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Comparative Spatial Analysis of Convenience Standards in State Electronic Waste Policies

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Comparative Spatial Analysis of Convenience Standards in State Electronic Waste Policies

By:

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The master's degree thesis of Isabelle R Law has been examined and approved by the thesis committee as satisfactory for the thesis requirement for the M.S degree in Sustainable Systems

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Abstract

The management of end-of-life electronics, or e-waste, is a complex challenge as these products contain both valuable and hazardous materials. Recycling electronics provides an opportunity to harvest and reuse valuable components while also mitigating environmental and health risks. However, recycling rates for electronic waste remain low in the United States. In response to this challenge, twenty-six states in the U.S. have enacted policies meant to limit landfill disposal and encourage electronics recycling. While most state policies rely on mass-based targets for the collection and recycling of e-waste, convenience standards are an emerging policy mechanism aimed at increasing consumer access to recycling locations. A review of the literature suggests that convenience is a key factor in consumer recycling behavior, but there may be a disparity between how consumers define convenience, and how convenience is defined in policies. This research aims to determine how convenience standards codified by state e-waste laws align with consumer definitions of convenience and how variation in these standards impacts the convenience of electronic collection site locations.

For this research, Illinois was chosen as a case study state. Using material flow analysis methods, with data from the United States Census Bureau and the Consumer Technology Association, we estimated the amount of electronic products ready for recycling in Illinois. Then, we created a spatially explicit model in ArcGIS Pro to simulate the locations of e-waste collection sites under three different state convenience standards. For each modeled standard, we calculated the amount of estimated electronic waste within a "convenient" distance of the simulated electronic waste collection sites as defined by literature on consumer recycling behavior. The modeled site locations and electronic waste estimations were validated against existing recycling locations and collection data in Illinois. The comparison between state convenience standards found that a baseline requirement for collection sites ensures convenient access to recycling in rural counties but is most convenient when combined with a population-based standard that provides additional sites for urban and densely populated areas. The result of this research provides insight into how the language of electronic recycling policies impacts the placement and convenience of recycling sites, which may inform policy development and participation in electronic waste recycling.

1. Introduction

Over the past several decades, consumer electronics have rapidly permeated nearly every aspect of day-to-day life in the United States. These products provide entertainment, serve as tools for communication and create numerous other benefits. When these ubiquitous devices are no longer in use, they become electronic waste, or “e-waste,” a term that refers to products containing electronic components, where the product has reached the end-of-life. The management of electronic waste presents a complex issue as these products contain hazardous materials as well as valuable resources.

Electronic waste can contain toxic and hazardous materials such as cadmium, lead, mercury, and nickel (Althaf et al., 2020, Bhutta et al., 2011). Disposal of electronics into landfills or through incineration can release hazardous material into the environment, harm the surrounding ecosystems, and increase health risks in humans (Bhutta et al., 2011, Grant et al., 2013). Fortunately, the hazardous content in electronic waste is declining as lead-containing cathode ray tube (CRT) glass and printed circuit boards have phased out of production, and liquid crystal display televisions, which commonly contain mercury, have peaked in popularity (Althaf et al., 2020). While the decrease in toxicity of electronic waste is a positive sign for end-of-life management, the products containing hazardous materials have not been completely eliminated from the waste stream. In 2018, CRT televisions still accounted for over one-third of total consumer electronic waste by mass in the United States (Althaf et al., 2020).

While the components of consumer electronics have become less hazardous overall, the complexity and value of electronic components have risen. The portion of metals such as cobalt and indium in electronic waste has increased in the last two decades (Althaf et al., 2020). The demand for cobalt, which is found in devices such as smartphones and laptops, is increasing due in part to its use in lithium-ion batteries in electric vehicles and other electronic products (Althaf et al., 2020, Fu et al., 2020). Both cobalt and indium are scarce metals, and their limited supply coupled with rising demand makes these resources economically valuable (Althaf et al., 2020). Gold as well is a valuable metal found in electronic products such as televisions and computers (Althaf et al., 2020, Zeng et al., 2018). Electronic waste represents a large "urban mine," a term that refers to the collection of resources and materials found in waste. Urban mining, or the extraction of these resources from various waste streams, is a process that can be applied to electronic waste. Harvesting scarce metals from end-of-life electronics can be an economically viable process, and this secondary production of metals can help to meet the demand for these metals (Shevchenko et al., 2019, Zeng et al., 2018).

Despite these material recovery benefits, there are multiple challenges to recycling e-waste. Frequent innovation and turnover of electronic devices have led manufacturers to prioritize lighter, smaller, and more efficient products in a process known as dematerialization (Althaf et al., 2020, Ryen et al., 2014). As a result, the overall mass of the electronic waste stream in the United States has decreased since 2015, as heavier technologies, for example, CRT televisions, have been replaced by comparatively lightweight devices, such as LED and LCD displays (Althaf et al., 2020). Another contributing factor to this decrease is that consumer electronics have experienced convergence, where one device can serve multiple functions, reducing the need for individual devices for each task (Althaf et al., 2020; Ryen et al., 2014). While these technological innovations improve the consumer experience, the changing composition of the waste stream and the increased complexity of smaller, multi-use devices makes recycling a complicated process. Additionally, the management of certain materials such as CRT glass which contains lead, or batteries which are highly flammable, necessitates proper infrastructure and safety protocols to mitigate the dangers presented by these hazardous components (Althaf et al., 2020). Specific processes are required to separate and extract valuable metals from e-waste successfully.

Consumer engagement is also a challenge facing e-waste recycling. In the United States, participation in electronic waste recycling schemes remains low. According to the United States Environmental Protection Agency, an estimated 38.5% of consumer electronics were recycled in the U.S. in 2018 (*Durable Goods: Product-Specific Data*, 2022). One method of combating these challenges is through legislation, which can regulate the management of e-waste, ban improper disposal, and create programs that provide opportunities for consumers to recycle electronics.

Existing international legislation includes the Waste Electrical and Electronic Equipment (WEEE) directive in Europe, which lays out recovery targets and standards for the treatment and collection of e-waste (Directive 2012/19/EU of the European Parliament-, 2012). Several Asian countries have implemented e-waste legislation, ranging from manufacturer collection requirements to regulations on imports of e-waste (Tran & Salhofer, 2018). Additionally, the Basel Convention is an international agreement that limits the international dispersion of hazardous waste such as electronics, which are frequently exported to developing countries and disposed of informally (Bhutta et al., 2011, Ongondo et al., 2011, Schumacher & Agbemabiese, 2019).

The United States has not ratified the Basel Convention, nor does it have a federal law specifically governing the recycling of electronic waste (Schumacher & Agbemabiese, 2019). Federal laws that do apply to electronic waste are focused on the management of hazardous materials within the devices. In 1976, the federal government passed the Resource Conservation and Recovery Act, which regulates the handling of solid and hazardous waste, but many electronic devices are exempted from the scope of this law (Schumacher & Agbemabiese, 2019). Cathode ray tubes, which are found in electronic devices such as televisions and monitors, are subject to federal guidelines for their processing and disposal, as CRT devices contain lead and other hazardous materials (§ 261.39, n.d.).

Due to the lack of federal electronic waste policies, the core legislative responsibility rests on the states. Currently, 25 states and Washington D.C. have electronic waste laws in place (Schumacher & Agbemabiese, 2019). This collection of state laws creates a "patchwork" of regulation with disparities between states (Hickle, 2014). The primary metric used in these state laws is mass-based targets, which set annual goals or quotas for the total weight of electronic waste to be collected in that state. However, as heavier technologies phase out in favor of lighter, multi-functional devices, these mass-based targets may not capture the dynamics of an evolving waste stream. This phenomenon combined with a national recycling rate below 40%, creates a challenge for policymakers in setting targets for e-waste collection and indicates a need for additional or alternative legislative approaches (United States Environmental Protection Agency, 2022). One alternative approach emerging in the policy landscape is convenience standards, which attempt to increase consumer participation rates by setting guidelines for the location of electronic waste collection sites.

1.1 Convenience Standards in State Electronic Waste Recycling Laws

Convenience standards are relatively new in the legislative landscape for electronics recycling. While some states, such as Vermont, have included convenience standards in electronic recycling policies from the beginning, others have recently amended legislation to add language about convenience (Collection And Recycling Of Electronic Devices, 2010). In Illinois, the e-waste legislation that was originally enacted in 2008 was replaced by the Consumer Electronics Recycling Act in 2017 (CERA - Electronics Recycling, n.d.). This act established convenience standards for e-waste collection facilities on a sliding scale according to county population density and to date, is the only e-waste recycling convenience standard of its kind in the United States (Consumer Electronics Recycling Act, 2017; E-Waste Program Review, 2016). New Jersey also updated its electronic waste law in 2017, requiring manufacturer plans to include methods for providing “convenient collection of covered electronic devices” (Electronic Waste Management Act, 2017).

Of the 25 states with electronic waste recycling policies, ten have convenience standards written out in the laws. A policy review of these laws found varying levels of convenience standards which have been grouped into three categories: population-based, jurisdiction-based, and distance based. Population-based standards assign a minimum number of collection sites based on population or population density. Jurisdiction-based standards assign a minimum number of sites per county, municipality, or another locality. Finally, distance-based standards set a distance around each site, in which a minimum portion of the state’s population must reside.

The importance of convenience standards as a policy mechanism is supported by Schumacher & Agbemabiese, 2019 which compared e-waste collection rates for states with recycling laws against different convenience standards. It was found that all states with population-based convenience standards had above-average collection rates while states with e-waste laws, but no convenience standards all had below-average collection rates (Schumacher & Agbemabiese, 2019). This indicates a positive correlation between convenience standards and electronic recycling collection rates.

While approximately half of states do not have e-waste recycling laws, some states, such as Arkansas, have proposed adopting such policies to establish statewide electronic recycling programs (SB585 Bill Information, 2021). Additionally, states with electronic waste laws may consider amending their regulations and adopting different approaches to collection. Convenience standards are a particularly relevant policy mechanism for states to consider as they work to improve participation in e-waste recycling schemes. As states contemplate developing or changing electronic waste legislation, understanding the effectiveness of policy mechanisms such as convenience standards will be crucial to shaping future policies.

1.2 Literature Review of Consumer Recycling Behavior

A literature review was conducted to understand how convenience influences electronic waste recycling behavior and how consumers define convenience. We began with a broader scope, looking at papers that identify factors that influence electronic recycling behavior. Then, we narrowed in on literature that looks at how convenience influences electronic recycling behavior. With an emphasis on convenience, this literature review also established definitions and parameters for what consumers find to be convenient when recycling. A considerable portion of the existing literature synthesized in this review focused on household recycling behavior rather than electronic waste recycling behavior. However, studies such as Bouvier & Wagner, 2011, Saphores et al., 2006, and Saphores et al., 2012, found similar relationships between convenience and electronic recycling behavior. Therefore, household recycling and electronic recycling are considered analogous behaviors for the purpose of this review. This literature review primarily contained papers studying drop-off recycling which is defined in Sidique et al., 2010 as a program with "designated sites" where consumers bring their recyclables for sorting and processing by the recycler.

The literature review determined that one key reason electronic devices are not recycled is that many people hold on to their electronics long after their useful life, in a process known as hoarding or hibernating (Ongondo & Williams, 2011; Shittu et al., 2022; Wilson et al., 2017). In a survey related to mobile phones, the primary reason for keeping previously used devices was to have a spare, while around a quarter of respondents noted that they were unsure what to do with their device once it was no longer in use (Wilson et al., 2017). While still-functional electronics are typically kept as backup devices, damaged or non-functional electronics are held onto for other reasons, such as a lack of disposal opportunities or limited knowledge about recycling (Shittu et al., 2022). Other reasons consumers may not recycle their devices relate to the design of the recycling network. The inconvenience of recycling is a barrier for consumers who identify recycling to be "inconvenient" for a variety of reasons (Knussen et al., 2004; Sidique et al., 2010; Tonglet et al., 2004). Knussen et al., 2004 also found that the perception of a lack of household waste recycling facilities limited people's intent to recycle.

Likewise, studies of recycling behavior have found that the convenience of recycling is a motivator for consumers (Domina & Koch, 2002; Vining & Ebreo, 1990). The findings of survey-based studies such as Chen & Tung, 2010, and Sidique et al., 2010 found households more likely to drop off household recycling when the action was considered convenient. An observational study identified attitudes and situational factors related to convenience to be influential in household recycling behavior (Boldero, 1995). Willingness to recycle electronic waste was also linked to convenience, particularly the distance to an electronic waste drop-off site (Saphores et al., 2006).

Our literature review identified convenience as an important factor in recycling behavior, however, convenience is a subjective construct that is defined in different ways depending on the consumer. Aspects that determine whether recycling is convenient can include proximity, opportunity, desirability, ease, and knowledge (Wagner, 2013). Surveys of consumers regarding their household recycling behavior found proximity to a recycling drop-off site to be an important factor of convenience (Berck et al., 2021; Saphores et al., 2006; Zaharudin et al., 2021). A 2006 survey of California residents found that willingness to recycle electronic waste doubles when the collection or drop-off site is located within five miles of their residence (Saphores et al., 2006). A survey of consumers in the United Kingdom found 93% preferred to travel directly from their homes to the recycling center and a majority preferred to travel between 5-15 minutes to the recycling center (Zaharudin et al., 2021). This indicates that although some consumers drop off their recycling enroute to or from other locations, the most important measurement of proximity is the distance and travel time from their residence.

In addition to proximity, accessibility and opportunity to use a collection site for recycling determines its convenience. Long wait times and limited hours at drop-off recycling locations make it inconvenient for a consumer to dispose of their waste (Berck et al., 2021; Bouvier & Wagner, 2011). A study of recycling centers in Maine found that recycling centers that were open consistently for more hours per day collected more e-waste per capita than facilities that offer limited hours or semi-annual collection events (Bouvier & Wagner, 2011). Co-location or the placement of e-waste collection sites near other services or additional recycling options makes it easier for consumers to partake in recycling schemes, potentially reducing travel time to the facility (Wagner, 2013). The range of accepted materials also affects consumers' preference in choosing between household waste recycling centers, with consumers preferring sites that accept a wide range of products (Zaharudin et al., 2021). The ability to recycle multiple different materials in one location streamlines the recycling process for the consumer, reducing confusion over where and what they can recycle.

Finally, knowledge about the recycling process can contribute to the convenience of recycling. In a U.S. survey about recycling electronic waste, those that do not recycle were more likely to be unaware of the location of recycling centers (Saphores et al., 2012). A UK study found that situational factors such as lack of space and time, and confusion about the process had a significant correlation with recycling intention and attitude (Tonglet et al., 2004). Confusion or lack of knowledge about the recycling process can make recycling more difficult and inconvenient for the consumer.

Ultimately, definitions of convenience can vary from consumer to consumer, adding a layer of difficulty for policymakers drafting recycling laws. However, understanding the attitudes and behaviors of consumers provides insight into the most effective solutions for the recovery of e-waste and the standardization of these policies throughout the United States.

1.3 Linking Policy Convenience Standards with Consumer Definitions of Convenience

As our literature review suggests, convenience is subjective, and lack of convenience can be a barrier to consumers recycling their electronic waste. The parameters that define convenience in state electronic waste policies may not align with the consumers’ experience and what they find to be convenient for recycling. Table 1 shows how policies define convenience for e-waste recycling compared to how consumers define convenience in the literature. For example, in

Pennsylvania, the Covered Devices Recycling Act stipulates that collection infrastructure must be “accessible on a regular and ongoing basis to at least 85% of the population” but does not require a minimum number of recycling sites (Covered Device Recycling Act, 2010). Though Pennsylvania has a number of other collection points for electronic waste, the majority accept only limited types of e-waste with the main restriction being on CRTs (Pennsylvania 2020 Annual Report: Covered Device Recycling Act, 2020). As of 2019, the state had only 8 collection sites that accepted all forms of e-waste covered by the law, which assuming a ten-mile radius of accessibility per site, serves only 23.7% of the state population (Pennsylvania 2020 Annual Report: Covered Device Recycling Act, 2020). The electronic waste recycling network that has resulted from Pennsylvania’s convenience standard may lack the ease and proximity that consumers find convenient. This demonstrates the importance of specific convenience guidelines that draw on the knowledge of consumer recycling behavior.

The literature on convenience and recycling discussed above is focused on consumer attitudes and behavior and the majority of these papers use surveys or observational studies for data collection. There is also an existing body of literature synthesizing and comparing electronic waste laws and policy mechanisms within the United States. However, there is a knowledge gap about how consumer definitions of convenience align with policy definitions of convenience. Understanding how these different convenience standards align with consumer concepts of convenience could inform future policy decisions as states look to enact or update e-waste laws or implement convenience standards within their existing legislative framework. Therefore, this research aims to overlay consumer definitions of convenience and policy definitions of convenience, in regard to electronic waste recycling. Using material flow analysis methods and a spatially explicit GIS model, we simulate the locations of e-waste collection sites locations, and estimate the amount of e-waste located within a convenient distance of such sites, for three state convenience standards. The goal of this research is to determine if the policy language used in these laws creates an electronic waste recycling network that consumers may define as convenient.

Table 1. Comparison of policy and consumer definitions of convenience.

Policy			Consumer		
Type of Convenience Standard	Definition	Example	Facet of Convenience	Definition	Example
Population	Minimum number of sites determined by population	Illinois: One program collection site in each county… that has a population density that is less than 250 individuals per square mile (Consumer Electronics Recycling Act, 2017)	Knowledge	How and where to recycle e-waste	Easy to obtain information about locations and procedures for recycling e-waste (Wagner, 2013)
Jurisdiction	Minimum number of sites per county/municipality	Connecticut: Minimum one collection site per municipality (Recycling of Covered Electronic Devices, 2015)	Opportunity	Ease of accessing recycling site	Wait time of less than 10 minutes (Berck et al., 2021) Site open at regular hours throughout the week (Bouvier & Wagner, 2011)
Distance	Site's locations determined by distance to population	New Jersey: >90% of the state's population must reside <15 miles from a collection site (Electronic Waste Management Act, 2017)	Proximity	Travel distance or time to recycling site	5-10 minutes travel time (Zaharudin et al., 2021) Less than 5 miles (Saphores et al., 2006)

2. Methods

2.1 Research Methods Overview

For this research, Illinois was chosen as a case study state. Illinois has the most robust set of convenience standards for electronic recycling in the United States after amending its existing electronic waste law in 2017 to replace mass-based collection targets with convenience standards (Consumer Electronics Recycling Act, 2017, Illinois Electronics Recycling Program, n.d.). Illinois' convenience standard for electronic waste recycling is unique among other states with electronic waste recycling laws. The population-based convenience standard has a robust set of minimum requirements for collection sites, and is one of the most recent convenience standards to be adopted into e-waste legislation in the U.S. Since the introduction of Illinois' convenience standard, the state has published statewide collection rates for electronic waste annually and publishes the locations of its collection sites. We were also able to obtain site specific collection data from the Illinois Environmental Protection Agency. This reported data made Illinois an ideal case study as it allowed for model validation by comparing our results to the real-world data from Illinois.

The model first used material flow analysis to estimate the amount of potential electronic waste in Illinois and where it is located. Second, the convenience standard in Illinois' Consumer Electronics Recycling Act (2017) was used to simulate potential locations of e-waste collection sites in Illinois. The coverage of potential electronic waste under the Illinois' convenience standard is defined as the percentage of the estimated potential electronic waste in Illinois located within a set distance of the simulated site locations. Real collection data from Illinois e-waste collection sites are compared to our simulated site locations and potential electronic waste estimations to validate our model.

