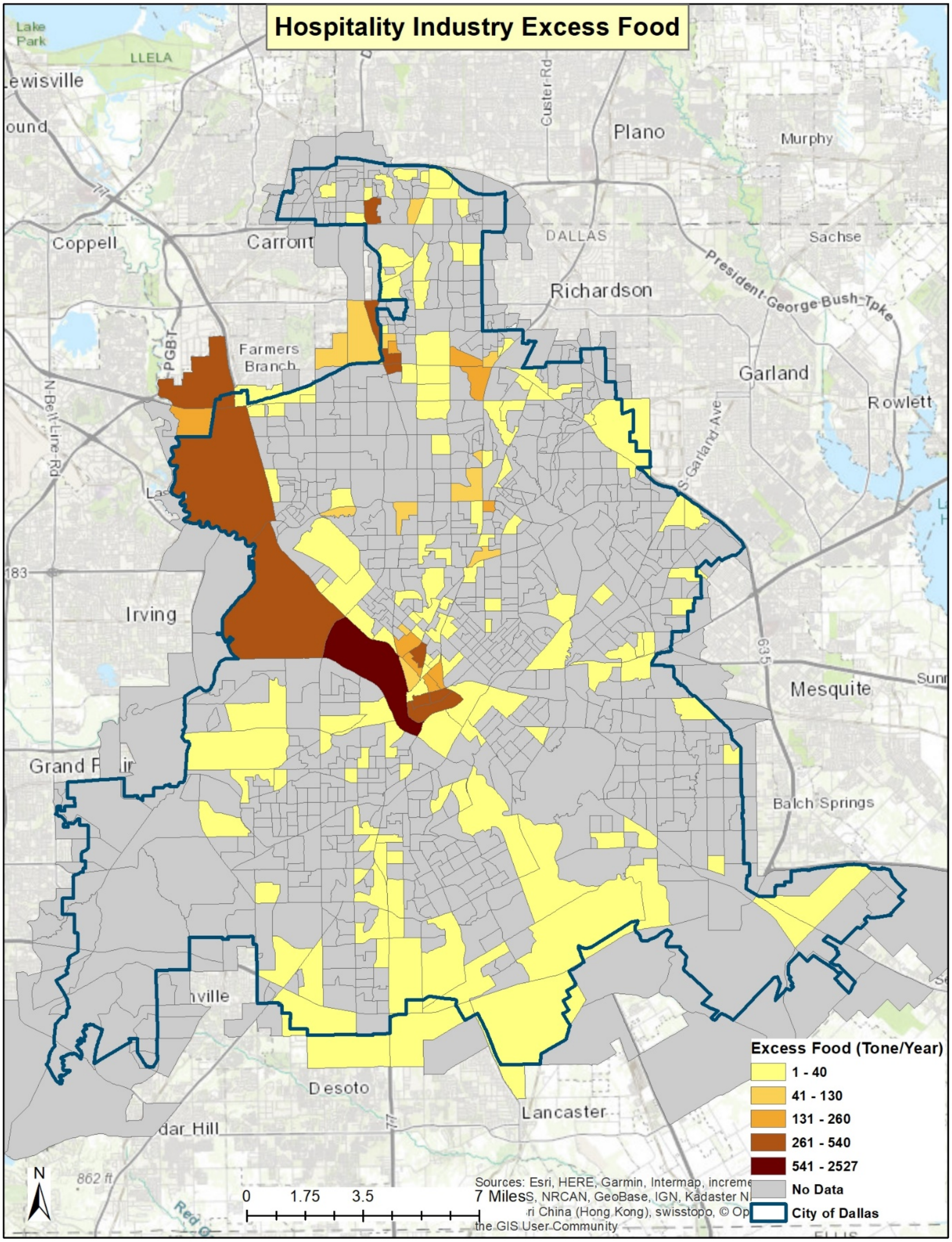

Educational Institutions Excess Food
Excess Food (Tone/Year)
0 - 20
21 - 50
51 - 150
151 - 300
301 - 717
No Data
City of Dallas
0
1.75
3.5
7 Miles
N
Sources: Esri, HERE, Garmin, Intermap, increme
S, NRCAN, GeoBase, IGN, Kadaster N
ri China (Hong Kong), swisstopo, © Op
the GIS User Community
Lewisville
Coppell
Plano
Murphy
Sachse
Richardson
Garland
Rowlett
Farmers Branch
Irving
Mesquite
Balch Springs
Desoto
Lancaster
President George Bush Tpke
Custer Rd
S Garland Ave
N Belt Line Rd
PGBT
LLELA
DALLAS
635
862 ft