To develop a framework for comparing different electronic recycling convenience standards, three additional convenience standards are used to simulate alternate collection site locations if Illinois' policy were reformulated with different convenience standards. For further analysis, three counties within Illinois were chosen as urban, suburban, and rural case studies. The modeled coverage in these three counties under Illinois' convenience standard is compared to coverage in the three alternative scenarios, to understand how each alternative convenience standard changes coverage in differently populated areas.

2.2 Illinois Case Study

2.2.1 Estimating the Amount of Electronic Stock in Illinois Households

An important input for our model is the estimated quantity and spatial location of electronic waste in Illinois. A useful tool to study electronic waste flows and determine this amount is Material Flow Analysis (MFA) (Islam & Huda, 2019). Previous literature using MFA methods includes Althaf et al., 2019, which project the flow of electronic products into the waste stream each year by combining historic sales data with the life span distribution for each type of device to calculate future quantities of e-waste at the end-of-life stage (Althaf et al., 2019). Our model uses Illinois population data combined with survey data on household ownership of devices to estimate the amount of electronic stock in Illinois households.

A key data source for this process came from the Annual Consumer Technology Ownership and Market Potential Study, which contains data on household ownership rates for a variety of electronic devices. This study, by the Consumer Technology Association (CTA), conducted surveys of over 2,000 people in the United States and disaggregated ownership data by income and other demographic variables. Ownership data for each income bracket is reported as the percentage of households in that income level that own 0, 1, 2, 3, or 4 or more devices. The study used for our research was published in March 2016, and contains ownership values from 2015 (*18th Annual Consumer Technology Ownership and Market Potential Study*, 2016).

The Illinois Consumer Electronics Recycling Act (2017) lists the devices that are allowed to be recycled under Illinois law. These are known as Covered Electronic Devices or CEDs. While the CTA survey collected consumer data on a wide range of electronic products, we are only interested in ownership rates for products that are CEDs under Illinois law. However, the terms for each device differ slightly between CERA and the CTA survey data, necessitating the creation of a dictionary table, shown in Table 1. This table maps each CED listed in CERA (2017) to the corresponding CTA category that was used to identify ownership rates of these devices.

Table 2. Illinois Covered Electronic Devices and the Corresponding CTA Category.

Illinois Covered Electronic Device	**Consumer Technology Association Device Categories**
Computer	Desktop Computer, Notebook Computer, Tablet Computer
Computer Monitor	Desktop Computer (assuming 1:1 monitor: desktop ownership)
Television	Flat Panel TV
Printer	Multi-Function Printer
Electronic Keyboard	Desktop Computer, Tablet Computer (assuming 1:1 keyboard: computer ownership)
Facsimile Machine	Multi-Function Printer
Videocassette Recorder	VCR
Portable Digital Music Player	Portable MP3/Digital Media Player
Digital Video Disc Player	DVD/Blu-Ray Player or Recorder
Video Game Console	Home Video Game Consoles, Portable Game Device
Electronic Mouse	Desktop Computer, Notebook Computer (assuming 1:1 mouse: computer ownership)
Scanner	Multi-Function Printer
Digital Converter Box	Excluded (no comparable data category)
Cable Receiver	Cable Modem
Satellite Receiver	Satellite Internet Connection
Digital Video Disc Recorder	DVD/Blu-Ray Player or Recorder
Small Scale Server	Excluded (no comparable data category)

The Consumer Technology Association survey did not include categories for all of Illinois' covered electronic devices, so several assumptions were made to determine ownership rates for devices without CTA data. For example, computer monitors are a covered electronic device under CERA (2017), but the CTA survey data does not include ownership data for computer monitors. Therefore, to estimate the number of computer monitors in Illinois, a one-to-one ratio of computer monitors to desktop monitors was used, based on the assumption that each household owns one monitor per desktop computer. CRT televisions are also not included in the CTA ownership data, but flat panel televisions are. Historic waste flow data for flat panels and CRT TVs were used to calculate CRT ownership (Althaf et al., 2019).

Additionally, small-scale servers and digital converter boxes are covered electronic devices under CERA but did not have a corresponding category in the CTA report (Consumer Electronics Recycling Act, 2017). Due to the lack of data on ownership of these two devices, they were excluded from the device estimations and are assumed to comprise an insignificant portion of overall electronics owned in Illinois. A complete explanation of methods, assumptions, and literature values for mapping CTA device categories to Illinois' covered electronic devices and obtaining device ownership rates is provided in the appendix.

To place ownership rates in the context of Illinois' population, census data containing household income data from the American Community Survey 5-Year Estimates was downloaded and used (*TIGER/Line with Selected Demographic and Economic Data*, 2015). This data set contains population and demographic data at a variety of scales, as well as mapping files. Census tracts were chosen over other geographic groupings of population data because census tracts are the smallest scale this data was offered at. Using census tracts for material flow analysis allows for a higher resolution that represents the population distribution.

In the CTA survey, consumer responses are grouped into four annual household income brackets: less than $25,000, $25,000 to $50,000, $50,000 to $75,000, and more than $75,000 (*18th Annual Consumer Technology Ownership and Market Potential Study*, 2016). The ACS 5-Year Estimate dataset disaggregates household income further, organizing household income in blocks of $5,000. Thus, the ACS data were aggregated into the same four income brackets to align with the CTA survey data.

For each device, the CTA survey reports the percentage of each income bracket that owns 0, 1, 2, 3, or 4 or more devices. Using these values, a weighted average of each device per household in one income bracket is calculated using Equation 1. For the percentage of households listed as owning 4 or more devices, it is assumed that each household owns 4 devices for this equation.

Equation 1.

$$\sum_{n=1}^{4} n * p_n = w$$

Where *n* is the number of devices {1,2,3,4}, and *p* is the percentage of households owning *n* devices. The weighted average of devices per household is represented by *w* and is calculated four times for each device, once for each income bracket.

Then for each census tract, the number of households in each income bracket is multiplied by the weighted average for that income bracket, giving the total amount of that device owned by that income bracket. These are summed across all income brackets for each census tract, to obtain the total estimated stock of each device in households in that census tract, as shown in Equation 2.

Equation 2.

$$\sum_{i=1}^{4} w * h_i = s$$

Where *w* is the weighted average devices per household, *h* is the number of households in that census tract and income bracket, *i*, and *s* is the estimated stock of the device in that census tract.

Finally, the numbers for each device in a census tract were summed, to generate the total units of estimated electronic stock per census tract. The estimated electronic stock per tract can be summed across all census tracts to produce the total estimated electronic stock, in units, for the state of Illinois.

2.2.2 Estimating the Mass of Electronic Stock in Illinois Households

Once the number of units for each device across all census tracts was estimated, the next step was calculating the total mass. To calculate the mass of electronic stock in Illinois households, mass data was taken from the Historic Product Sales Data document within the supplemental information dataset from Althaf et al., 2020. This data shows the annual average mass in kilograms for various electronic devices between 1990 and 2018. This represents the dynamic mass of electronic devices such as laptops, which decreased in mass between 1992 and 2018 (Shahana Althaf, 2020). The mean lifespan of each device, obtained from Althaf et al., 2019, is used to determine the years preceding 2015 to average the device mass. For example, laptops have a mean lifespan of four years, so the mass for laptops was averaged from 2011 to 2015.

This document also contains static masses, which were used for devices that did not have dynamic masses listed. There are four covered electronic devices not included in the Althaf, 2020 mass dataset. These are electronic mice, electronic keyboards, cable receivers, and satellite receivers. To obtain mass values for these products, a best effort was made to average the masses provided in online listings from reputable online retailers such as Best Buy. These values are included in the Supplemental Information.

The average masses are multiplied by the total units of a device per census tract, to obtain the total mass value in kilograms for each device and census tract. These mass values are then summed across all devices in a census tract to obtain the estimated electronic stock, in kilograms, located in that tract. These estimates are then summed across all census tracts, to obtain the total estimated electronic stock, in kilograms, for the state of Illinois.

2.2.3 Estimating the End-of-Life Portion of Electronic Stock in Illinois Households

The estimations of electronics in Illinois so far represent the total units or weight of devices owned by consumers. To estimate the portion of these devices that are reaching end of life and are potentially ready to enter the recycling system, the electronic stock for each device is divided by the device's mean lifespan (Equation 3). Lifespan data was obtained from Althaf et al., 2019.

Equation 3.

$$s * \frac{1}{l} = e$$

Where *s* is the total estimated stock of a device, *l* is the mean lifespan of the device, in years, and *e* is the stock of that device which is estimated to be at end-of-life, potentially ready for disposal.

The end-of-life portion of electronic stock in Illinois households is intended to serve as an estimation of potential electronic waste in Illinois. For the remainder of this document, "potential electronic waste" refers to the portion of estimated electronic stock in Illinois that is estimated to be at end-of-life, or ready for disposal.

2.2.4 Simulating Electronic Waste Collection Sites under the Illinois Convenience Standard

The Electronic Products Recycling & Reuse Act (EPRRA) in Illinois was passed in 2008 and amended in 2011. This law created a landfill ban on all certain consumer electronic devices (CEDs) and required manufacturers of those devices to develop recycling programs. The metrics outlined in EPRRA were mass-based, with a statewide electronic recycling goal set annually. Additionally, each manufacturer was responsible for collecting and recycling a minimum percentage of their Illinois product sales from prior years (The Electronic Products Recycling and Reuse Act, 2011).

In 2017, the Consumer Electronics Recycling Act (CERA) replaced EPRRA (Consumer Electronics Recycling Act, 2017). CERA maintains a statewide annual collection goal but added convenience standards to the state electronic recycling program (Illinois Electronics Recycling Program, n.d.). The convenience standard operates on a sliding scale, where counties that opt to participate in the state's electronic recycling program are assigned a minimum number of drop-off collection sites based on the population density of the county (Consumer Electronics Recycling Act, 2017). The minimum number of required collection sites are listed in Table 2.

Table 3. Minimum Required E-Waste Collection Sites per County in Illinois (Consumer Electronics Recycling Act, 2017).

County Population Density (people per square mile)	**Minimum Required Number of Collection Sites**
Less than 250	1
250 to 499	2
500 to 749	3
750 to 999	4
1,000 to 4,999	5
Greater than or equal to 5,000	10
Municipality with a population over 1,000,000 people	15

Figure 1 shows the assignment of minimum sites per county under the Illinois Consumer Electronics Recycling Act (Consumer Electronics Recycling Act, 2017). Although Illinois' law provides counties the opportunity to opt-in to participation, 52 counties chose to partake in 2020, up from 48 counties in 2019 (*Illinois Electronics Recycling Program: 2019 Collection Summary Report*, n.d.; *Illinois Electronics Recycling Program: 2020 Collection Summary Report*, n.d.). During 2020, approximately 85% of Illinois residents lived in a county that participated in the

CERA program (*Illinois Electronics Recycling Program: 2020 Collection Summary Report*, n.d.).

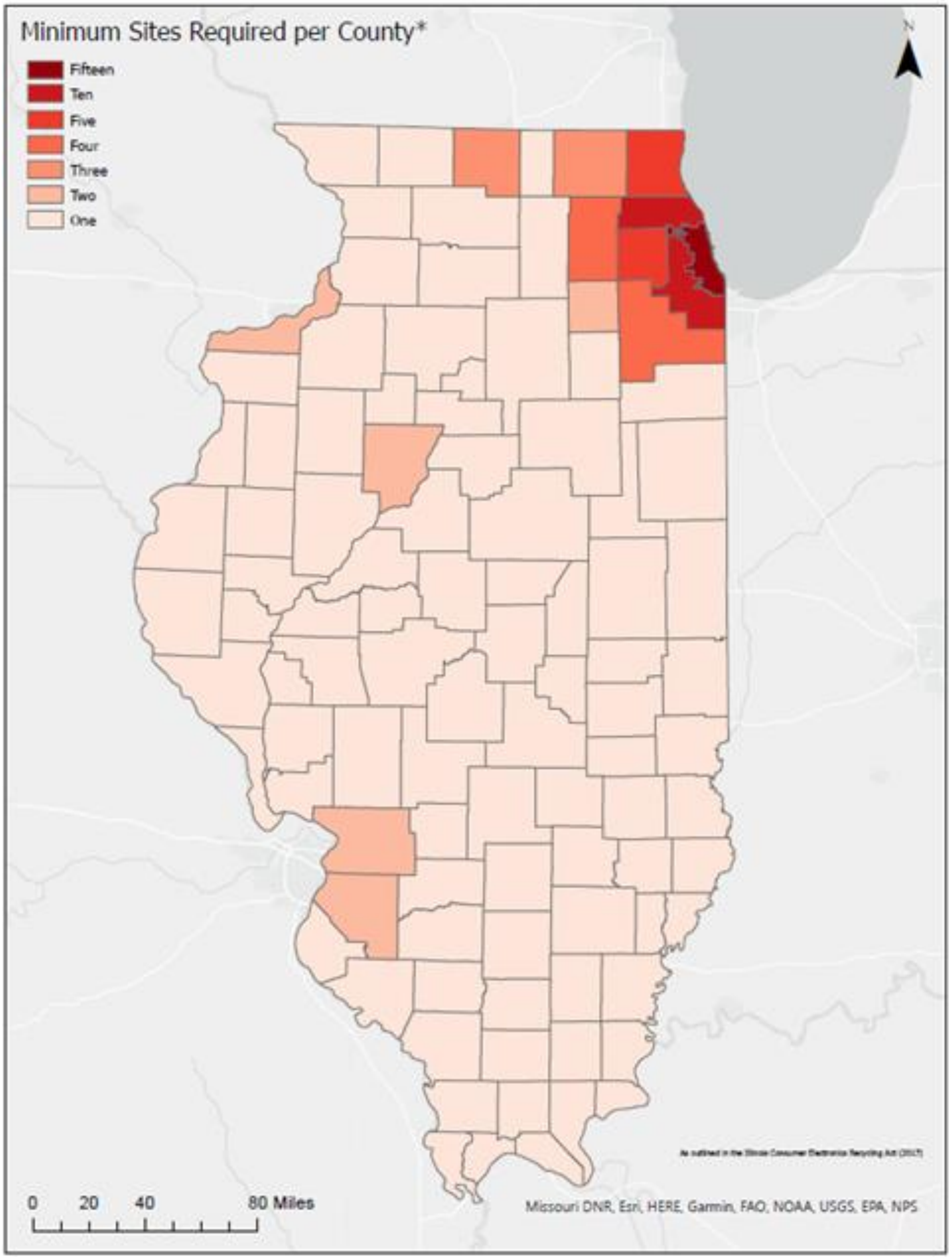


Figure 1. The minimum required number of e-waste collection sites per county as determined by the Consumer Electronics Recycling Act (2017).

To model the Illinois convenience standard, each county was assigned the minimum collection facilities based on population density, as stated by law. To locate sites in each county, the goal is to place the minimum number of sites across the county, proportional to population. As household electronic waste was estimated at the census tract level, we also have population data at the census tract level. Each county is comprised of multiple census tracts, giving some insight into the population distribution within a county. Rather than placing sites randomly or equally distributed throughout the county, our intent was to place sites near the population centers of each county.

First, each county was split into zones according to the minimum number of sites. For the 90 counties that only required one site, no zones were created. These zones were created using the Build Balanced Zones tool in ArcGIS Pro 3.1.0. This tool can create a target number of zones, in this case, the minimum sites, as well as ensure the zones have roughly equivalent values of a chosen variable, in this case, households. This tool aggregates the census tracts into a set number of spatially contiguous zones, such that the number of households in each zone is as balanced as possible.

Then, the centroid of each census tract is generated, and the centroids are spatially joined to the zones for each county. Using the Central Feature tool, a weighted central feature is generated for each zone within a county, using the total households in each census tract as the weighted variable. These central features are the modeled drop-off collection sites for electronic waste. For example, in a county that requires four sites, this process will split the county into four balanced population zones, and place a facility within each zone, the exact location of which is weighted by population inputs at the census tract level. This method does not analyze the feasibility of specific locations or include site selection criteria. This model is not intended to replicate the real-world recycling network of Illinois, but rather to demonstrate the potential distribution of e-waste collection sites, given a set of convenience criteria.

2.2.5 Calculating the Coverage of Potential Electronic Waste under Illinois' Convenience Standard

The coverage of potential electronic waste is defined as the percentage of potential e-waste within a set distance of a modeled site. Our research objective is to overlay consumer definitions of convenience with policy definitions of convenience to determine if policy convenience standards align with consumer preferences. As coverage of potential e-waste approximates the collection network's convenience, the distances used to determine coverage of modeled collection sites are based on what consumers consider to be a convenient distance to travel to recycle electronic waste. A study of California residents found that people were twice as likely to recycle their electronic waste if the drop-off location was within five miles of their home (Saphores et al., 2006). A survey of United Kingdom residents found that a majority preferred to travel between five and fifteen minutes to a household recycling center (Zaharudin et al., 2021). Based on the findings of the literature review, the convenience radii chosen are three and five miles, to capture a range of preferences as well as account for differences in travel distance between rural and urban areas.

Using the buffer tool in ArcGIS Pro, a convenience radius of three miles is generated around each modeled site location. All buffers are combined into one feature class using the Merge tool and the Dissolve Boundaries tool to remove any overlaps in buffers. The Tabulate Intersection tool calculated the percentage of each census tract within a buffer. The subsequent tabulate intersection table was joined to the census tract feature class containing the electronic waste estimations and exported to Microsoft Excel. Assuming a homogenous distribution of electronic waste throughout a census tract, the total mass of estimated electronic waste in each census tract was multiplied by the percentage of each census tract within a site buffer. Summing across all census tracts and dividing by the total potential e-waste in Illinois, we find the percentage of potential electronic waste located within three miles of a modeled site under the Illinois convenience standard. This process is repeated with five-mile buffers to obtain the percentage of potential electronic waste located within five miles of a modeled site.

2.2.6 Validation of Model Using Real Collection Data from Illinois

To validate the locations of the sites we modeled, existing e-waste collection site locations in Illinois were also found, and mapped in ArcGIS Pro. These site locations were obtained from The Illinois Environmental Protection Agency's Beyond the Bin map, filtered by locations that accept electronics (*Illinois EPA Beyond the Bin Map*, n.d.). The locations of the existing e-waste collection sites in Illinois were compared to the sites modeled using Illinois' convenience standard.

To check the model, real collection data for eight sites in 2021 was compared to the modeled e-waste within a convenient distance of the closest modeled site. The Illinois Environmental Protection Agency provided this real-site data through a Freedom of Information Act request. This data included the 2021 collection amounts in pounds, for eight fixed-location drop-off collection sites, as well as the locations and collection amounts for e-waste collection events (*Collector's Electronic Products Collection & Transportation Reports*, n.d.). For each of the eight electronic waste collection sites with 2021 data, the closest modeled site under the Illinois convenience standard was compared. Convenience radii of 3 and 5 miles were generated around the closest modeled site and the existing site. Utilizing the same process mentioned before, the Tabulate Intersection tool was used to calculate the percentage of each census tract within each convenience radius. This percentage is multiplied by the mass of electronic waste estimated to be in each census tract and summed to obtain the estimated mass of e-waste within 3 and 5 miles of each site.

It is important to note that the three- and five-mile radii used in our model create a circular buffer around each site, which may not accurately reflect the distance a consumer must drive to drop-off e-waste, as these radii do not consider the density or distribution of the road network in Illinois. Drive time areas can be calculated in ArcGIS Pro, to represent the distance one can travel from a node within a set amount of time. This method requires inputs such as the locations of roads and speed limits to calculate the drive time area accurately. In calculating the coverage of potential e-waste, or the amount of potential e-waste located within three or five miles of a modeled collection site, our highest resolution of data is at the census tract level, as we assumed a homogenous distribution of population and estimated potential e-waste within each census tract. We hypothesized that creating a drive time area at the level of the road network was unnecessary as our estimated e-waste data was not resolved to that level of detail.