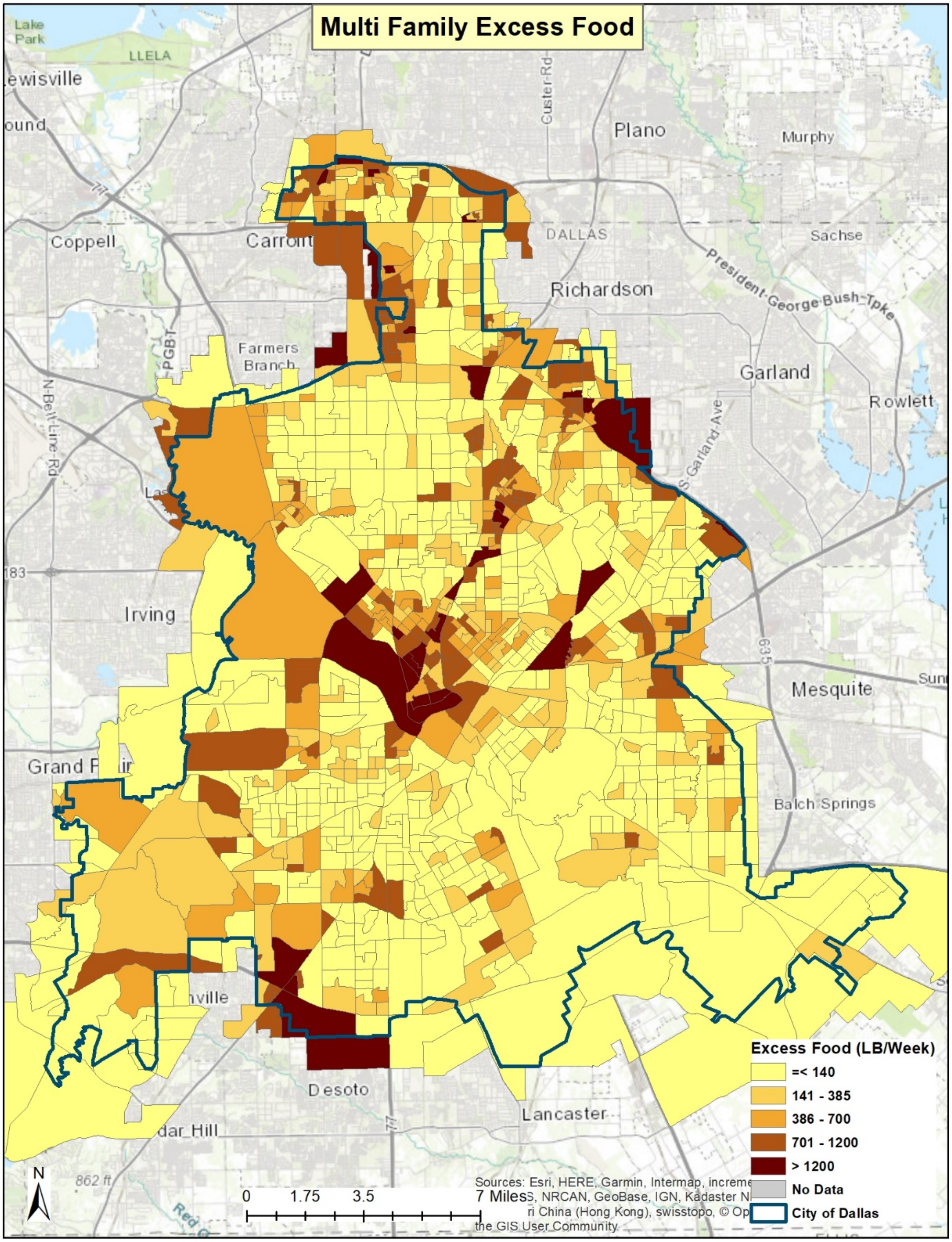

Food Banks Excess Food in Block Groups 2010
Lake Park
LLELA
Plano
Murphy
Coppell
DALLAS
Sachse
President George Bush Tpke
Richardson
Farmers Branch
Garland
Rowlett
PGBT
N Belt Line Rd
S Garland Ave
Irving
635
Mesquite
Grand Prairie
Balch Springs
Desoto
Lancaster
862 ft
N
0
1.75
3.5
7 Miles
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community
Excess Food (Tone/Year)
1163
City of Dallas


Food Manufacturers and Processors Excess Food
Excess Food (Tone/Year)
0 - 170
171 - 620
621 - 1420
1421 - 3000
3001 - 7720
No Data
City of Dallas
0 1.75 3.5 7 Miles
N
Plano
Murphy
Coppell
Richardson
Garland
Rowlett
Irving
Mesquite
Balch Springs
Desoto
Lancaster
Farmers Branch
Sachse
President George Bush Tpke

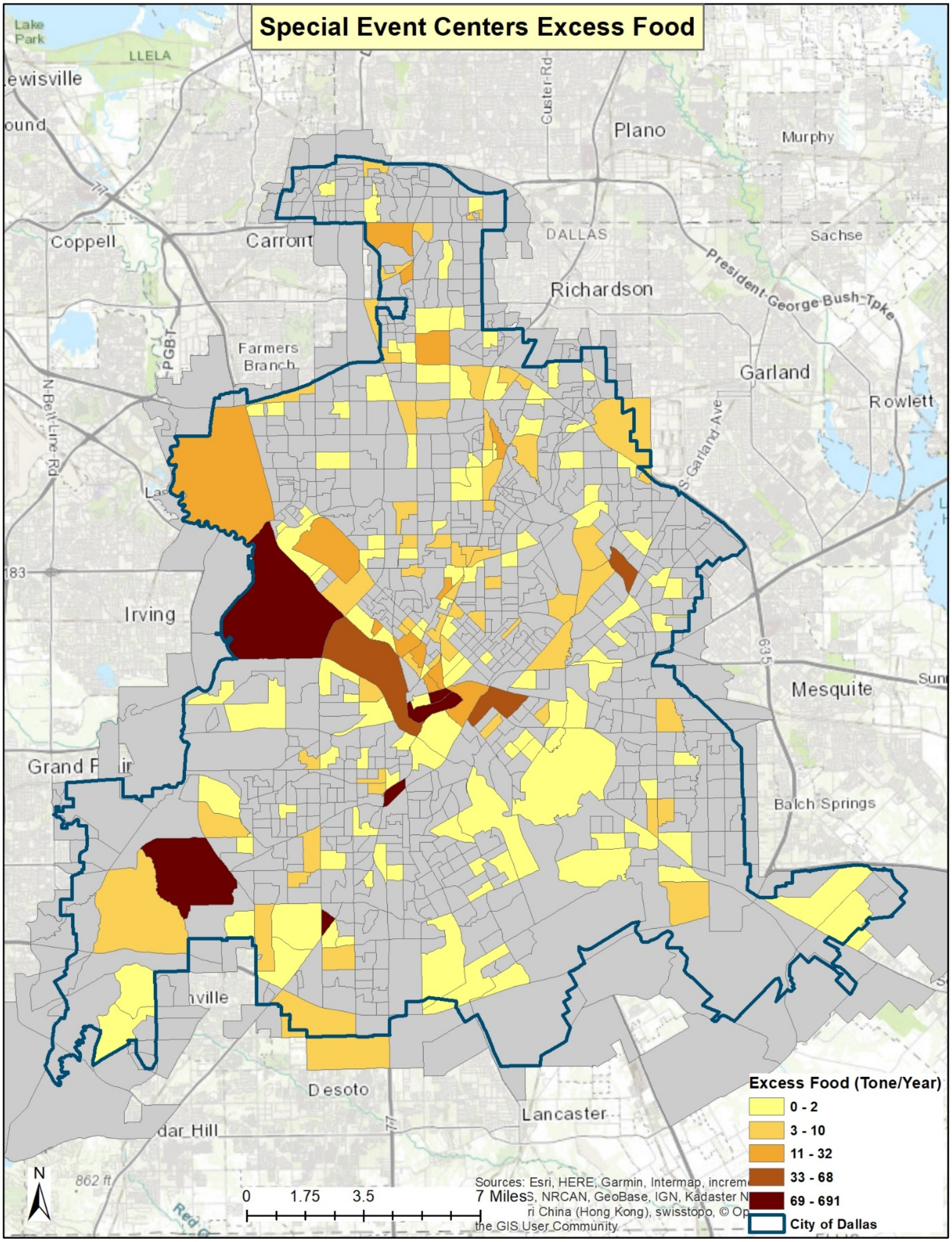

Food Wholesale and Retail Excess Food
Excess Food (Tone/Year)
59 - 110
111 - 275
276 - 610
611 - 1440
1441 - 2489
No Data
City of Dallas
0 1.75 3.5 7 Miles
N
Plano
Murphy
Richardson
Garland
Rowlett
Mesquite
Balch Springs
Irving
Coppell
Farmers Branch
Lewisville
Desoto
Lancaster
Sachse
President George Bush Tpke