To test this, however, we did complete a sample drive time area model to check our results using the buffer method. This additional analysis serves to check whether the results calculating the potential coverage of estimated e-waste using distance differ greatly from potential coverage calculated using travel time. The tool Generate Drive Time Trade Areas was used to shade areas radiating from each modeled site, that represent 5-, 10-, and 15-minute drive times. These values were chosen due to the consumer preference for traveling 5 to 15 minutes to a recycling center, as identified in our literature review (Zaharudin et al., 2021). Data on road classifications, including data such as speed limits of each road were not found at the statewide level for Illinois. Therefore, these drive time areas were calculated using the ESRI base map as the input for the

Illinois road network (ESRI, 2017). The 15-minute drive time areas were used to calculate the coverage of potential e-waste in Illinois, using the Tabulate Intersection tool and the same methods as mentioned in Section 2.2.5.

2.3 Applying Alternative Convenience Standards to Illinois

To understand how the language of convenience standards in policy impacts the distribution and coverage of collection sites, three alternative convenience standards are modeled in Illinois. These three scenarios simulate where collection sites might be placed if Illinois reformulated its convenience standard. The first alternative convenience standard requires three sites per county. The second requires three sites per county and one site per municipality of over 10,000 people. The third convenience standard scenario requires 90% of Illinois' population to live within 15 miles of a collection site. The first and second scenarios are based on parts of the convenience standard outlined in Vermont's electronic waste recycling statute. The third scenario is based on New Jersey's electronic waste recycling law. In our policy review we found that states did not publish explanations for the parameters set in their e-waste recycling convenience standards. Therefore, when modeling these alternative convenience standards, we followed the language of the policy as written, and chose states convenience standards that represent each of the three types of convenience standards that we identified in our policy review, as defined in Section 1.1. Scenario 1 represents the jurisdiction-based convenience standards, Scenario 2 represents the population-based convenience standards, and Scenario 3 represents the distance-based convenience standards.

2.3.1 Scenario 1: Convenience Standard of Three Sites per County

The Vermont statute on electronic waste recycling takes a two-part approach to its convenience standard. The first part of this standard mandates a minimum of three collection sites per county (Collection And Recycling Of Electronic Devices, 2010). This part of the convenience standard is simulated within Illinois first, to understand how a uniform number of sites per county will create coverage of potential electronic waste.

To model this convenience standard within the context of Illinois, we used the estimated potential electronic waste per census tract as an input, just as we did when simulating sites under Illinois' actual convenience standard. To place sites, the Build Balanced Zones tool was used again, however instead of creating a target number of zones equivalent to the minimum number of sites required under Illinois law, three zones were created for each county. The centroids of each census tract within a county were spatially joined to these zones, and a central feature weighted by population was created in each zone, to represent the modeled site locations. This way, three simulated e-waste collection sites are generated for each county in Illinois.

Some issues that we ran into during this process occurred in some of the rural counties. Some counties had only three census tracts, and therefore the Build Balanced Zones tool would not work for these counties as the tool requires more than one feature per zone. For these counties, each census tract represented a population zone, and the modeled sites were placed at the centroid of each census tract. For the few counties with just two census tracts, the census tracts represented two population zones, with two of the modeled sites located at the centroid of the census tracts. The third site was located at the centroid of the county. For these rare cases, the differences in population between census tract proxy zones were within the same margin as population zones created by the Build Balanced Zones tool. With 102 counties in Illinois, this convenience standard resulted in 306 modeled collection sites.

To generate a convenience radius for each site, the Buffer tool was used again. Three- and five-mile buffers were generated around each site to represent the 3 to 5 miles that consumers are willing to travel to drop off their electronic waste. The Merge tool and Dissolve Boundaries tool were used on each set of buffers to eliminate overlaps. Then Tabulate Intersection was run to generate a table with the percentage of each census tract within a three- or five- mile radius of a modeled site. Finally, the tabulate intersection tables were joined to the census tract feature class in ArcGIS Pro and exported to Microsoft Excel, where the mass of electronic waste in a census tract was multiplied by the percentage of the census tract within 3 or 5 miles of a modeled site. This calculation resulted in the amount of potential electronic waste in each census tract that is covered by a modeled collection site.

The potential e-waste per census tract that is within a three- or five- mile distance of a modeled site is summed across all census tracts and divided by the total estimated potential electronic waste in Illinois, to obtain the percentage of potential electronic waste in Illinois that is covered when the state convenience standard mandates three sites per county.

2.3.2 Scenario 2: Convenience Standard of Three Sites per County with a Municipality Requirement

The Vermont policy regarding electronic waste recycling also requires at least one site for each municipality with a population of over 10,000 people (Collection And Recycling Of Electronic Devices, 2010). This scenario builds off Scenario 1, using the same sites modeled in Scenario 1, to satisfy the three sites per county requirement. Then, for each municipality with a population over 10,000 people, one site is assigned.

To determine which municipalities had populations over 10,000, TIGER/Line shapefiles and population data from the American Community Survey (ACS) 5-year estimates were downloaded at the county subdivision level (*TIGER/Line with Selected Demographic and Economic Data*, 2015). This dataset provides shapefiles for municipalities within Illinois. To identify which municipalities, have a population over 10,000, annual population estimates for incorporated places in Illinois for the years 2010 to 2019 were downloaded from the U.S. Bureau of the Census (*City and Town Population Totals: 2010-2019,* n.d.). Incorporated places are defined by the U.S. Bureau of the Census as legal entities which provide governmental services to a set population, and typically are a “city, town, village, or borough, but can have other legal descriptions” (*2019 TIGER/Line Shapefiles Technical Documentation*, 2019). The county subdivision shapefiles in the former dataset were cross referenced with each incorporated place with a population of over 10,000 people in 2015 in the latter dataset. A new layer in ArcGIS Pro was created of only municipalities with a population of over 10,000 once all were identified and selected through this process. Then, any of these municipalities that already contained one of the three modeled sites per county were excluded from the layer, leaving only those municipalities with the minimum population and no modeled site. A new modeled site was placed at the centroid of each of these entities, resulting in an additional 114 modeled sites in Illinois.

2.3.3 Scenario 3: Convenience Standard Based on Distance to Population

New Jersey’s electronic waste recycling policy, which was updated in 2017, requires that the state’s electronic waste recycling program “designate collection locations throughout the State such that at least 90 percent of consumers are located within no more than 15 miles of a collection location” (Electronic Waste Management Act, 2017). Rather than mandating a minimum number of sites per county or municipality, this convenience standard bases collection site locations on their distance to the state's population. This convenience standard is simulated in Illinois to determine the coverage of potential e-waste in the state if Illinois were to adopt this convenience standard.

To model the locations of these sites, a different approach was used from the first two convenience standards. As no minimum number of sites are set, there are multiple ways to model this convenience standard. In our model, each county was ranked from highest to lowest population. Then, one site was placed in each county, using the Central Feature tool to generate a weighted central point for the county, based on the population of the census tracts within the county. This process was done incrementally. For each additional county site, a fifteen-mile radius was created around the new site, using the Buffer tool. The fifteen-mile buffers for all sites up to that point were run through the Merge tool and the Dissolve Boundaries tool to eliminate overlapping. Then, as with the other convenience standards, Tabulate Intersection was run to calculate the percentage of each census tract within a site's fifteen-mile radius. Again, assuming an equal distribution of population throughout each census tract, the percentage of tract within fifteen miles of a site was multiplied by the number of households in that tract. This provides the estimated number of households in each census tract that are within fifteen miles of a modeled e-waste collection site. Summing across all census tracts in Illinois, we calculated the total number of households in Illinois that are estimated to live within fifteen miles of a modeled site.

This process was repeated until the number of households within fifteen miles of a modeled site reached 90% of Illinois' total household population. The results of this model generated 75 sites, in the 75 most populated Illinois counties. For our model, 90.3% of Illinois' population is estimated to be located within fifteen miles of these 75 modeled sites.

To remain consistent with the analysis of other state convenience standards, three and five-mile buffers were created around these 75 sites. Once the buffers were merged, the Tabulate Intersection tool was used to calculate the percentage of each census tract within 3 and 5 miles of a modeled site. Using the same process as Scenarios 1 and 2, we calculated the amount of Illinois' estimated potential e-waste within a 3 and 5-mile radius of a modeled site.

2.4 Three Case Study Counties

Three counties were selected as case studies for comparison between convenience standards. These counties were chosen to represent urban, suburban, and rural scenarios in Illinois. Cook County, where Chicago is located, serves as the urban case study, as Chicago is the largest city in Illinois, and Cook County is the most populous county, both in overall population and population density. Sangamon County, which contains Springfield, Illinois, the state capital, serves as the suburban case study, as the county has an urban population center, but its overall population density is below 250 people per square mile. Finally, Clay County was chosen as the rural case study. Clay County is classified as a rural county (*Illinois Counties by Rural/Urban Classification*, 2020).

3. Results and Discussion

3.1 Illinois Case Study

3.1.1 Estimating the End-of-Life Portion of Electronic Stock in Illinois

The estimated potential electronic waste in Illinois totaled 16.5 million units and 70 million kilograms. The composition of potential electronic waste by units of devices was different than the composition of potential e-waste by mass. Televisions and printers contributed more to the total potential e-waste by mass than they did to the total potential e-waste by units. For example, televisions, consisting of CRT and Flat Panel TVs, represented 12% of the total devices by units but represented 50% of the total estimated mass of potential electronic waste in Illinois, the largest contribution of any device. Flat Panel TVs make up an estimated 29% of the potential electronic waste in Illinois by mass, while CRT TVs comprise 22% of Illinois' potential e-waste by mass. Within the computer category, which contains desktop, tablet, and notebook computers, tablet computers represented the largest share of potential computer e-waste by units, while desktop computers represented the largest share of potential computer e-waste by mass.

The largest contribution to the total estimated potential e-waste mass in Illinois is televisions, followed by computers at 19% and computer monitors at 9.0%. This value is in line with Illinois' collection data, as in 2020, Illinois reported that 54.8% of the e-waste collected by mass came from televisions, representing the largest device category by weight (*Illinois Electronics Recycling Program: 2020 Collection Summary Report*, n.d.). Table 3 and Figure 2 show the final results of potential electronic waste estimations by device type in Illinois.

Table 4. Estimated Potential Electronic Waste (by units and by mass) in Illinois for each Device Type.

Type of Device	Estimated Potential Electronic Waste (units)	% of Total Potential Electronic Waste (units)	Estimated Potential Electronic Waste Mass (kg)	% of Total Potential Electronic Waste Mass (kg)
Televisions	1,900,000	12%	35,000,000	50%
Computers	4,300,000	26%	13,000,000	19%
Computer Monitors	620,000	3.8%	6,300,000	9.0%
Video Players	1,500,000	9.0%	5,500,000	7.8%
Printers	520,000	3.1%	3,800,000	5.5%
Video Game Devices	1,300,000	8.0%	3,700,000	5.3%
Computer Peripherals	4,700,000	28%	1,800,000	2.5%
Cable and Satellite Receivers	650,000	3.9%	580,000	0.8%
Digital Music Player	1,000,000	6.2%	96,000	0.1%

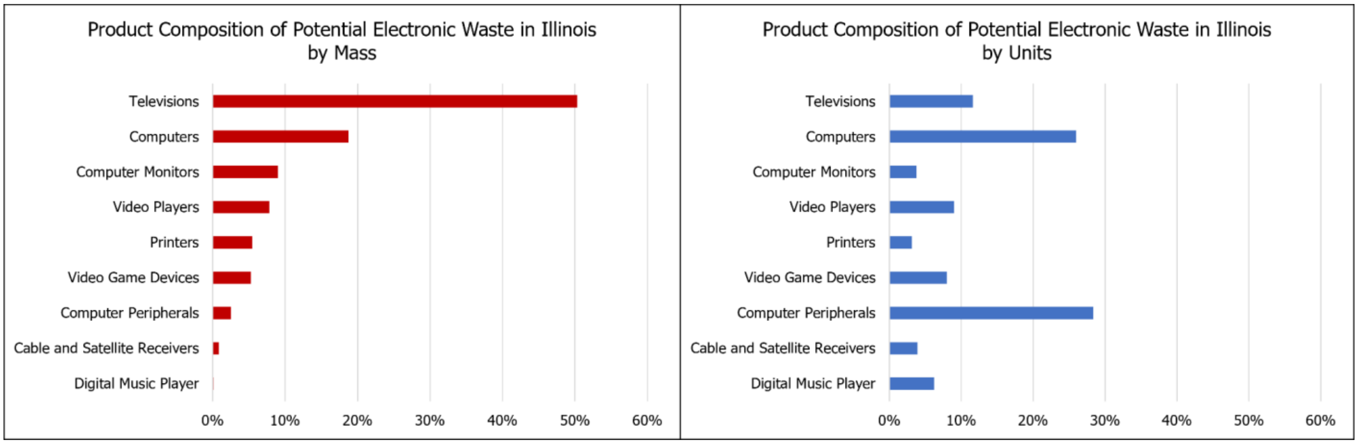


Figure 2. Product composition of total potential electronic waste in Illinois, by mass and by units.

The number of households per census tract is shown in Figure 3. The distribution of electronic waste in Illinois, when mapped by census tract, follows the general population patterns. Figure 4 shows the mass of estimated e-waste per census tract. There are higher concentrations of electronics in urban areas, such as Cook County, which contains the city of Chicago. Additionally, there are pockets of central Illinois with higher amounts of potential electronic waste, which are due to the presence of smaller cities creating populations clusters, such as Peoria, Champaign, and the state capital Springfield.

To understand the distribution of potential electronic waste further, the map below shows the average estimated potential electronic waste per household in each census tract. When normalized by the number of households in each tract, the distribution of e-waste aligns with the income distribution. The differences between rural and urban census tracts are not as stark when the e-waste mass is normalized by households, as seen in Figure 5.

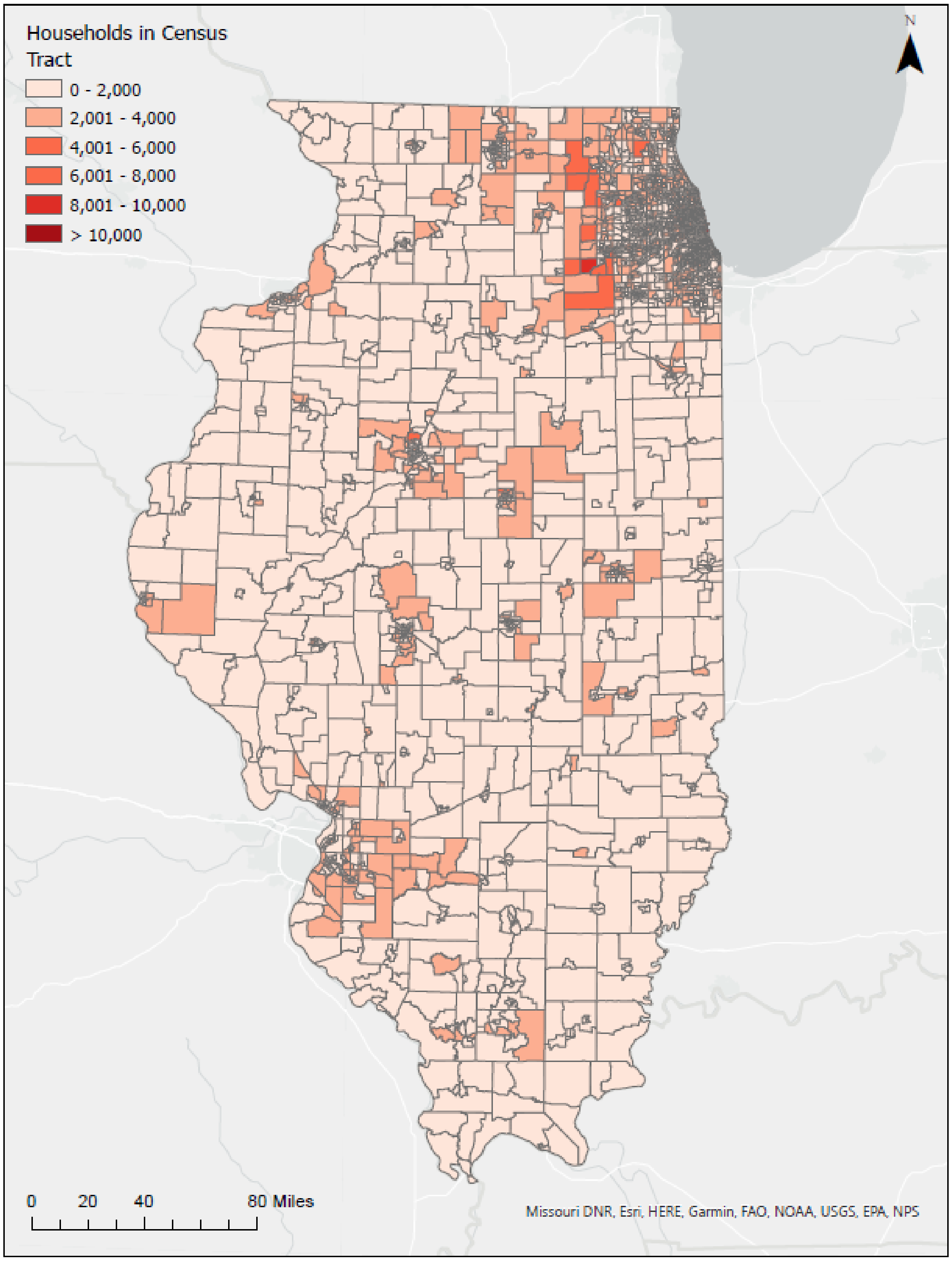


Figure 3. The number of households per census tract in Illinois, according to the 2015 American Community Survey 5-year Estimate (TIGER/Line with Selected Demographic and Economic Data, 2015).

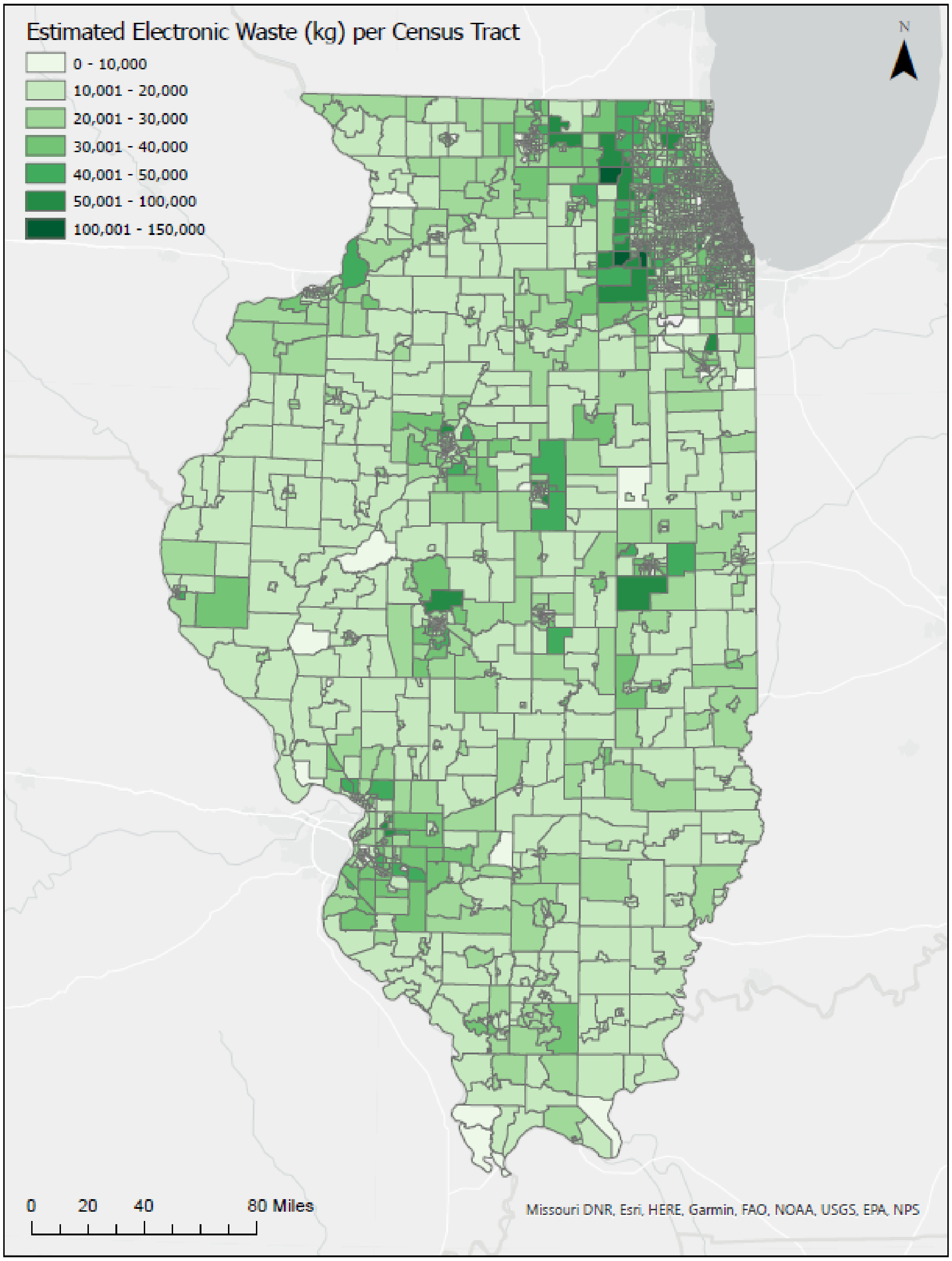


Figure 4. Estimated potential electronic waste, in kilograms, per census tract in Illinois.

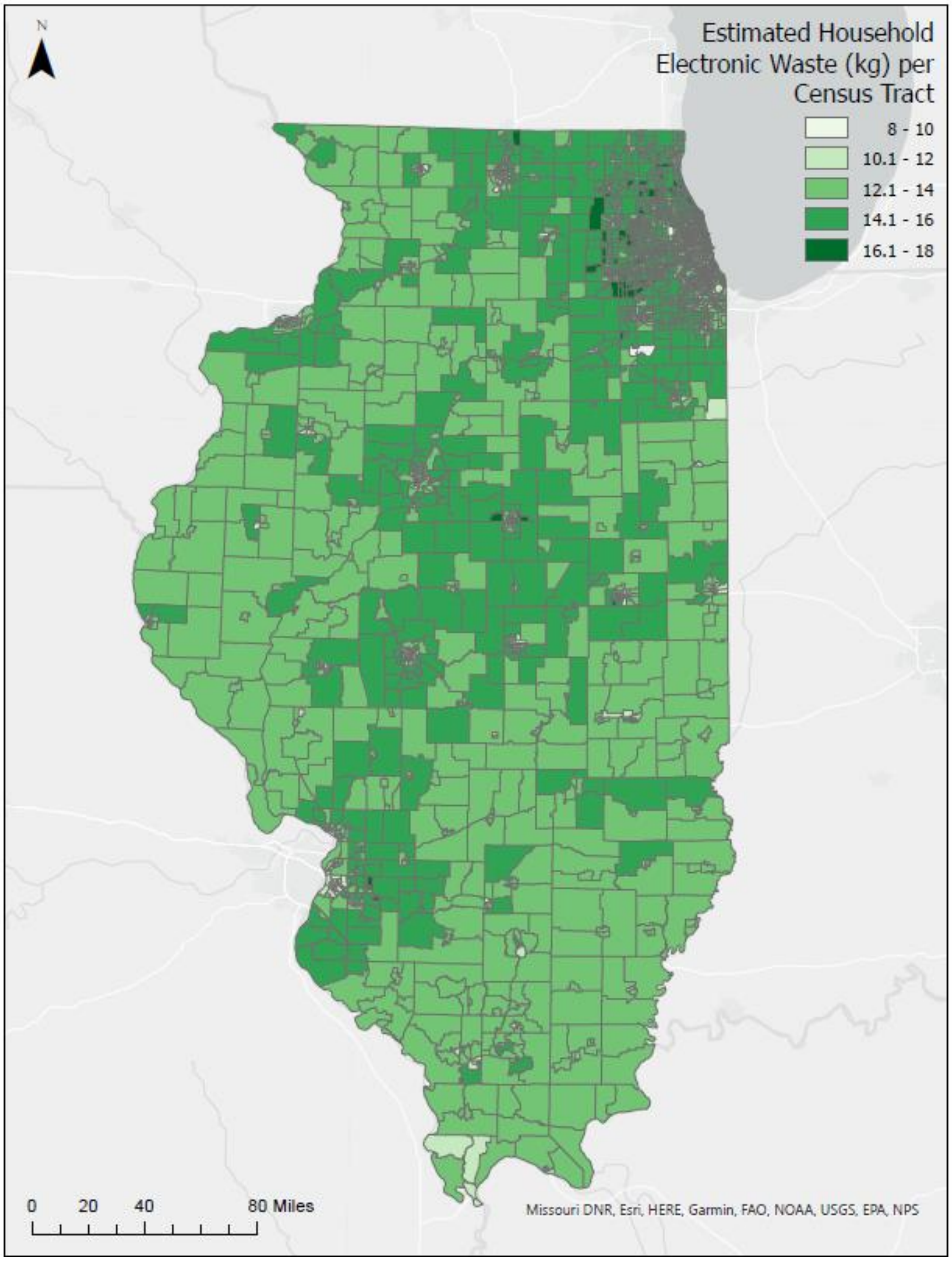


Figure 5. The estimated potential electronic waste per census tract in Illinois, normalized by the number of households in each census tract.

3.1.2 Simulating Collection Sites and Calculating Coverage under the Illinois Convenience Standard

Of the 102 counties in Illinois, 90 counties had a population density of less than 250 people per square mile, and therefore were required to have just one site under the Consumer Electronics Recycling Act (2017) convenience standard. Five counties were required to have two sites, two counties were required to have three sites, one county was required to have four sites, two counties were required to have five sites, and one county was required to have ten. The city of Chicago is required to have 15 sites within the municipality as the city has a population of over one million people.

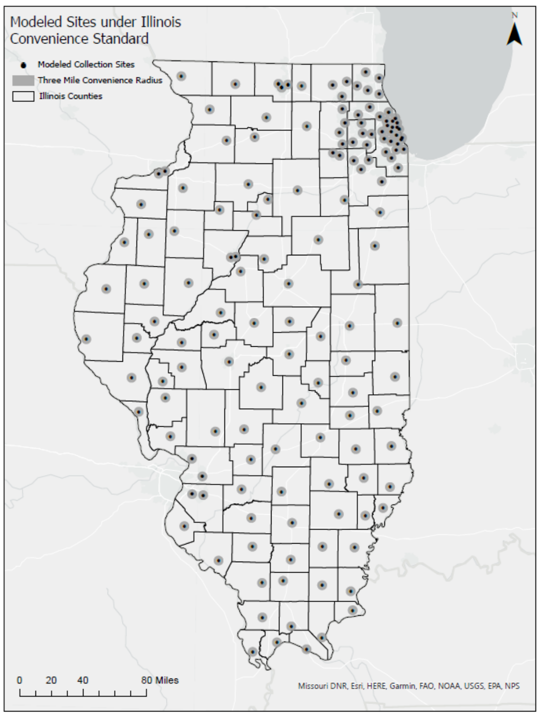
Under Illinois' electronic waste recycling convenience standard, outlined in CERA, a total of 145 sites were modeled. The locations of these sites with a three- and five-mile radius are shown in Figures 6 and 8, respectively. We calculated the percentage of each census tract that is within a three-mile radius of a modeled site, and from there, calculated the mass of potential electronic waste in each census tract that is within 3 miles of a modeled site. The results of these calculations found that 48% of the estimated potential electronic waste in Illinois is located within three miles of a site modeled under the CERA convenience standard. A distance of 3 miles was chosen based on consumer definitions of convenience in literature. Therefore, this finding indicates that if a consumer is only willing to travel a maximum distance of three miles to drop their electronic waste off at a collection site, the sites modeled based on Illinois' convenience standard are located within a convenient distance of less than half of the state's estimated potential e-waste.

The percentage of each census tract within a five-mile radius of a modeled site was also calculated and used to determine the percentage of Illinois' estimated potential electronic waste located within five miles of a modeled e-waste collection site. This calculation found that 70% of Illinois' estimated potential electronic waste is located within five miles of a modeled site under the CERA convenience standard. The distance of five miles was chosen for this analysis based on consumer definitions of convenience identified in our literature review. The result indicates that if a consumer's definition of convenience or willingness to travel to a collection site is a maximum of 5 miles, 70% of Illinois' estimated potential e-waste is located within a convenient distance of a modeled collection site.

Figures 7 and 9 show the percentage of each census tract that is covered by a three- or five-mile radius around the modeled sites. These visuals highlight the geographic distribution of this coverage. For both the three- and five-mile radii, coverage of census tracts is highest in urban areas, such as Cook county which contains the city of Chicago, as well as Lake and DuPage counties, which are located adjacent to Cook County in northeast Illinois. We define a census tract as having high coverage when more than 80% of the tract is located within the defined radius of a modeled e-waste collection site. With a three-mile radius around modeled sites, 48% of Illinois' census tracts have high coverage, while 70% have high coverage with a five-mile radius around modeled sites.

The least amount of coverage occurs in counties with less than 250 people per square mile, as those counties are only required to have one site under CERA. We define a census tract as having low coverage when less than 20% of the tract is located within the defined radius of a modeled e-waste collection site. With a three-mile radius around the modeled sites, 40% of census tracts have low coverage, and with a five-mile radius around the modeled sites, 20% of census tracts have low coverage. This indicates that in this model, if consumers consider collection sites located farther than five miles away to be inconvenient, 20% of census tracts in

Illinois are underserved by the modeled sites. When coverage is defined by a three-mile radius around the modeled sites, 27% of Illinois' census tracts had 0% coverage, while 11% of census tracts had 0% coverage when determined with a five miles radius. These census tracts represent the locations most severely underserved by the modeled sites under the Illinois convenience standard.



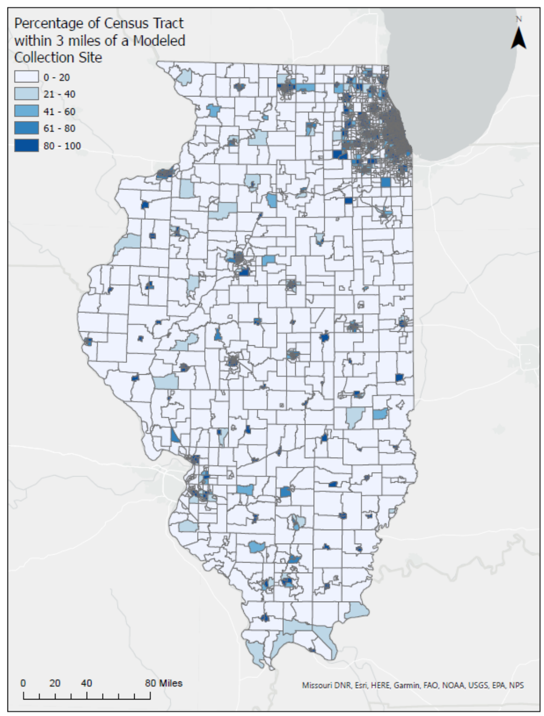
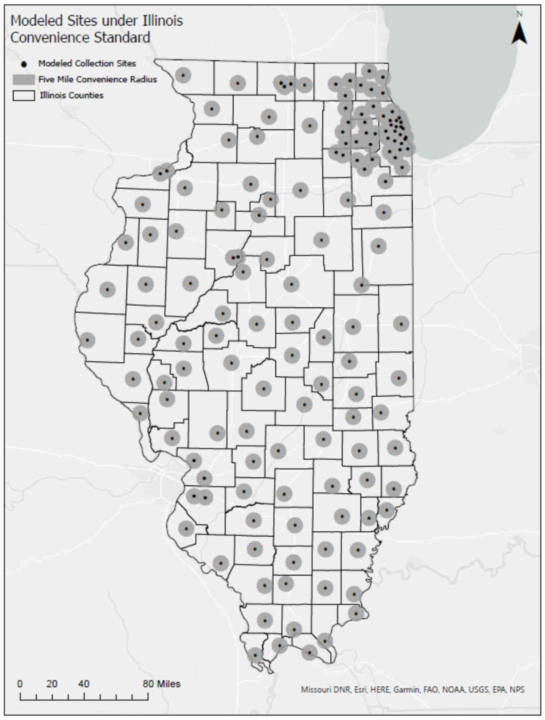


Figure 6. (Left) Modeled collection sites under Illinois' convenience standard, with a three-mile radius.

Figure 7. (Right) The percentage of estimated potential e-waste within three miles of a modeled site per census tract.



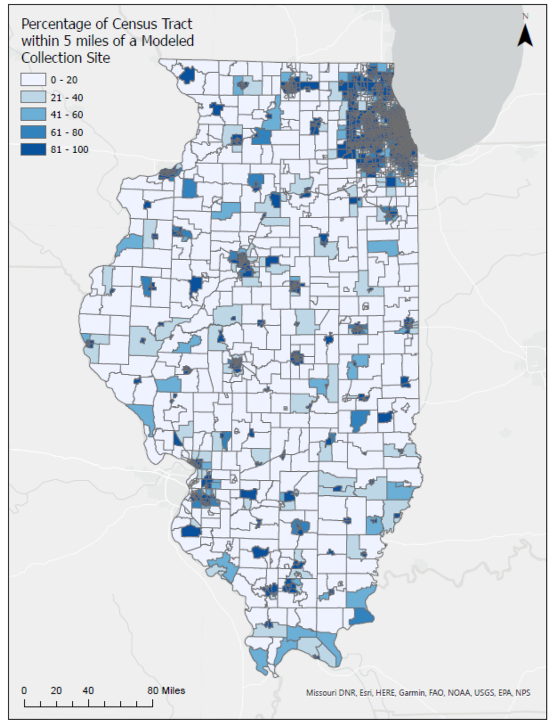


Figure 8. (Left) Modeled collection sites under Illinois' convenience standard, with a five-mile radius.

Figure 9. (Right) The percentage of estimated potential e-waste within five miles of a modeled site per census tract.

3.1.3 Validation of Model Using Real Collection Data from Illinois

To validate our model, we compared the locations of our modeled sites to the locations of existing sites in Illinois. The locations of existing electronic waste collection sites were gathered from The Illinois Environmental Protection Agency's Beyond the Bin map (*Illinois EPA Beyond the Bin Map*, n.d.). The existing Illinois sites total 387 locations, which outnumbered the 145 sites generated by our model. This is because Illinois' Consumer Electronics Recycling Act (2017) sets minimum standards for the number of collection sites per county but does not prohibit additional collection sites. Retail take-back of electronics is also common in Illinois, with 43 Best Buy locations and 25 Staples locations included in the list of existing sites. Thrift stores such as Goodwill and Salvation Army accept used electronics to resell, and through a nationwide partnership with electronics manufacturer Dell, Goodwill accepts electronics for recycling as well (Deck, 2016). Together, these two companies comprise 158 of the listed e-waste collection site locations in Illinois. Figure 10 shows the locations of Illinois' existing e-waste collection sites overlaid by the sites we modeled based on Illinois' convenience standard.

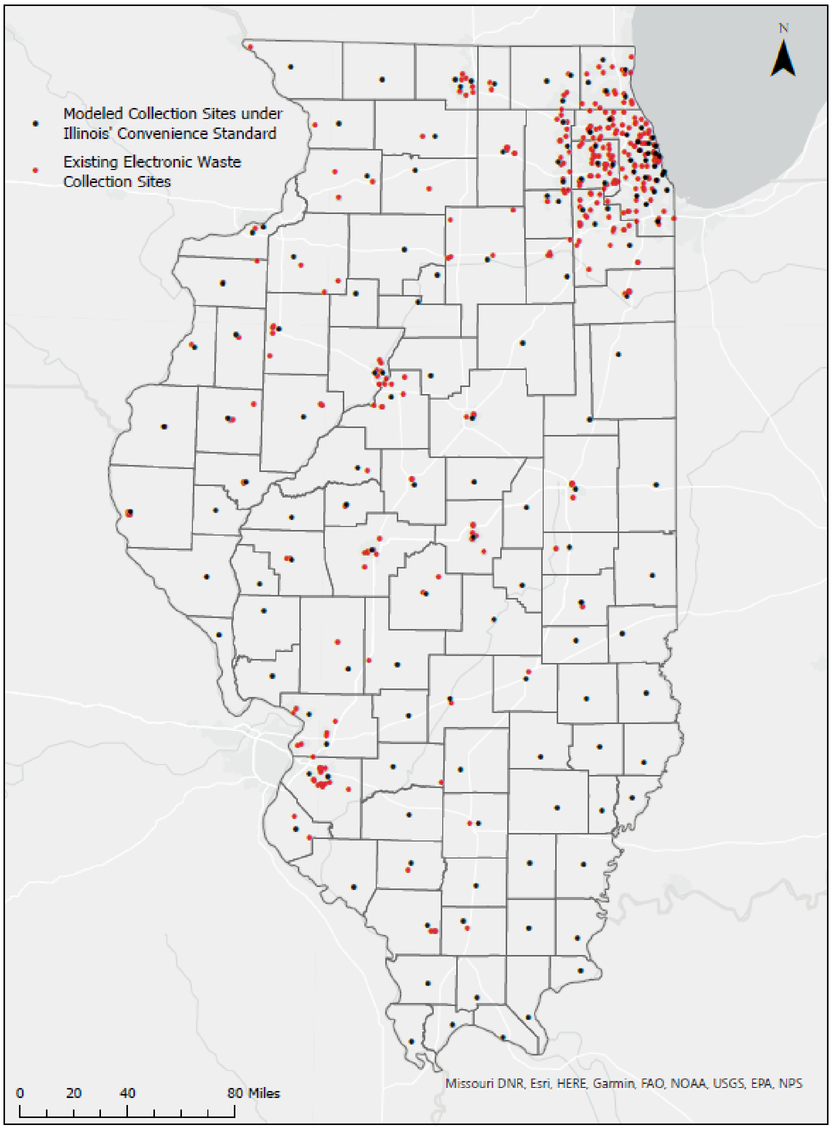


Figure 10. Existing electronic waste collection sites in Illinois and modeled sites under Illinois' convenience standard.

We obtained collection data for eight sites in Illinois from the Illinois Environmental Protection Agency. This collection data was reported in total pounds collected during 2021 for each site. This data was compared to the coverage of Illinois' estimated potential e-waste in our model, to check that our results are possible in the context of Illinois' e-waste collection. The mass of electronic waste collected at the existing site was charted next to the coverage of estimated potential e-waste within 3 and 5 miles of the real site and the closest modeled site. A representative sample of this data comparison is shown in Figure 11 and Table 4. The remaining seven comparisons are included in the Appendix. For all but one site, the mass of e-waste collected in 2021 was less than the modeled coverage of potential e-waste for both the existing and modeled sites. The modeled coverage measures the amount of potential electronic waste that is located within the radius of the site, or the potential electronic waste that could be collected by that site. With electronic waste recycling rates estimated to be at 38.5% in the United States, the mass of e-waste collected in 2021 being lower than the potential e-waste within three and five miles of that site, aligns with our expectations.