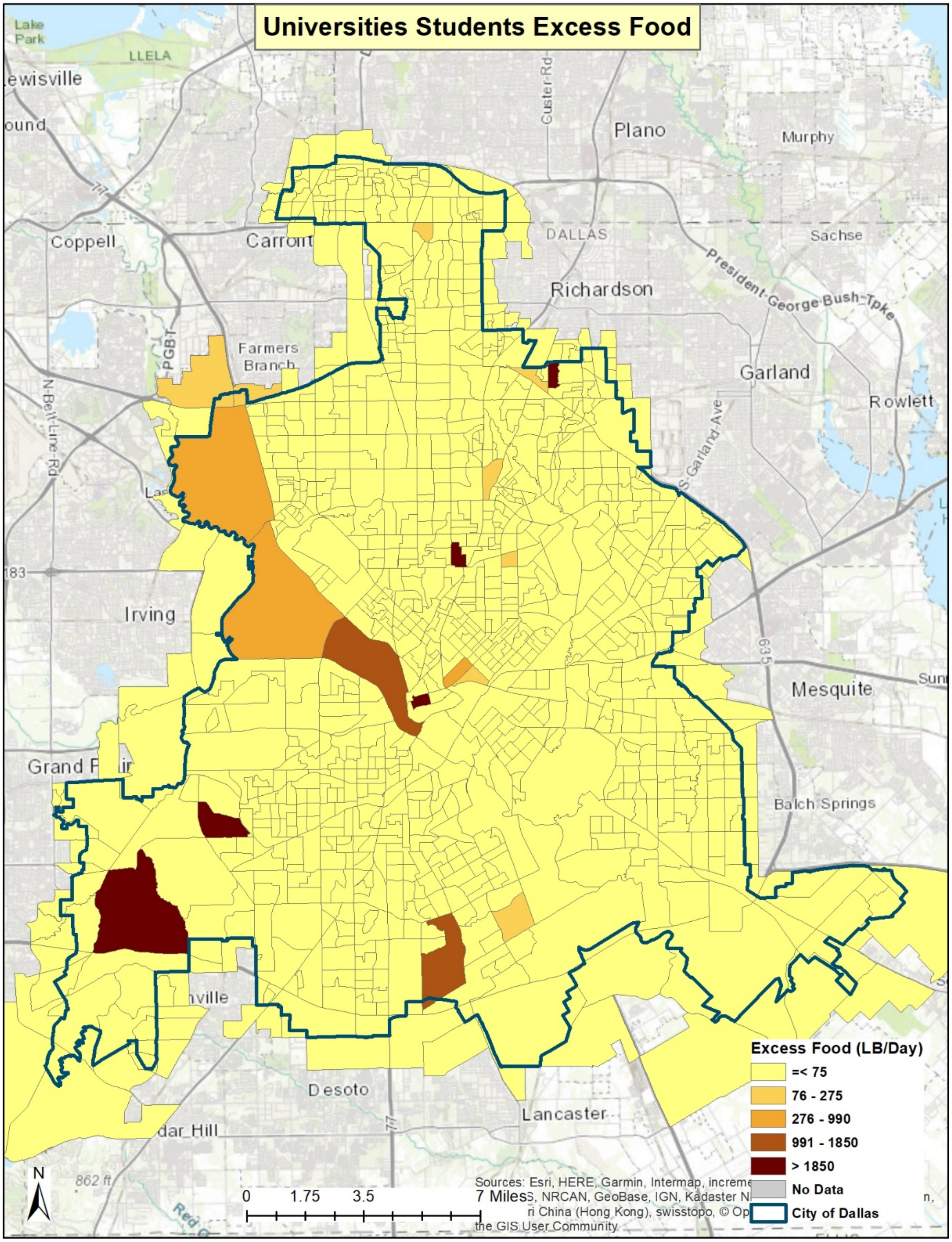

Healthcare Facilities Excess Food
Excess Food (Tone/Year)
6 - 20
21 - 50
51 - 90
91 - 230
231 - 557
No Data
City of Dallas
0 1.75 3.5 7 Miles
N


Hospitality Industry Excess Food
Excess Food (Tone/Year)
1 - 40
41 - 130
131 - 260
261 - 540
541 - 2527
No Data
City of Dallas
0 1.75 3.5 7 Miles
N
Plano
Richardson
Garland
Mesquite
Irving
Coppell
Farmers Branch
Desoto
Lancaster
Balch Springs
Rowlett
Murphy
Sachse
DALLAS