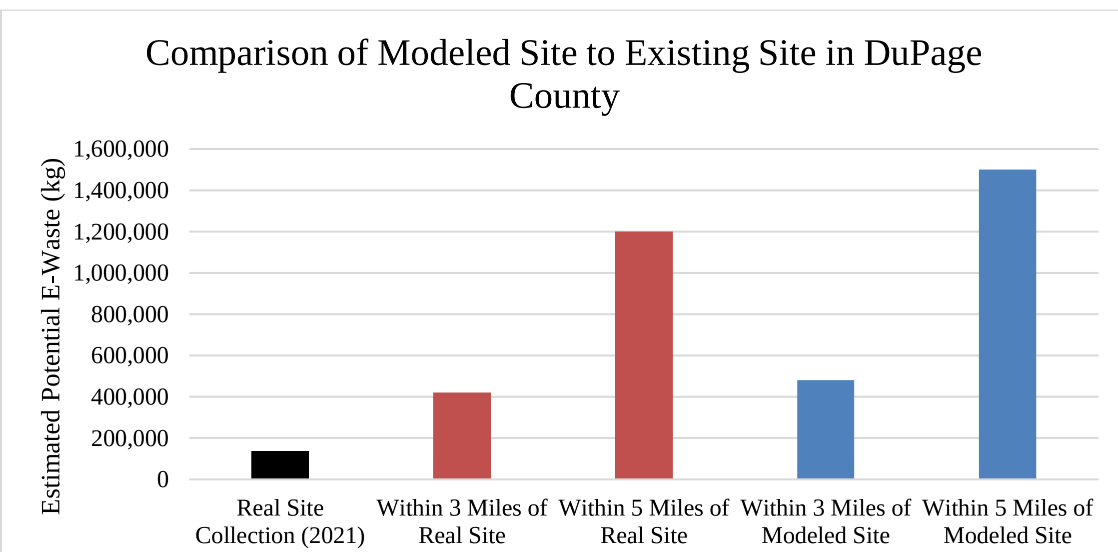


Figure 11. Comparison of collection data from a site in DuPage County, Illinois, with the estimated coverage in our model.

Table 5. Comparison of collection data from a site in DuPage County, Illinois, with the estimated coverage in our model.

Scenario (DuPage County)	**Estimated Potential E- Waste (kg)**
Real Site Collection (2021)	137,329
within 3 Miles of Real Site	420,000
within 5 Miles of Real Site	1,200,000
within 3 Miles of Modeled Site	480,000
within 5 Miles of Modeled Site	1,500,000

Finally, we generated a map of drive time areas, radiating from each modeled site under the Illinois convenience standard. Three levels of drive time areas were created, representing the distance that one could drive from the modeled site, in 5, 10 or 15 minutes. These drive time areas are shown in Figure 12. The 15-minute drive time areas were used to calculate the coverage of estimated potential e-waste in Illinois. The results of this calculation found that 77% of Illinois' total estimated potential electronic waste is located within a 15-minute drive of the modeled site locations. The 15-minute drive time covers 7% more of the state's potential e-waste than the coverage of potential e-waste within five miles of a modeled site. This result is in line with the calculated coverage results using distance as it is possible for an individual to cover more than five miles in a 15-minute drive. For instance, if traveling at 30 miles per hour, for 15 minutes, an individual could reach a distance of 7.5 miles. Therefore, the coverage of potential e-waste should be higher when using a 15-minute drive time instead of a five-mile radius and is in line with the results of our 3- and 5-mile buffer calculations.

However, drive time is dependent on traffic conditions, and there could be a difference in the size of a 15-minute drive time area in an urban area compared to a rural area. Driving time can also vary depending on the time of day as traffic conditions change in real time, and in urban areas drive time may not encompass the distance a consumer could travel using public transportation which may result in different travel times. This method of calculating coverage was used as a check to determine if our results for the distance-based coverage calculations were reasonable, but the drive time method was not used for the remainder of our analyses due to a lack of statewide data on road classification and speed limits that are necessary for accurate drive time area modeling. Without this information, the calculated drive time areas used to model the coverage of estimated potential e-waste in Illinois could result in overestimations of coverage in urban areas and underestimations in rural areas. However, the results of our drive time area model using base map inputs does indicate that the coverage of estimated potential electronic waste calculated using buffers are adequate with the resolution of data that we have, with drive time areas serving as a further method of analysis in the future.

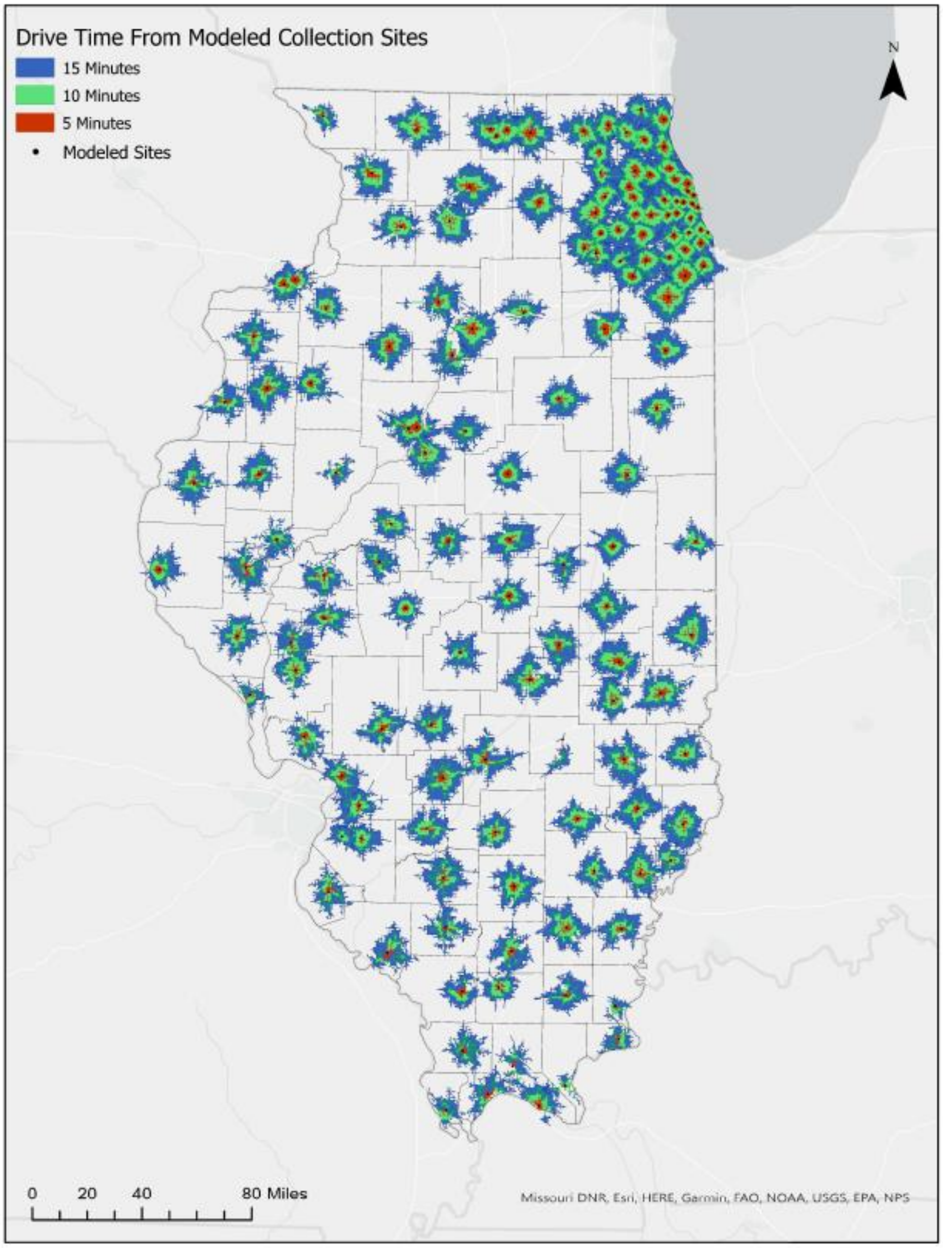


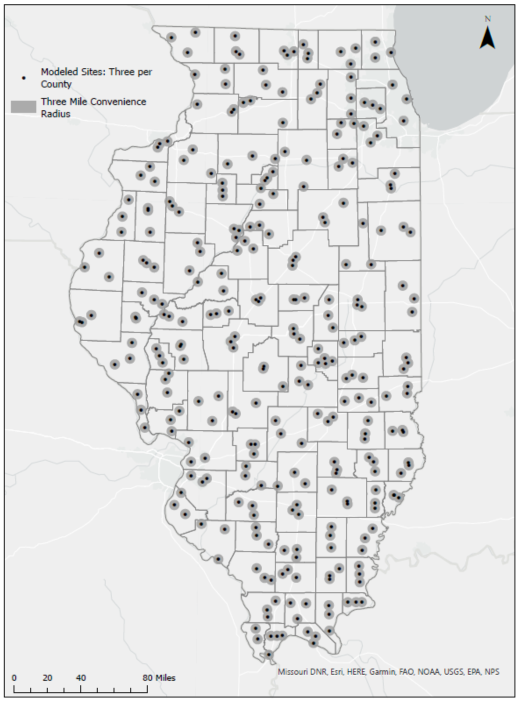
Figure 12. Drive time from modeled collection sites under the Illinois convenience standard, in increments of 5, 10, and 15 minutes.

3.2 Applying Alternative Convenience Standards to Illinois

3.2.1 Scenario 1: Convenience Standard of Three Sites per County

To understand how coverage of potential electronic waste would change in Illinois, if the state government reformulated its convenience standard, we simulated the locations and coverage of sites with different convenience standards. In Scenario 1, we modeled a convenience standard that requires at least three collection sites per county. This scenario is based on the Vermont statute on electronic waste recycling, which has multiple requirements for site locations, the first of which is a minimum requirement of three sites per county (Collection And Recycling Of Electronic Devices, 2010).

As Illinois has 102 counties, a total 306 sites were modeled under a convenience standard of three sites per county. A three- and five-mile radius was created around each modeled site and used to calculate the coverage of potential electronic waste statewide. 30% of Illinois' estimated potential e-waste was located within three miles of the modeled sites, while 52% of the estimated potential e-waste statewide was located within five miles of a modeled site. The distribution of modeled sites throughout the state of Illinois is fairly uniform, as every county has the same number of sites.



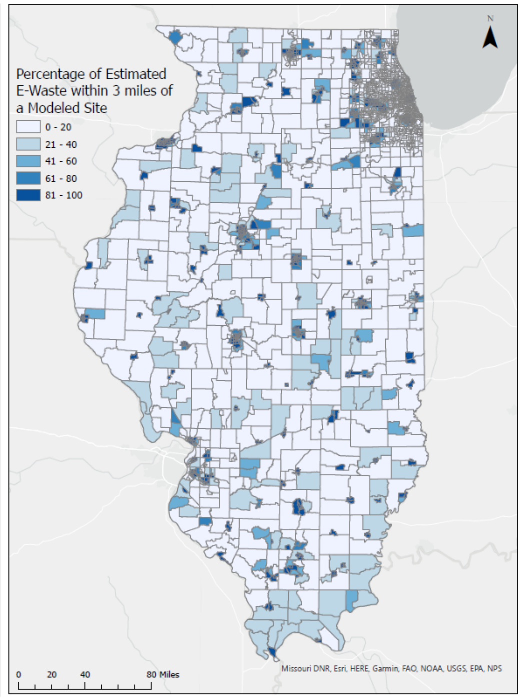
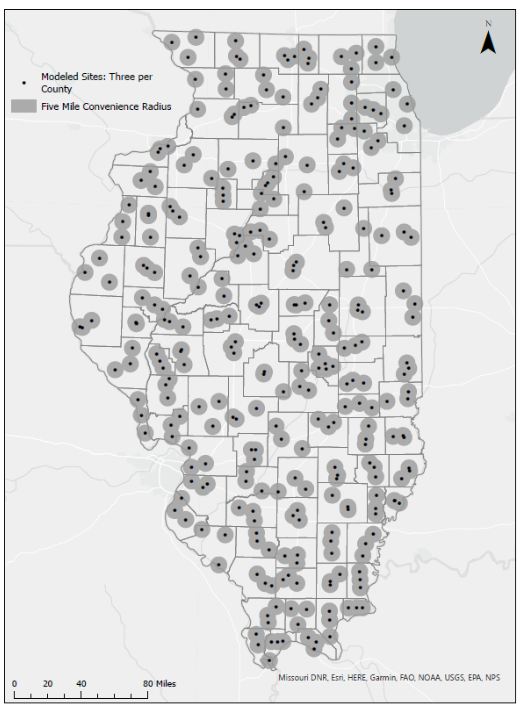


Figure 13. (Left) Collection sites with a three-mile radius, as modeled under a convenience standard of three sites per county. Figure 14. (Right) The percentage of estimated potential e-waste within three miles of a modeled site per census tract.



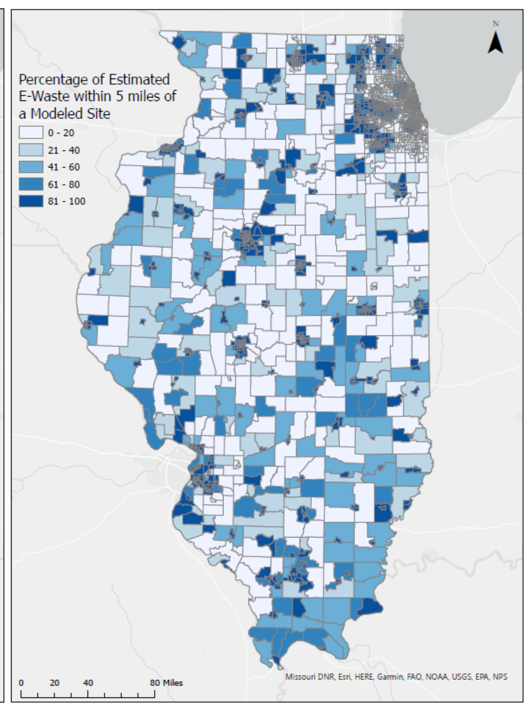
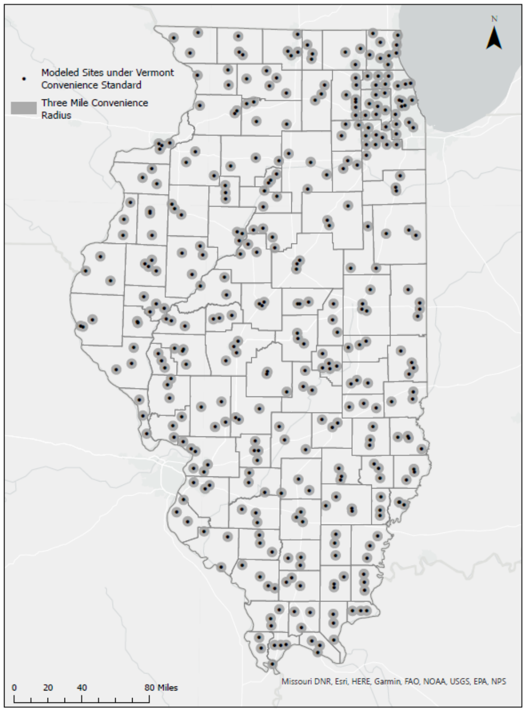


Figure 15. (Left)). Collection sites with a five-mile radius, as modeled under a convenience standard of three sites per county. Figure 16. (Right) The percentage of estimated potential e-waste within five miles of a modeled site per census tract.

3.2.2 Scenario 2: Convenience Standard of Three Sites per County with a Municipality Requirement

For Scenario 2, the convenience standard used to model collection site locations takes a combination approach. This scenario is based on the Vermont Collection and Recycling of Electronic Devices statute, which requires a minimum of three sites per county, but also a minimum of one site per municipality with a population over 10,000 people (2010). This convenience standard builds off the standard used in Scenario 1, which requires three collection sites per county. When the municipality stipulation is added to the model, the amount of Illinois' estimated potential e-waste within three and five miles of a modeled site increases. In Scenario, 49% of Illinois' estimated potential e-waste mass is located within three miles of a modeled site, and 76% of the state's estimated potential e-waste mass is located within five miles of a modeled site. The results of Scenario 2 represent a 19% and 24% increase from Scenario 1, in the coverage of potential e-waste, with the 3 and 5-mile convenience radii respectively.



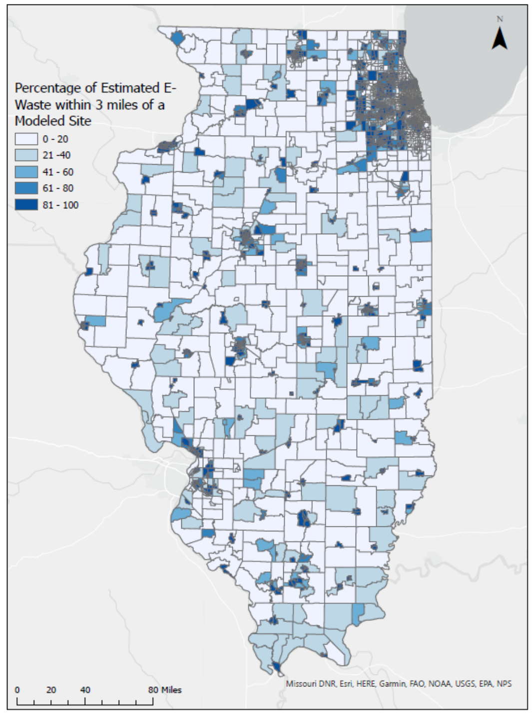
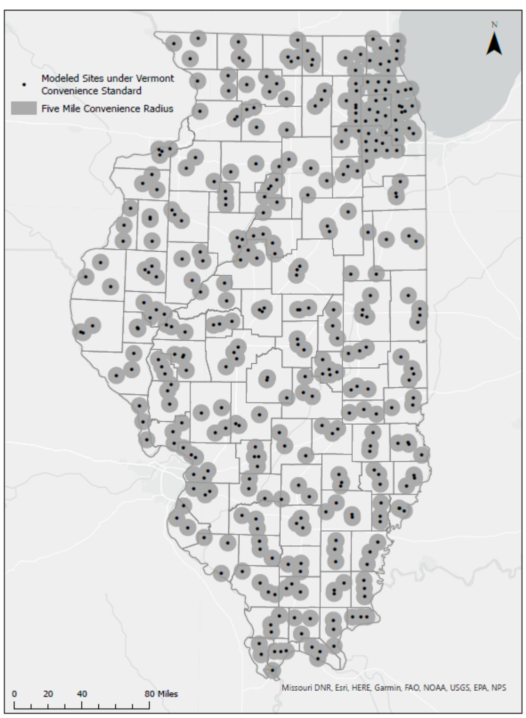


Figure 17. (Left) Collection sites with a three-mile radius, as modeled under a convenience standard of three sites per county with a municipality requirement. Figure 18. (Right) The percentage of estimated potential e-waste within three miles of a modeled site per census tract.



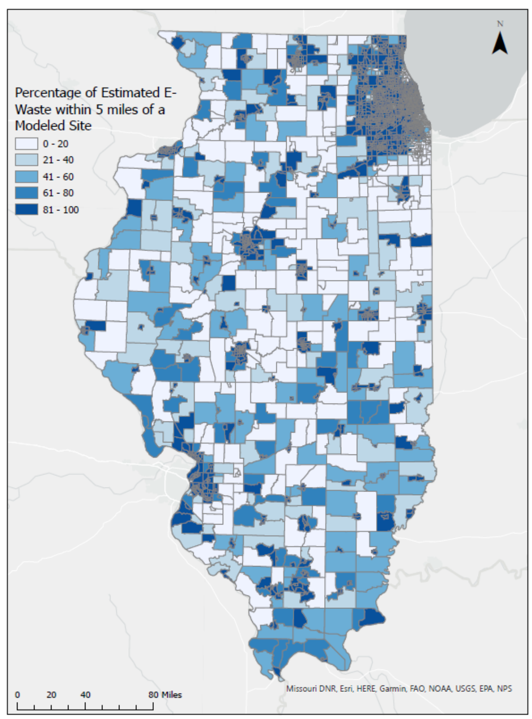
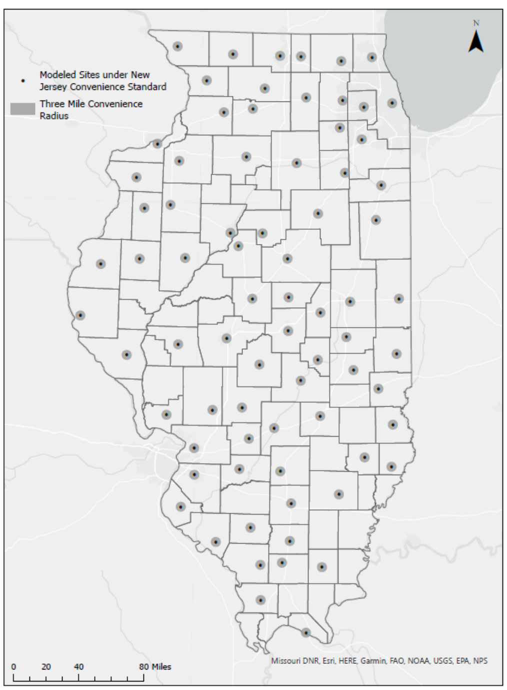


Figure 19. (Left) Collection sites with a five-mile radius, as modeled under a convenience standard of three sites per county with a municipality requirement. Figure 20. (Right) The percentage of each census tract within five miles of a modeled site.

3.2.3 Scenario 3: Convenience Standard Based on Distance to Population

The final alternative convenience standard modeled in Illinois is based on the distance of sites to the population. This scenario is based on the New Jersey's electronic waste law, which contains a convenience standard mandating at least 90% of residents must be located within 15 miles of an e-waste collection site (Electronic Waste Management Act, 2017). The result of this model generated 75 sites, one in each of the 75 most populated counties, with 90.3% of the population within 15 miles of a modeled site. The estimated potential e-waste mass in Illinois located within three miles of these modeled sites is 13%. The estimated potential e-waste mass in Illinois location within five miles of a modeled site is 27%.



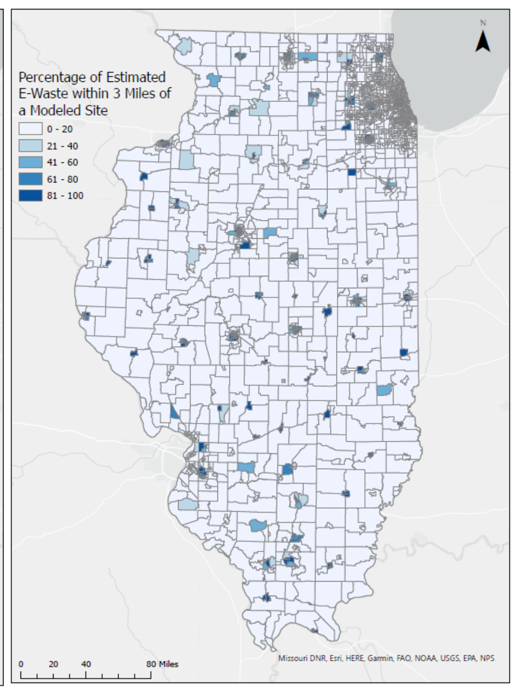
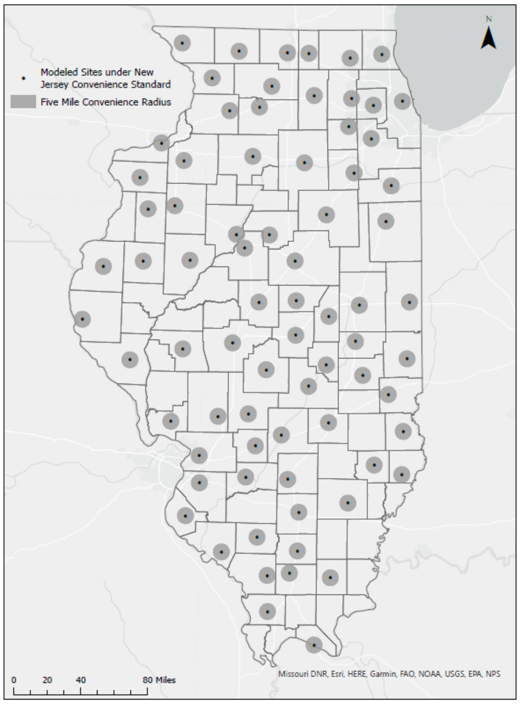


Figure 21. (Left) Collection sites with a three-mile radius, as modeled under convenience standard based on distance to population. Figure 22. (Right) The percentage of estimated potential e-waste within three miles of a modeled site per census tract.



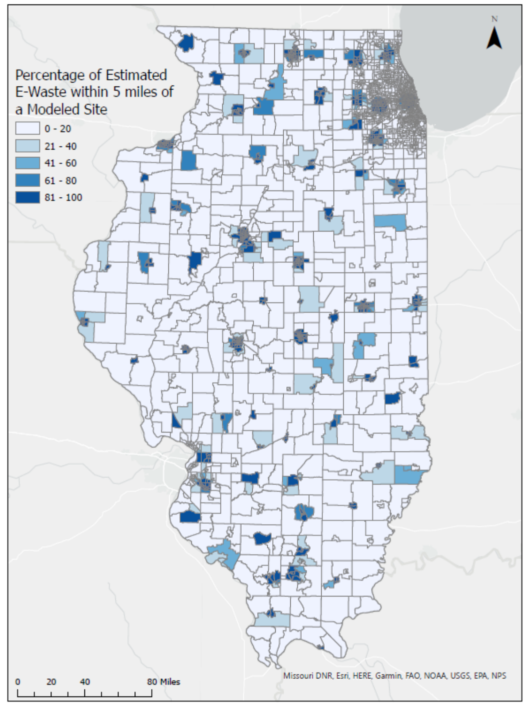


Figure 23. (Left) Collection sites with a three-mile radius, as modeled under convenience standard based on distance to population. Figure 24. (Right) The percentage of each census tract within five miles of a modeled site.

These results are significantly lower than the previous three modeled convenience standards. There are two possible reasons for this. First, the Electronic Waste Management Act (EWMA) outlines 15 miles as a convenient distance. Based on our literature review, travel times of 5 to 10 minutes, or distances up to five miles are considered by consumers to be most convenient for electronic and households recycling drop-off (Saphores et al., 2006; Zaharudin et al., 2021). If consumers do not find 15 miles to be a convenient distance to travel, this policy may not result in site locations that adequately serve at least 90% of the population. Second, there are also different ways this convenience standard can be modeled, which may impact the percentage of e-waste within a convenient distance of a site.

3.2.4 Synthesis of Results for Modeling Alternative Convenience Standards

In total, four variations of convenience standards were modeled in Illinois. The first convenience standard modeled is from Illinois' Consumer Electronics Recycling Act, which sets minimum site requirements per county based on population density (2017). The locations of these modeled sites were used to calculate the coverage of Illinois' estimated potential e-waste and results were validated against real data from Illinois' Environmental Protection Agency. Then, three alternative convenience standards were modeled in Illinois, to demonstrate how site locations and coverage of estimated potential e-waste in Illinois may change if Illinois adopted a different convenience standard. Table 5 summarizes the coverage of potential e-waste in Illinois for each of these scenarios.

Table 6. Summary of Results from All Modeled State Convenience Standards.

Convenience Standard	% of Total Illinois' Estimated Potential E-Waste Mass	
	Within 3 miles of a modeled site	Within 5 miles of a modeled site
Illinois Convenience Standard	48%	70%
Scenario 1: Three Sites per County	30%	52%
Scenario 2: Three Sites per County and Municipality Requirement	49%	76%
Scenario 3: Based on Distance to Population	13%	27%

The parameter distances for calculating coverage are three and five miles, which are based on literature values of what distance consumers consider convenient to travel to an electronic waste collection site. Therefore, the coverage for each scenario is intended to suggest the amount of

Illinois' estimated potential electronic waste that is located within a convenient distance of a modeled collection site. Overall, the e-waste sites modeled in Scenario 2 provided the most coverage of Illinois' potential electronic waste mass. The second most coverage is provided by the sites modeled under Illinois' current convenience standard, outlined in the Illinois Consumer Electronics Recycling Act (CERA) (2017). The convenience standard modeled in Scenario 2 sets a county minimum of three sites, with additional sites required in municipalities of over 10,000 population. This means that regardless of population, every county is served by at least three collection sites. Meanwhile, under CERA, the counties with the lowest population density, under 250 people per square mile, the minimum number of collection sites required is one. With this lower baseline of sites per county, counties with lower population density receive less coverage from collection sites under CERA, than they would under Scenario 2.

As noted, before, Scenario 1 does not provide as much coverage of Illinois' potential electronic waste mass as Scenario 2. This is because Scenario 2 is modeled with an additional convenience standard requirement for municipalities over 10,000 people. This results in a higher number of required collection sites than Scenario 1, which only requires three sites per county. In Scenario 2, sizable towns and urban populations receive additional sites, to maximize coverage. The additional municipality requirement in Scenario 2 resulted in an approximately 20% increase in coverage over Scenario 1.

Scenario 3, which modeled a convenience standard based on distance to population had the lowest coverage of potential e-waste mass out of all modeled convenience standards in Illinois. As mentioned earlier, this convenience standard required sites to be located within fifteen miles of 90% of the state population. As our model uses three- and five-mile radii around collection sites to calculate coverage, the resulting coverage of potential electronic waste will be significantly lower than this convenience standard aims for. This convenience standard can also be modeled in multiple ways, resulting in different site locations and coverage. This is discussed later in the limitations of our research.

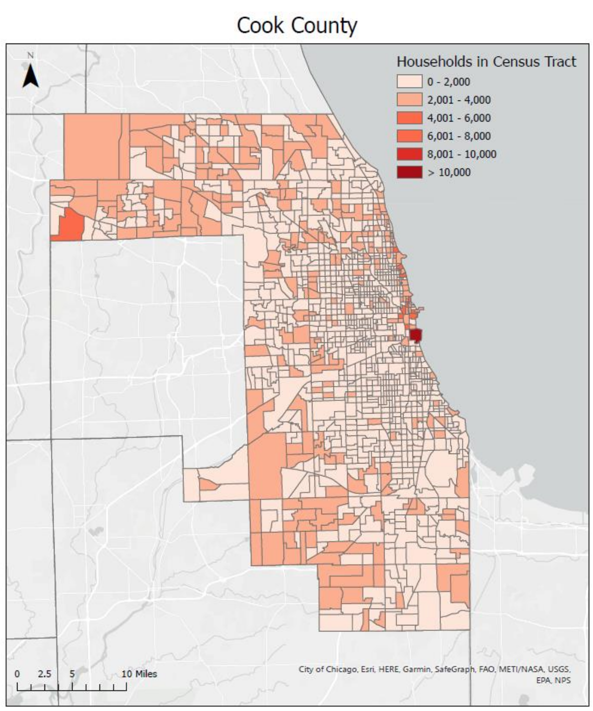
Comparing the results of modeling alternative convenience standards in Illinois at a statewide level, it is clear that coverage varies between urban and rural regions. Different convenience standards offer more rural or urban coverage than others. Therefore, coverage of estimated potential e-waste in three counties are compared to understand the differences between the modeled convenience standards at the county scale.

3.3 Three Case Study Counties

The geographic distribution of estimated potential e-waste mass in Illinois is not uniform. There is a stark difference in the estimated potential electronic waste in rural and urban areas of Illinois, with higher concentrations of potential e-waste in urban areas. This is because potential electronic waste was estimated using household ownership rates of devices and population as inputs. Therefore, counties such as Cook, Lake, and DuPage, which contain Chicago and its suburbs and have high population density, will have higher concentrations of estimated potential electronic waste. Three case study counties were chosen to represent urban, suburban, and rural areas in Illinois. These counties are Cook County, Sangamon County, and Clay County. The site locations and coverage of potential e-waste in these counties are compared across all modeled convenience standard scenarios, to see if there are differences in how each convenience standard covers these counties. For simplicity, only coverage of potential electronic waste within a five-mile radius of a modeled site is analyzed for these case studies.

3.3.1 Cook County

Cook County is located in Northeast, Illinois and as of 2015, had 1,942,959 households in the county (*TIGER/Line with Selected Demographic and Economic Data*, 2015). The population density in Cook County is over 5,000 people per square mile, so under CERA, Cook County is assigned a minimum of ten collection sites (Consumer Electronics Recycling Act, 2017). Since Chicago has over 1,000,000 people it is also required to have fifteen sites in addition to Cook County's ten, if the city chooses to opt into the state recycling program (Consumer Electronics Recycling Act, 2017). The households per census tract and estimated electronic waste per census tract in Cook County are shown in the figures below. The 2015 American Community Survey 5-Year Estimates data for Cook County contains 1318 census tracts, with 866 tracts in the city of Chicago.



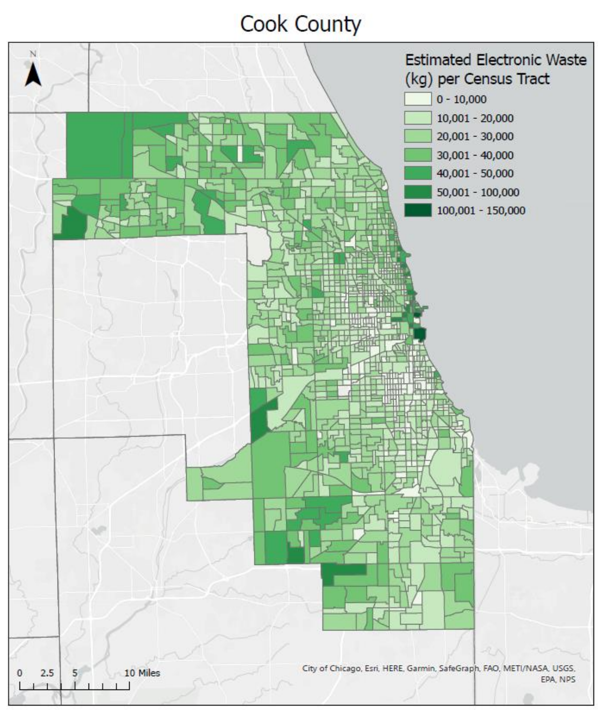


Figure 25. (Left) The number of households per census tract in Cook County Illinois. Figure 26. (Right) The estimated potential electronic waste, in kilograms, per census tract in Cook County, Illinois.

Under the Illinois convenience standard, Cook County receives 25 sites, ten for the county, and fifteen for the city of Chicago. In Scenario 1, Cook County was assigned three sites, as were all counties in Illinois. In Scenario 2, Cook County contained 19 modeled collection sites. In Scenario 3, Cook County was assigned one site, as the modeling method placed one site in each county, until 90% of the population was within 15 miles of a site. Figures 24 to 27 show the locations of the Cook County sites in each model. All modeled scenarios in the figures below are shown in Cook County with a five-mile convenience radius.

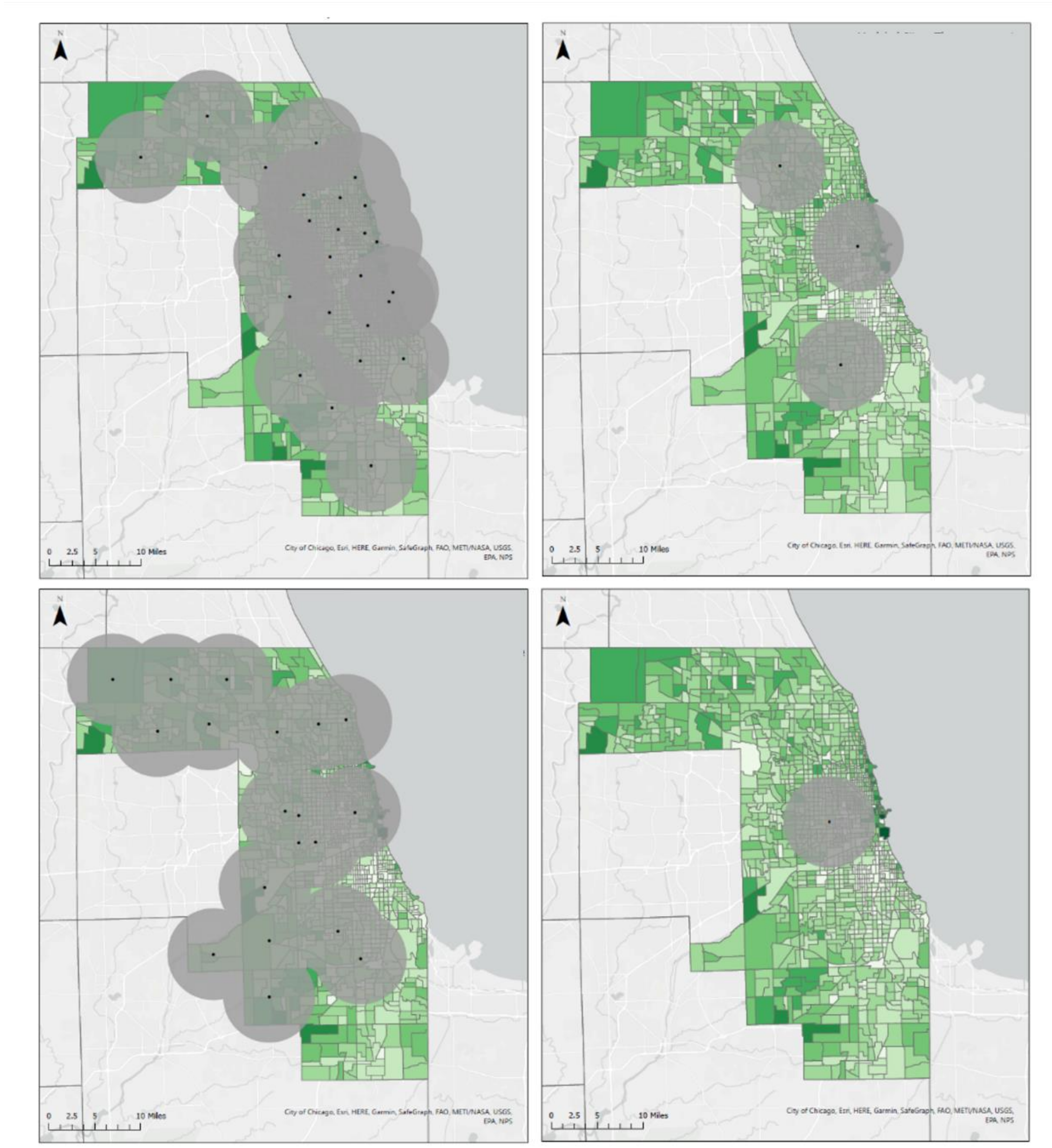
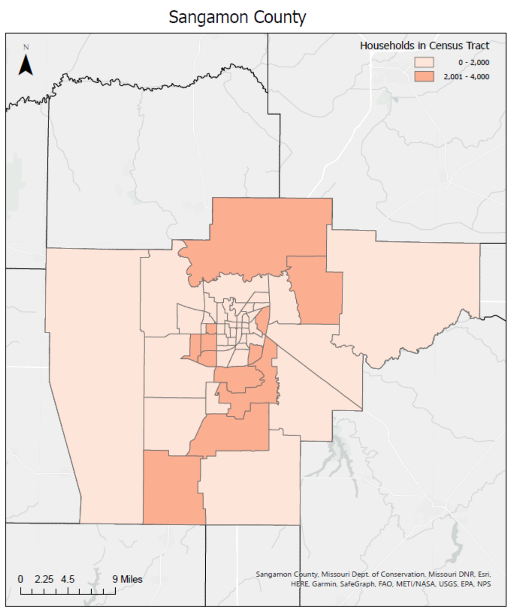


Figure 27. Collection site locations in Cook County, as modeled under the following convenience standards: (Top Left) Illinois (Top Right) Scenario 1 (Bottom Left) Scenario 2 (Bottom Right) Scenario 3

3.3.2 Sangamon County

The suburban case study county is Sangamon County. Sangamon County is not as densely populated as Cook County, but it is not considered to be rural (*Illinois Counties by Rural/Urban Classification*, 2020). Sangamon County is located in central Illinois, and contains Springfield, Illinois' capital city. In 2015, Sangamon County had a population of 82,885 households

(*TIGER/Line with Selected Demographic and Economic Data*, 2015). With a population density below 250 people per square mile, Sangamon County has a minimum requirement of one e-waste collection site per the requirements in CERA (Consumer Electronics Recycling Act, 2017).