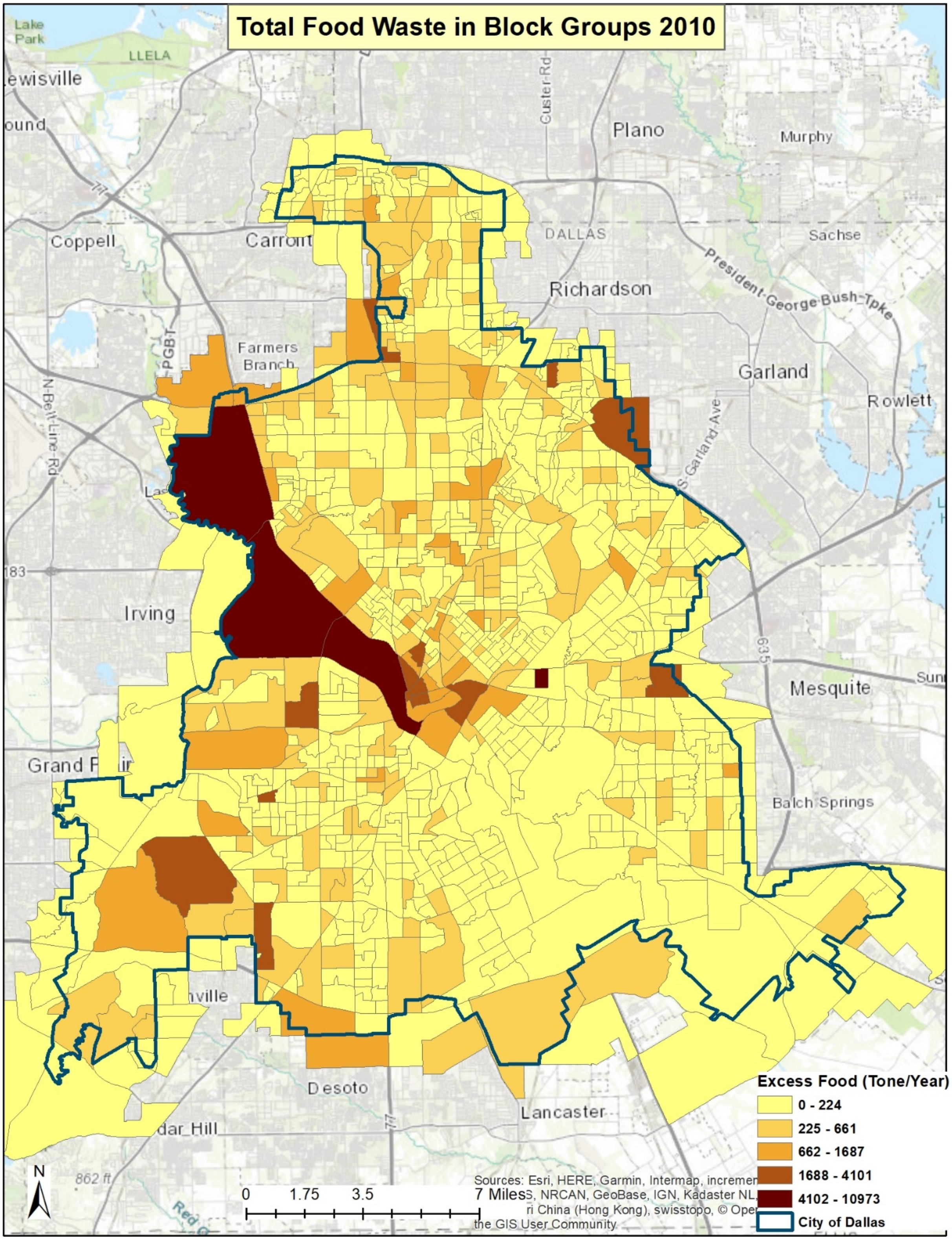


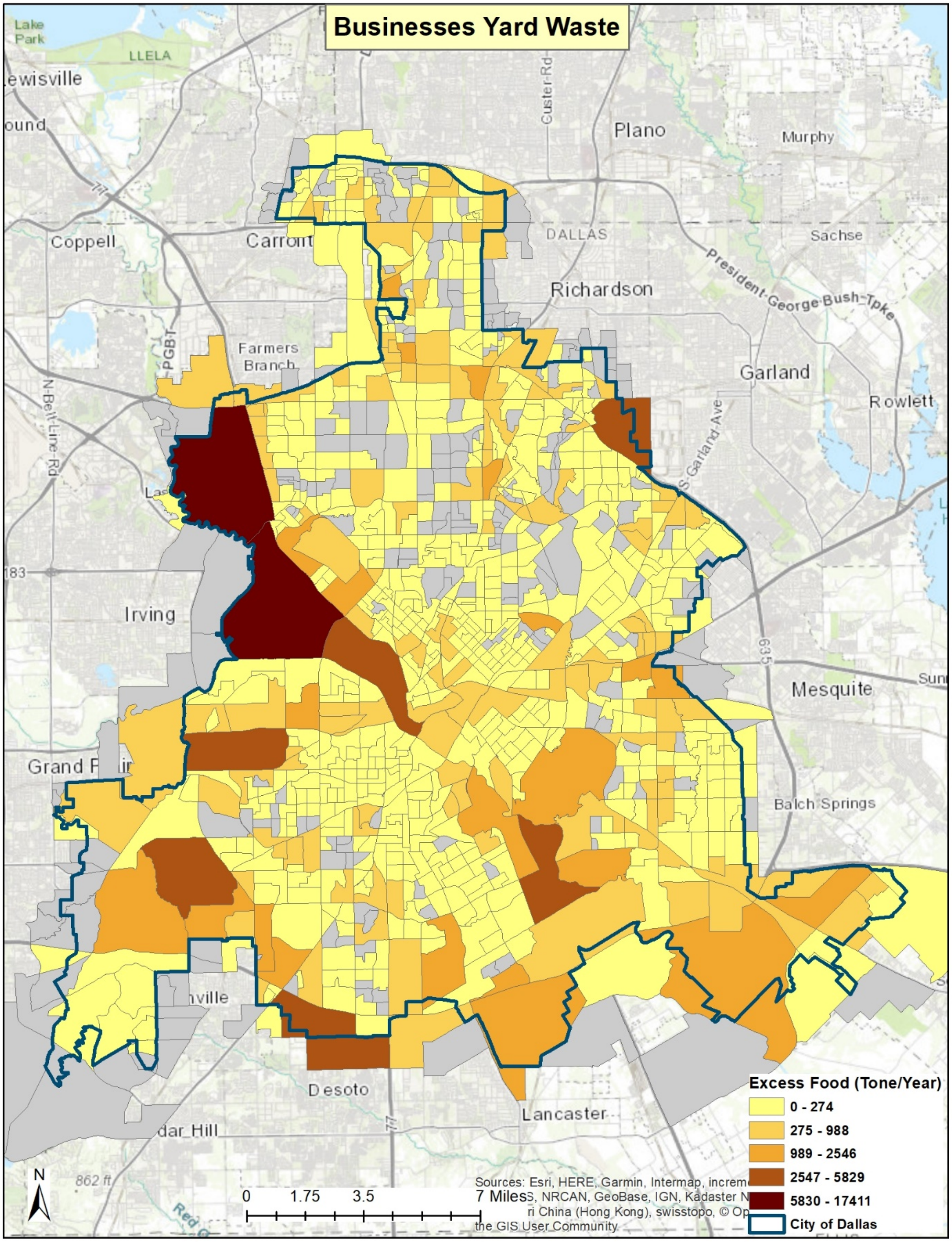
Multi Family Excess Food
Excess Food (LB/Week)
=< 140
141 - 385
386 - 700
701 - 1200
> 1200
No Data
City of Dallas
0 1.75 3.5 7 Miles
Sources: Esri, HERE, Garmin, Intermap, increme
S, NRCAN, GeoBase, IGN, Kadaster N
ri China (Hong Kong), swisstopo, © Op
the GIS User Community
Plano
Richardson
Garland
Mesquite
Irving
Coppell
Farmers Branch
Desoto
Lancaster
Balch Springs
Rowlett
Sachse
Murphy