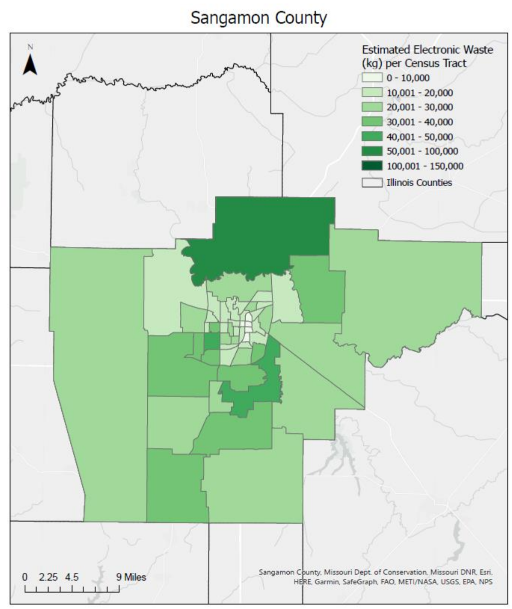


Figure 28. (Left) The number of households per census tract in Sangamon County Illinois. Figure 29. (Right) The estimated potential electronic waste, in kilograms, per census tract in Sangamon County, Illinois.

Under the Illinois convenience standard, Sangamon County was modeled to have one site. For Scenario 1, Sangamon County received three sites. Sangamon County had four modeled collection sites in Scenario 2. In Scenario 3, Sangamon County received one collection site, the same as under the Illinois convenience standard. The four figures below show Sangamon County's modeled sites for each scenario, as well as a five-mile radius.

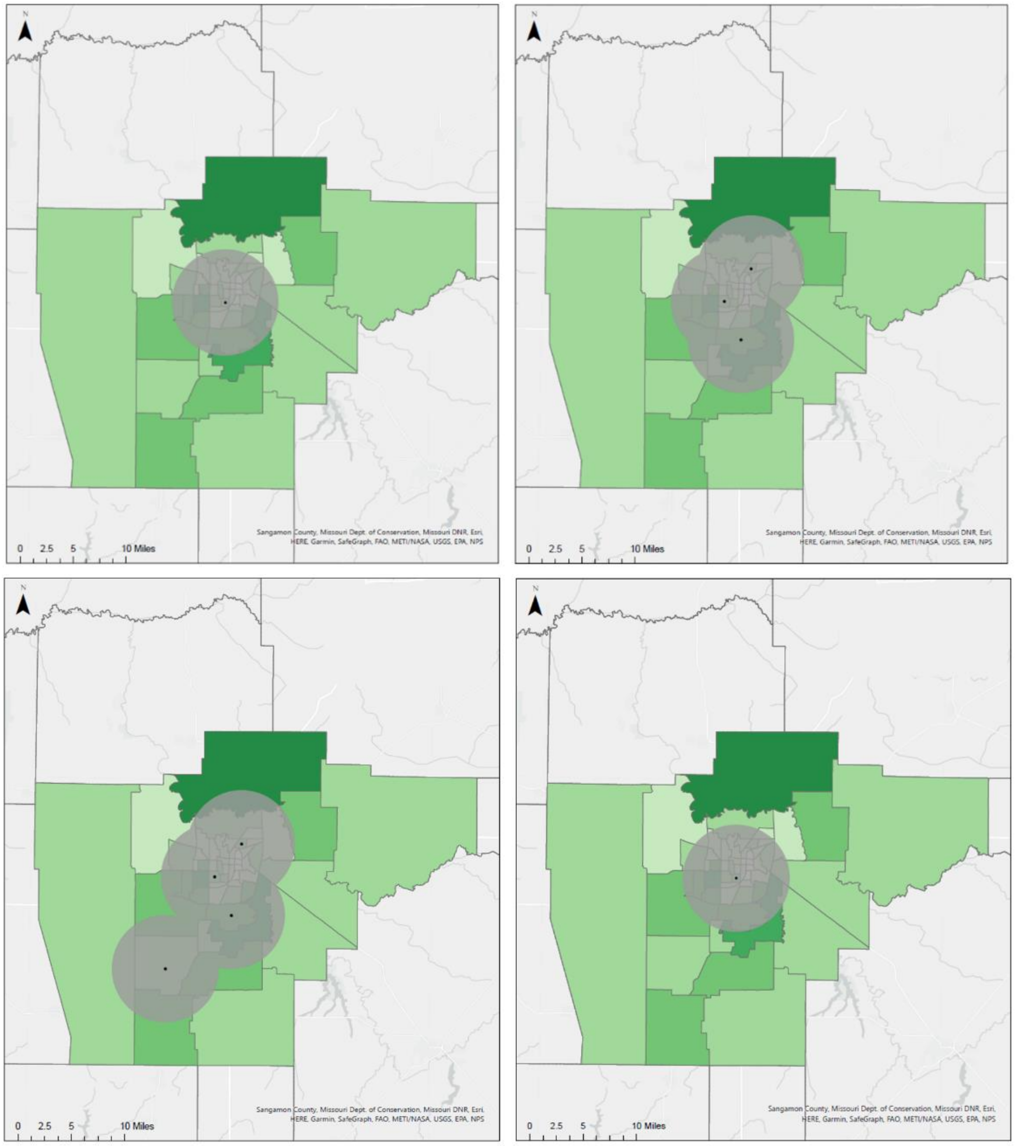
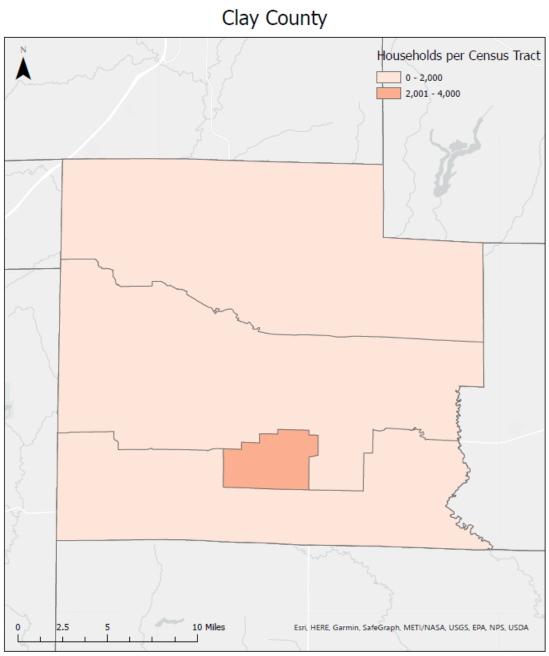


Figure 30. Collection site locations in Sangamon County, as modeled under the following convenience standards: (Top Left) Illinois (Top Right) Scenario 1 (Bottom Left) Scenario 2 (Bottom Right) Scenario 3

3.3.3 Clay County

The final county chosen as a case study is Clay County. Clay County is considered a rural county and in 2015 had a population of 5,525 households (*TIGER/Line with Selected Demographic and Economic Data*, 2015). With a population density below 250 people per square mile, Clay

County has a minimum requirement of one e-waste collection site under CERA's convenience standard (Consumer Electronics Recycling Act, 2017).



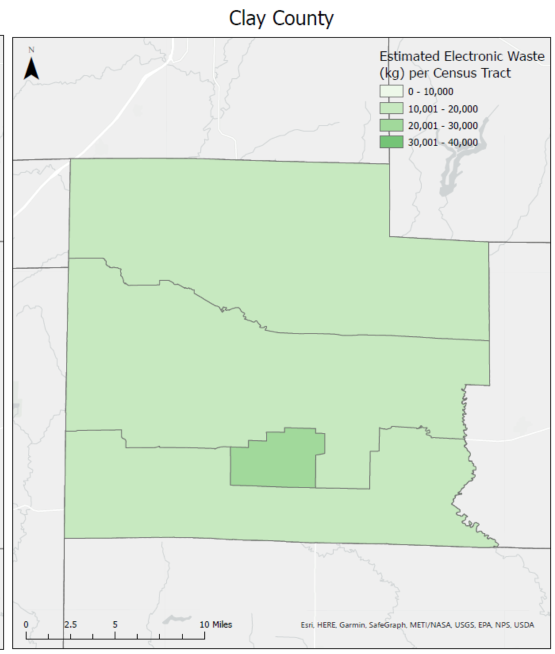


Figure 31. (Left) The number of households per census tract in Clay County, Illinois. Figure 32. (Right) The estimated potential electronic waste, in kilograms, per census tract in Clay County, Illinois.

Under the Illinois convenience standard, Clay County had one modeled site, and for Scenario 1, Clay County had three modeled collection sites. In Scenario 2, Clay County had three sites, while under Scenario 3, Clay County had no sites. Figure 33 shows the locations of the modeled collection sites in each scenario with a five-mile radius around each site.

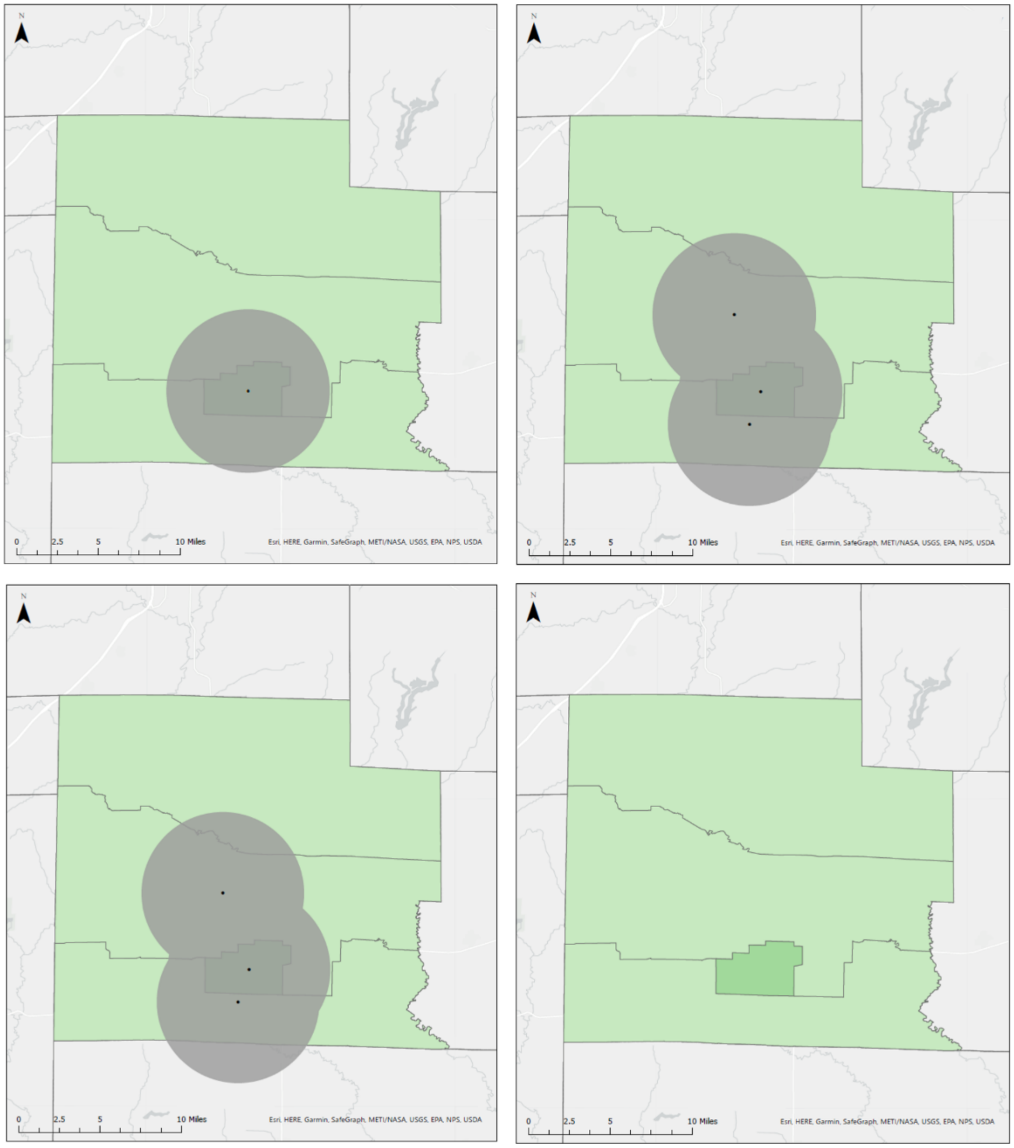


Figure 33. Collection site locations in Clay County, as modeled under the following convenience standards: (Top Left) Illinois (Top Right) Scenario 1 (Bottom Left) Scenario 2 (Bottom Right) Scenario 3

3.3.4 Synthesis of Case Study Counties' Results

The three different case study counties had varying levels of potential electronic waste coverage under each modeled convenience standard. In Cook County, some sites from neighboring counties were located within five miles of the Cook County boundary, leading some of Cook's estimated e-waste to be located within a convenient distance of another county's modeled site.

This led to increased coverage in Cook County. Sangamon County and Clay County did not have any coverage from modeled sites in other counties. To analyze the coverage of each county's potential electronic waste under each convenience standard, we calculated the percentage of estimated potential e-waste mass in each county that is located within a five-mile radius of a modeled site. A side-by-side comparison of coverage results for all four modeled convenience standards are shown in Figures 34 to 37.

Cook County had the most coverage under the Illinois convenience standard, with 93% of its estimated potential e-waste mass within five miles of a modeled collection site. This was followed by Scenario 2, with 84% of estimated potential e-waste mass within five miles of a modeled site. For Scenario 1, and Scenario 3, the amount of estimated potential e-waste mass within five miles of a modeled site was 18% and 6% respectively.

Sangamon County had the most coverage under Scenario 2, with 78% of estimated potential e-waste mass within five miles of a modeled site. The second-best convenience standard for Sangamon County was Scenario 1, which found 73% of the estimated potential e-waste mass located within five miles of a modeled site. The standards with the least amount of coverage for Sangamon County were the Illinois convenience standard and the Scenario 3 convenience standard. Each placed one site in Sangamon County, resulting in 62% of the estimated potential e-waste mass located within five miles of a modeled site for both standards.

Clay County had equal coverage under Scenarios 1 and 2, as both of these modeled convenience standards resulted in three sites located in the county. 54% of the estimated potential e-waste mass in Clay County was located within five miles of a modeled site under both of these standards. Under the Illinois convenience standard, 47% of Clay County's estimated potential e-waste mass was within five miles of a modeled site. The Scenario 3 convenience standard did not place a site in Clay County, nor was any site from a neighboring county within five miles of a census tract in Clay County, so 0% of the estimated potential e-waste mass was located within a convenient distance of a site.

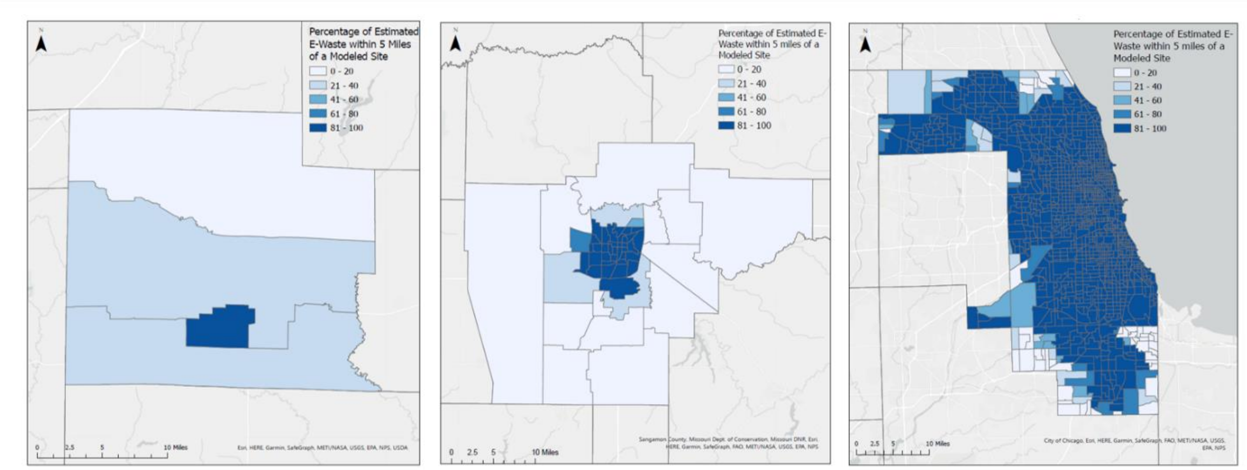


Figure 34. Coverage of Potential Electronic Waste Mass under Illinois convenience standard.

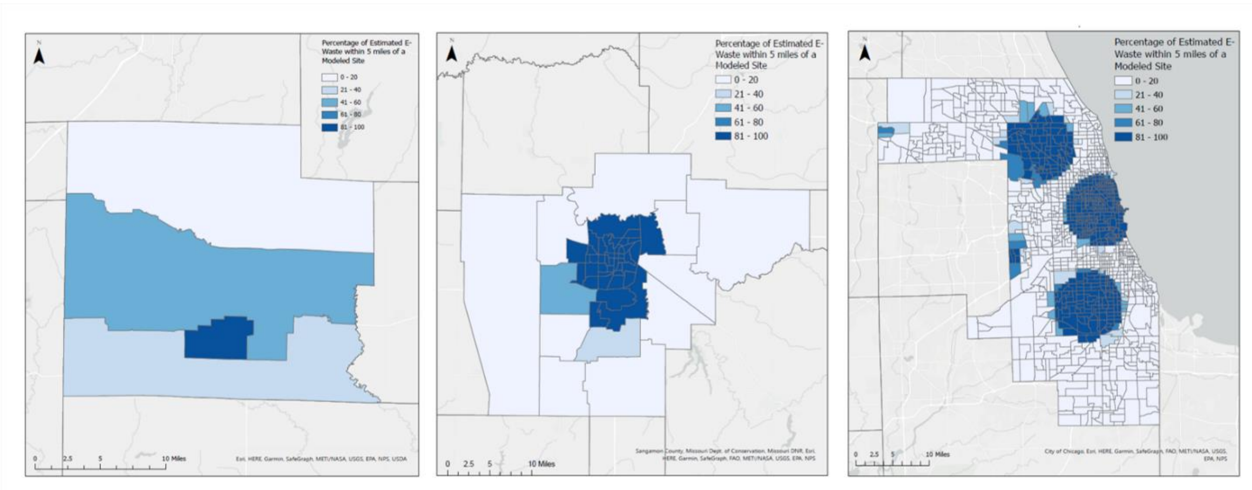


Figure 35. Coverage of Potential Electronic Waste Mass under the Scenario 1 convenience standard.