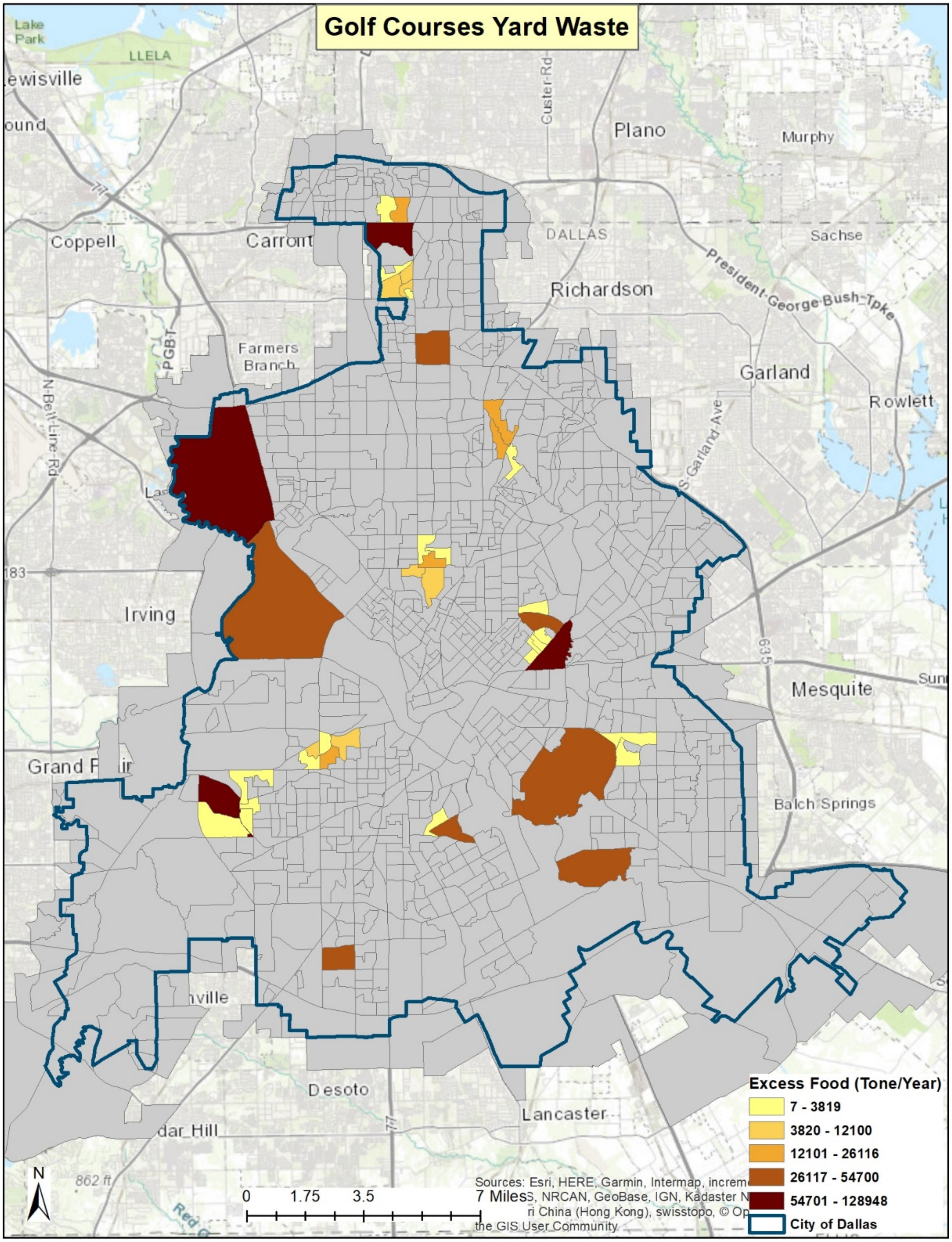

Special Event Centers Excess Food
Excess Food (Tone/Year)
0 - 2
3 - 10
11 - 32
33 - 68
69 - 691
City of Dallas
0 1.75 3.5 7 Miles
Plano
Richardson
Garland
Irving
Mesquite
Coppell
Farmers Branch
Desoto
Lancaster
Murphy
Sachse
Rowlett
Balch Springs

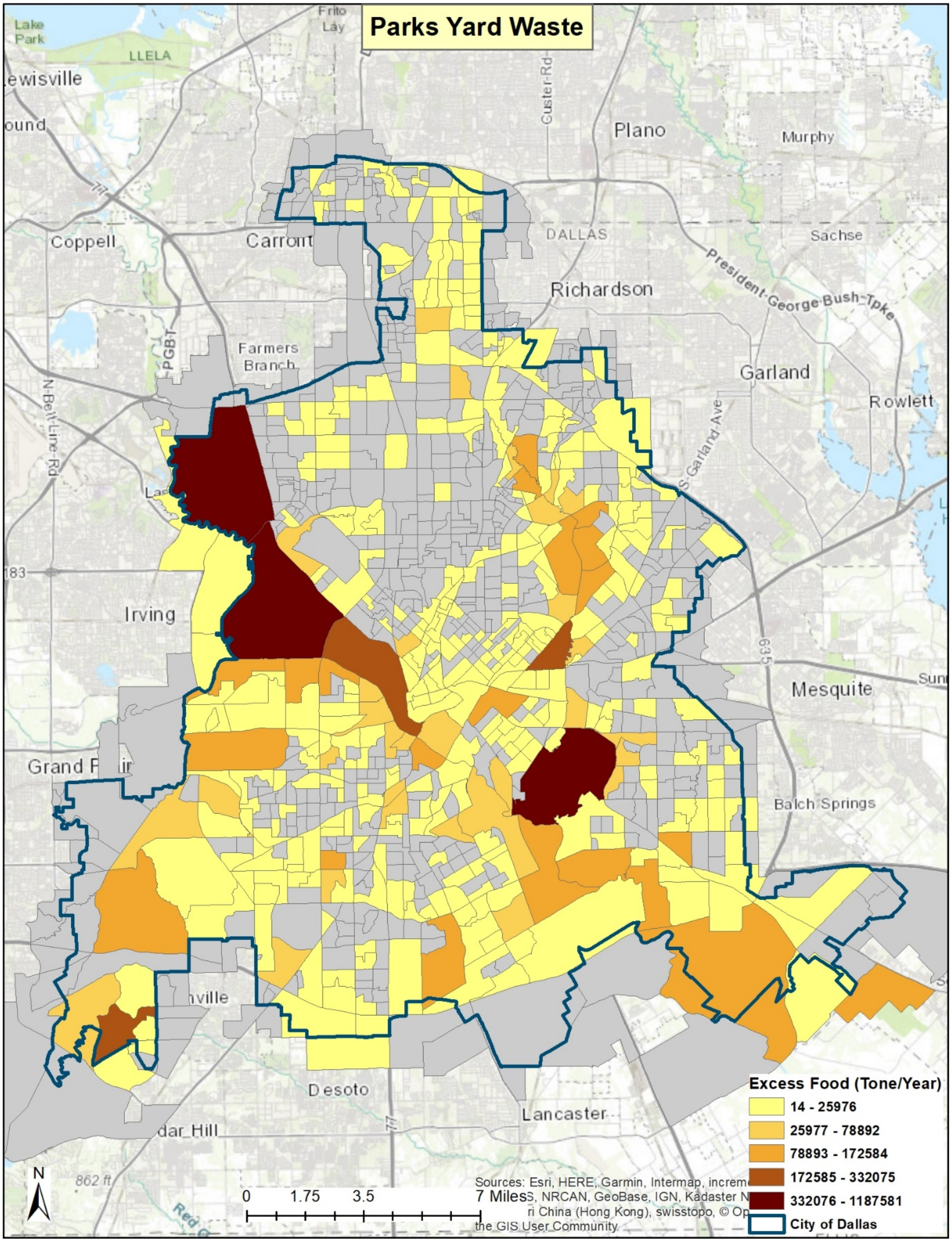


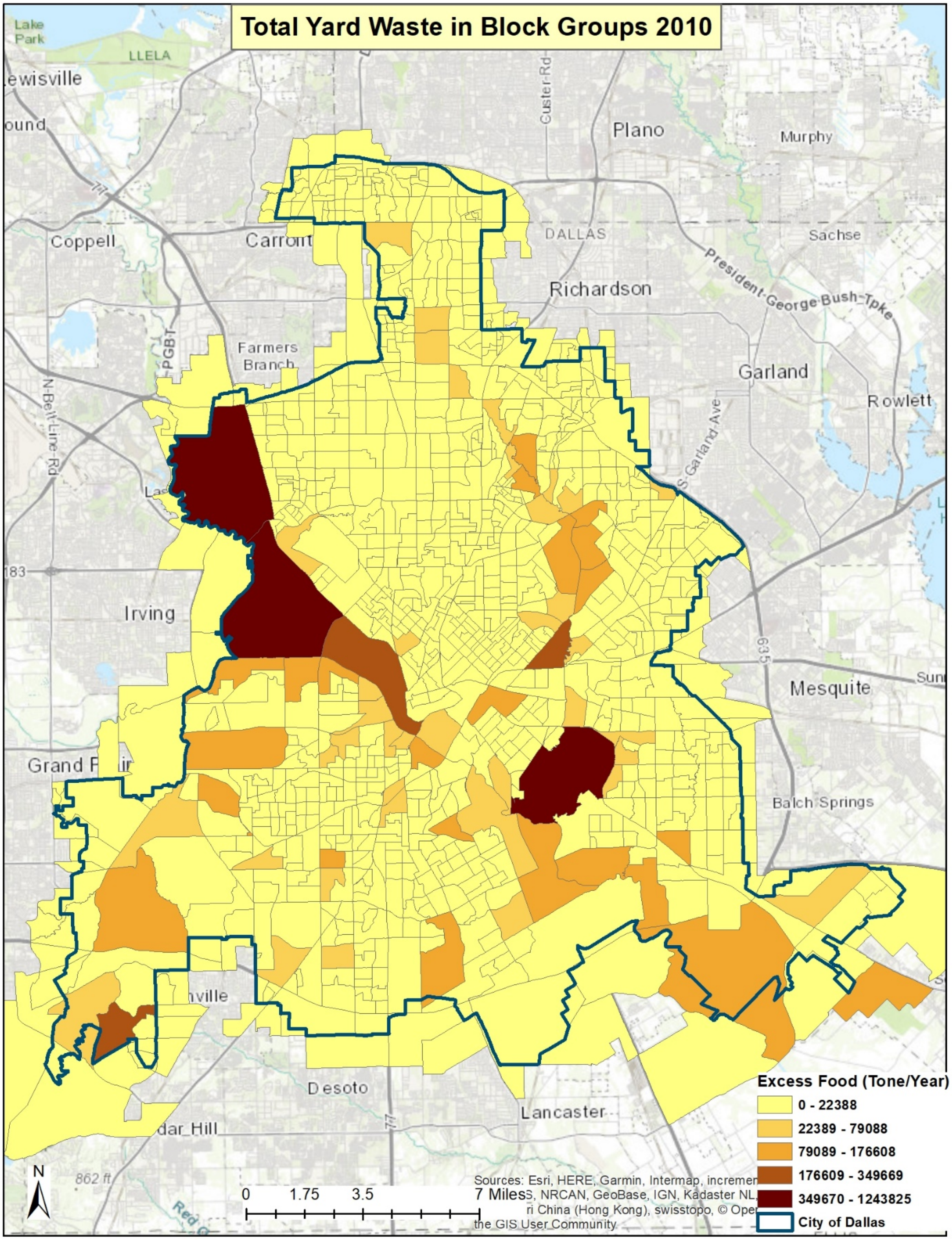
Universities Students Excess Food
Excess Food (LB/Day)
=< 75
76 - 275
276 - 990
991 - 1850
> 1850
No Data
City of Dallas
0
1.75
3.5
7 Miles
N
Plano
Richardson
Garland
Irving
Mesquite
Coppell
Farmers Branch
Desoto
Lancaster
Balch Springs
Rowlett
Sachse
Murphy
DALLAS
President George Bush Tpke


Total Food Waste in Block Groups 2010
Excess Food (Tone/Year)
0 - 224
225 - 661
662 - 1687
1688 - 4101
4102 - 10973
City of Dallas
0 1.75 3.5 7 Miles
Plano
Richardson
Garland
Irving
Mesquite
Coppell
Farmers Branch
Desoto
Lancaster
Balch Springs
Rowlett
Sachse
Murphy


Businesses Yard Waste
Lake Park
LLELA
Custer Rd
Plano
Murphy
Coppell
DALLAS
Sachse
Richardson
President George Bush Tpke
Farmers Branch
PGBT
N Belt Line Rd
Garland
Rowlett
S Garland Ave
Irving
635
Mesquite
Balch Springs
Desoto
Lancaster
862 ft
N
0 1.75 3.5 7 Miles
Excess Food (Tone/Year)
0 - 274
275 - 988
989 - 2546
2547 - 5829
5830 - 17411
City of Dallas


Golf Courses Yard Waste
Excess Food (Tone/Year)
7 - 3819
3820 - 12100
12101 - 26116
26117 - 54700
54701 - 128948
City of Dallas
0
1.75
3.5
7 Miles
N


Parks Yard Waste
Excess Food (Tone/Year)
14 - 25976
25977 - 78892
78893 - 172584
172585 - 332075
332076 - 1187581
City of Dallas
0
1.75
3.5
7 Miles
N
Plano
Richardson
Garland
Irving
Mesquite
Coppell
Carrollton
Farmers Branch
Murphy
Sachse
Rowlett
Balch Springs
Desoto
Lancaster
President George Bush Tpke


Total Yard Waste in Block Groups 2010
Excess Food (Tone/Year)
0 - 22388
22389 - 79088
79089 - 176608
176609 - 349669
349670 - 1243825
City of Dallas
0 1.75 3.5 7 Miles
N

Appendix B: F^4 Tool Data Collection Survey Questions

Wastewater Treatment Plants

Questions associated with Anaerobic Digester Capital Costs

1. What is the cost associated with the land area required by each digester?
2. What is the cost for AD tanks, including the foundation?
3. What is the overall cost for a turbine or combustion engine coupled with a generator, with the purpose of generating electricity?
4. What is the cost to upgrade and compress the gas for vehicle fuel (CNG) or pipeline injection? (If any)

Questions associated with Anaerobic Digester Operation and Maintenance Costs

5. What is the overall cost for maintenance of temperature for microorganisms' growth (i.e., if heating needed to be added)?
6. What is the cost for pH maintenance (i.e., adding a base to raise pH)?
7. What are the overall annual operation and maintenance costs (like maintenance, repairs, parts, labor, and insurance) for AD?

Waste Collection Services/Fleet Managers

1. Monthly cost of waste collection for regular bins or (30/60/90 gallons bin), special can-on-wheels bin, or plastic bags for collecting food waste separately from each house
2. Capital costs for waste collection trucks for city routes, as well as larger tractor/trailer for taking waste from transfer station to landfill
3. Average capacity of trucks
4. Lifetime of vehicles (trucks) on average
5. Miles traveled per truck per year
6. What type of fuel is used mostly in vehicles (diesel, natural gas or gasoline)?
7. Amount of fuel used per vehicle per year
8. Cost of fuel per vehicle per year
9. Ownership of refueling stations (city, private)

Garbage Truck Manufacturers

1. Is it possible to add separate compartments in an existing garbage trucks?

2. How much can ir cost overall to add separate compartments in existing garbage trucks?
3. How much does a new truck cost that already has built-in separate compartments?
4. Which one is better economically - adding a compartment in an existing truck or buying a new truck?
5. In general rear-loading trucks that have two separate compartments; how much waste separately can be carried per route (i.e., capacity)?

AD Manufacturers

1. What is the cost for different sizes of AD reactors to process food and yard waste?
2. What factors need to be considered in AD expansion?
3. How much can AD expansion cost?
4. What is the cost of different types of digester materials?
5. What is the difference in cost for wet and dry digestion?

Appendix C: Waste Mass Calculations

Mass of food waste generated per area either obtained from GIS based on the EPA Excess Food Opportunities database, or estimated by:

Mass of food waste generated per area = (Mass of food waste produced per person per year) * (Population per Area)

Mass of food waste produced per person per year = 248 lb (US national average, US EPA, 2018a)

Fraction of food waste fed to hungry people: Default = 2/3 (Hoover, 2017)

Fraction of food waste available for fuel generation = 1 – (Fraction of food waste fed to hungry people):

Default = 1 – 2/3 = 1/3

Volume of food waste available for fuel generation = (Mass of food waste to be added per day)/(Density of food waste)

Density of food waste = 1513.5 lb/yd^3 (Miller, 2000)

Mass of yard waste generated per area either obtained from GIS (see procedure documented in "Methods for Obj. 1"), or estimated by:

Mass of yard waste generated per area = (Mass of yard waste produced per person per year) * (Population per Area)

Mass of yard waste produced per person per year = 67.3 lb (US EPA, 2018a)

Volume of yard waste available for fuel generation = (Mass of yard waste to be added per day)/(Density of food waste)

Density of yard waste = 1567.57 lb/yd^3 ()

Mass of sludge = (Volume of sludge) * (Density of sludge)

Density of sludge assumed to equal that of water (1 kg/L)

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