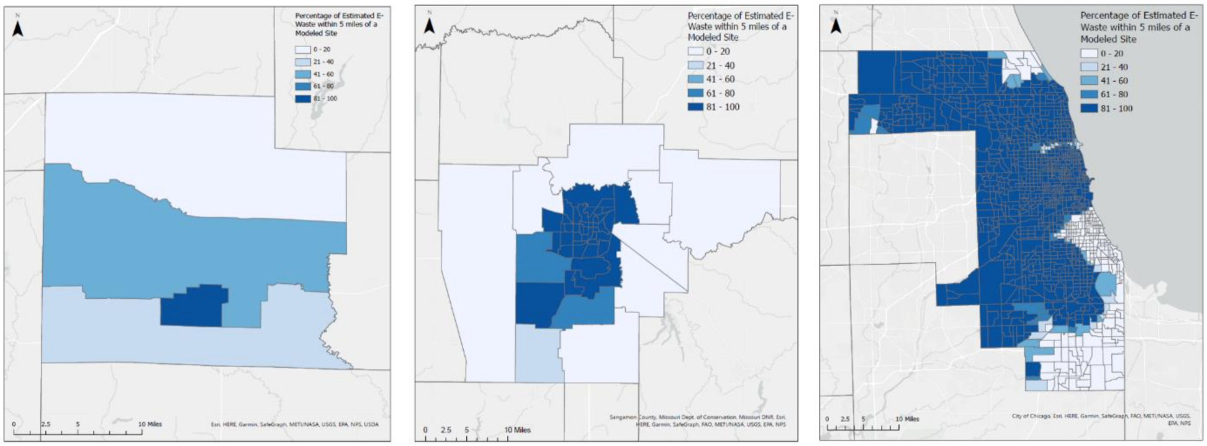


Figure 36. Coverage of Potential Electronic Waste Mass under the Scenario 2 convenience standard.

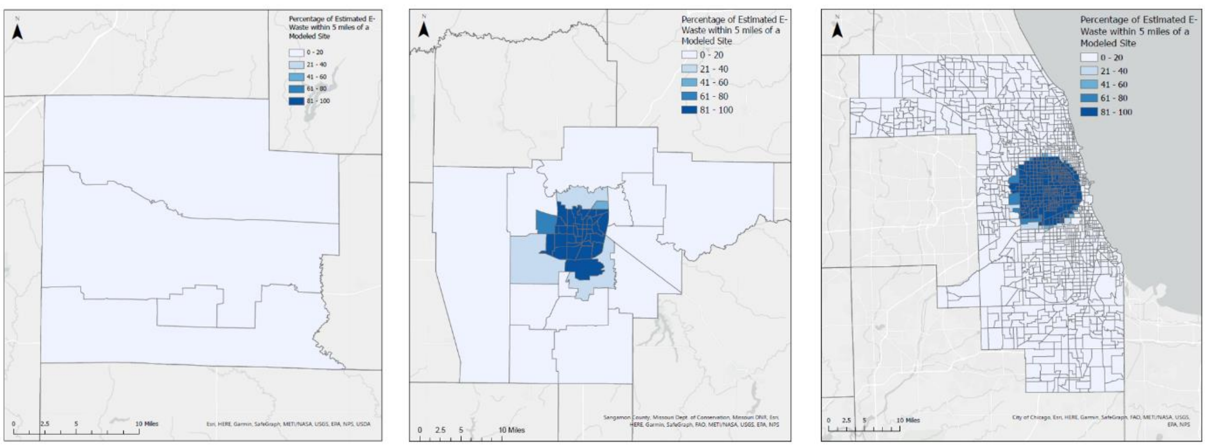


Figure 37. Coverage of Potential Electronic Waste Mass under the Scenario 3 convenience standard.

4. Conclusion and Policy Recommendations

Each modeled convenience standard provided a different level of coverage for Illinois' estimated potential electronic waste. The convenience standard modeled in Scenario 2, had the highest level of coverage when applied to Illinois's landscape, with 76% of Illinois' estimated potential e-waste mass located within five miles of a modeled site. The Illinois' convenience standard, when modeled, resulted in 70% of the state's estimated potential e-waste located within five miles of a modeled site. Under the current formulation of Illinois' convenience standard, urban areas have the highest coverage of potential e-waste by modeled sites. This can be seen in the urban case study, Cook County, which had 93% of its estimated potential e-waste located within five miles of the sites modeled using the Illinois convenience standard. However, the Illinois convenience standard formulation resulted in less coverage for suburban and rural areas than Scenario 2.

Scenario 2 generated the highest coverage for both the suburban and rural case studies, with three modeled sites in both Sangamon County and Clay County. Sangamon and Clay county are only required to have a minimum of one collection site under CERA, but under the convenience standard in Scenario 2, are required to have a minimum of three sites. Ultimately, the Illinois convenience standard offered the most coverage of potential electronic waste in urban areas, but Scenario 2, offered the most coverage of potential electronic waste in suburban and rural counties. Both the Illinois convenience standard and the Scenario 2 convenience standard require additional sites in locations with higher population. The disparity in coverage between urban counties and rural counties under the Illinois convenience standard formulation, indicates that the minimum number of sites required for the least populated counties must be increased to increase coverage for a state like Illinois.

Scenario 1, which required a minimum of three sites per county, did not provide adequate coverage of estimated potential e-waste mass in Illinois. While this convenience standard offered adequate coverage in rural counties, it performed poorly in densely populated areas like Chicago and Cook County. This formulation of convenience standard, which is jurisdiction based, prescribes the same number of collection sites for all counties in the state, therefore urban counties with a high population are assigned the same number of minimum sites as rural counties with a significantly lower population resulting in a disparity in coverage of potential electronic waste. This type of convenience standard may offer adequate coverage in a state with a more uniform population.

No state has a perfectly homogenous population distribution, but for example, in the state of Wyoming, all counties have a population density less than 38 people per square mile (Wyoming: 2020 Census, 2021). If the Illinois convenience standard were applied to a state like Wyoming, which is the least populous state in the U.S, all Wyoming counties would be required to have one site, as no county exceeds the 250 people per square mile minimum population density that triggers additional county site requirements (Wyoming: 2020 Census, 2021). If the convenience standard from Scenario 1 were applied to Wyoming, it would prescribe a minimum of three sites per county for e-waste collection, which would result in higher coverage of potential electronic waste than if the Illinois convenience standard were applied in Wyoming. However, it is worth nothing that in this example, a uniform, jurisdiction-based convenience standard that requires one site per county would have the same effect in Wyoming as the Illinois' population-based convenience standard. In this way, the exact parameters and language of the convenience standard are as important as the type of convenience standard and should be determined based on factors such as population distribution and quantity of potential electronic waste in the counties or state.

Illinois has a highly uneven population distribution between counties, with a high concentration of the state population located in Chicago and the surrounding suburbs. This unequal population distributed is better served by convenience standards that adjust minimum site requirements proportional to population, to ensure that urban areas receive additional sites to serve the larger population in those areas. Based on our model, we recommend that Illinois maintain a tiered convenience standard with the number of collection sites per county based on population density, in line with Illinois' current electronic waste policy. For most other states with an uneven population distribution, we recommend a population-based convenience standard that prescribes more collection opportunities to higher populated areas. However, as noted in the results, our model of Illinois' convenience standard showed an urban-rural divide in coverage of estimated potential electronic waste. Scenario 2, which modeled a minimum of three sites per county, resulted in higher levels of coverage of potential e-waste in suburban and rural areas compared to Illinois' convenience standard model, which only required one site for most rural counties. Therefore, our results suggest that e-waste recycling opportunities would increase in Illinois if the minimum number of sites required for the least populated counties was raised from one site to three.

At present, there is no federal law in the United States governing the recycling of electronic waste. As long as this remains the case, the legislative responsibility of regulating electronic waste recycling will remain with the states. With roughly half of the states in the U.S. having electronic waste recycling laws on the books, there is space for states without laws to consider adopting policies and for states with existing laws to update them. The most effective convenience standard for electronic waste recycling will vary by state, based on the state's demographics and potential generation of electronic waste. Though there is no one size fits all solution that will provide the most coverage for every state's electronic waste recycling program, states can learn from the experiences of states with established e-waste recycling policies and convenience standards...

When developing electronic waste policies with convenience standards, states must also consider the trade-offs associated with the implementation of those convenience standards. Introducing a convenience standard that provides substantial coverage of electronic waste in a state may result in an increase in the number of e-waste collection sites that are required or currently exist. Whether these sites are maintained by local and state governments, or by manufacturers through extended producer responsibility, the expansion of a state's e-waste recycling network will require resources due to the costs and labor associated with maintaining these locations. For instance, Scenario 3 modeled a convenience standard that required a minimum of three collection sites per county and a minimum of one collection site per municipality with a population over 10,000 people. This scenario resulted in higher modeled coverage of potential e-waste in rural and suburban areas of Illinois, than the current Illinois convenience standard. This is because Illinois' current standard only requires a minimum of one site per county where the population density is less than 250 people per square mile, a criterion that applies to 90 of Illinois' 102 counties. While the implementation of a convenience standard like Scenario 2 increases the modeled coverage of potential electronic waste, the additional collection sites will require resources to build and operate. Future work expanding on this research could include further analysis of where to site e-waste collection locations to minimize costs while maintaining convenience for consumers.

The methods outlined in this research provide a framework for comparing coverage of electronic waste under different convenience standards, and these methods can be applied to any state. With low electronic recycling rates in the United States, there is a need for policy mechanisms that can increase participation in electronic recycling. Convenience standards aim to increase the convenience and access of e-waste collection sites. Understanding how different formulations of convenience standards impact the coverage of potential electronic waste, can inform policy decisions to make e-waste collection infrastructure more convenient, and in return, increase consumer participation in electronic waste recycling schemes.

5. Limitations and Future Work

This research aims to compare the coverage of potential electronic waste in Illinois under different formulations of convenience standards. However, several assumptions made in the process of conducting this research introduce uncertainty. Product ownership rates for various devices were not all included in the Consumer Technology Association report. For the devices without data, we assumed ownership based on the ownership of other devices. For example, electronic keyboards are covered devices under Illinois' Consumer Electronics Recycling Act, but the CTA report did not contain ownership rates for these devices, so we assumed for each desktop and tablet computer a household owned, they also owned one electronic keyboard. If households use the same electronic keyboard for multiple computers, this assumption will result in an overestimation of the potential electronic waste in Illinois for this device.

An additional uncertainty in product ownership calculations comes from the role of household income. The Consumer Technology Association reports product ownership per household in each income bracket. The product ownership rates for each income bracket were not state-specific, so due to differences in cost of living across states, the product ownership rates for each income bracket in Illinois could differ from the national average of product ownership rates by income. Income could also play a role in consumer recycling behavior and a household's likelihood of participating in an electronic waste recycling scheme (Wang et al., 2016). Previous studies analyzing the link between household income and recycling behavior have generated mixed results. A study of consumers in Michigan found that income was related to recycling intention, but this study focused on household recycling not electronics, with higher income households recycling more (Sidique et al., 2010). Another study in China found that higher income was negatively correlated with e-waste recycling intentions (Wang et al., 2016). Additionally, a California survey on e-waste recycling found no statistically significant link between recycling behavior for e-waste and income (Saphores et al., 2012). If households at certain income levels have more positive attitudes towards electronic waste recycling, they may be willing to travel further to recycle their e-waste. In this way, their definitions of convenience may differ from those with negative attitudes towards recycling, and therefore income may play a role in the participation in e-waste recycling and its convenience.

Additionally, the parameters of what distance consumers find convenient are based on a literature review of consumer recycling behavior, however, many of the papers in this field focus on household recycling rather than electronics recycling. Though these behaviors have similarities, consumers may have varying definitions of convenience for household waste versus electronic waste. The primary source of consumer convenience parameters for electronics recycling in the United States is Saphores et al., 2006. This paper was based on a survey of California residents conducted in 2004 and therefore the responses may be outdated (Saphores et al., 2006).

For this research, we used convenience radii of three and five miles to determine the estimated e-waste mass within a convenient distance of modeled recycling sites. However, these convenience radii were generated using circular buffers in ArcGIS Pro. These radii represent a linear distance from each modeled site, while in reality the road network may not follow the same path. A three-mile radius around a collection site will differ from three miles driving distance around a collection site, as the roads leading from a site may turn or wind rather than follow a straight path. As a result, there is uncertainty in our coverage of potential e-waste calculations, likely resulting in an overestimation of potential e-waste coverage from our modeled sites, particularly in urban areas, as the true road network is likely to be more condensed and contain traffic, so a consumer driving three miles from a site would be within our generated three-mile radius rather than at the edge.

As noted earlier, we conducted an additional analysis of coverage for potential electronic waste using drive time areas, which use the road networks to calculate the distance one could drive from a modeled site in a set amount of time. Instead of a distance parameter, we used a 15-minute drive time, which was obtained from our literature review as a convenient travel time according to consumers (Zaharudin et al., 2021). The resulting coverage of potential electronic waste calculated within 15 minutes of a modeled collection facility was in line with our expectations based on our three- and five-mile radius results. This suggests that although drive time areas based on the road network may be more representative of consumer travel time or distance, the buffer method generated results that were reliable when compared to the drive time results.

Additionally, consumer definitions of convenience may vary between urban and rural settings and drive time areas can be particularly useful for calculating coverage in those situations. Rural residents may be willing to travel further distances to recycle e-waste than urban residents, who may have to walk or rely on public transportation to reach a collection site. Additionally, the high density of housing in urban areas can limit storage space for bulky electronic products. Limited storage space poses a barrier to recycling and may impact how frequently urban residents recycle their waste (Miafodzyeva et al., 2013). If rural residents are willing to travel further to recycle their electronic waste, our modeled coverage of potential e-waste is underestimated for rural areas in Illinois, and if urban residents are not willing to travel as far as our parameters are set, then our modeled coverage of potential e-waste is overestimated in urban areas of Illinois. Calculations of potential electronic waste coverage would differ if radii of different distances or different travel times are used for rural versus urban settings, which can be modeled using drive time areas. The increased traffic flow in urban areas and density of streets could result in smaller drive time areas for the same amount of time, compared to rural areas with less traffic and more dispersed road networks. This is a modeling method that can be introduced in future work to increase the accuracy of assessing convenience standards based on their coverage of potential e-waste.

As noted in Section 4, future work relevant to the development of e-waste recycling programs is analyzing the tradeoffs of implementing convenience standards for electronic waste recycling in case study states. These tradeoffs include factors such as the potential for increased e-waste collection and consumer participation, as well as increased labor, capital, and maintenance costs associated with the addition of e-waste collection sites to the existing collection network. Similar research has been conducted on household recycling schemes, for example, Zaharudin et al., 2021 looks at household waste recycling networks using a spatial interaction model of consumer recycling behavior and preferences for centers. This model provides a basis for scenario analysis to see how alterations in the recycling locations will impact consumer recycling behavior (Zaharudin et al., 2021). The tradeoff between the cost of maintaining and monitoring these new e-waste collection facilities with the increased capacity for electronic waste collection are important considerations for any state developing electronic waste recycling policy.

In counties or regions with a lack of convenient access to collection sites, electronics recycling events can serve to meet the demand for recycling sites. Under the Consumer Electronics and Recycling Act in Illinois, counties can replace a required site with four collection events (Consumer Electronics Recycling Act, 2017). These recycling events in some parts of Illinois can be expected to collect up to 16,000 pounds of electronics in one day (*E-Waste Program Plan for 2022*, 2021). Including recycling events as a temporal piece in our convenience model could improve our analysis of access to recycling services in areas where events are offered. Additionally, there is little data on how consumers view recycling events through the lens of convenience. If recycling events are adequate for convenient collection of electronic waste, or advantageous, in remote areas where permanent collection sites are less feasible, this could influence policy recommendations.

The lack of comprehensive data on consumer definitions of convenience for electronic waste recycling indicates a clear need for future research that is focused on consumers. This future research can address the lack of ownership data for certain devices, as well as define consumers definitions of convenience through surveys or interviews. Understanding what convenience means to consumers is crucial to effectively model convenience standards and determine how policy definitions of convenience align with consumers' definitions. Convenience is a subjective construct, so this future work can also determine what factors influence a consumer's definition of convenience, such as whether a consumer's perception of convenience changes between urban and rural settings. Further research focused on consumers will greatly enhance our understanding of consumer preferences and allow for a more robust comparison of the coverage of electronic waste under different convenience standards. Thorough comprehension of consumer definitions of convenience will clarify the policy recommendations that we take away from our results.

Sources

§ 261.39 Conditional Exclusion for Used, Broken Cathode Ray Tubes (CRTs) and Processed CRT Glass Undergoing Recycling. https://www.ecfr.gov/current/title-40/chapter-I/subchapter-I/part-261/subpart-E/section-261.39

18th Annual Consumer Technology Ownership and Market Potential Study. (2016). Consumer Technology Association.

2019 TIGER/Line Shapefiles Technical Documentation. (2019). U.S. Bureau of the Census. https://www2.census.gov/geo/pdfs/maps-data/data/tiger/tgrshp2019/TGRSHP2019_TechDoc.pdf

Althaf, S., Babbitt, C. W., & Chen, R. (2019). Forecasting electronic waste flows for effective circular economy planning. *Resources, Conservation and Recycling*, *151*, 104362. https://doi.org/10.1016/j.resconrec.2019.05.038

Althaf, S., Babbitt, C. W., & Chen, R. (2020). The evolution of consumer electronic waste in the United States. *Journal of Industrial Ecology*, *25*(3), 693–706. https://doi.org/10.1111/jiec.13074

ArcGIS Pro (3.1.0). (2023). [GIS software]. Redlands, CA: Environmental Systems Research Institute, Inc.

Berck, P., Blundell, M., Englander, G., Gold, S., He, S., Horsager, J., Kaplan, S., Sears, M., Stevens, A., Trachtman, C., Taylor, R., & Villas-Boas, S. B. (2021). Recycling Policies, Behavior and Convenience: Survey Evidence from the CalRecycle Program. *Applied Economic Perspectives and Policy*, *43*(2), 641–658. https://doi.org/10.1002/aepp.13117

Bhutta, M. K. S., Omar, A., & Yang, X. (2011). Electronic Waste: A Growing Concern in Today's Environment. *Economics Research International*, *2011*, 1–8. https://doi.org/10.1155/2011/474230

Bouvier, R., & Wagner, T. (2011). The influence of collection facility attributes on household collection rates of electronic waste: The case of televisions and computer monitors. *Resources, Conservation and Recycling*, *55*(11), 1051–1059. https://doi.org/10.1016/j.resconrec.2011.05.019

CERA - Electronics Recycling. (n.d.). Illinois Environmental Protection Agency. Retrieved June 7, 2022, from https://www2.illinois.gov/epa/topics/waste-management/electronics-recycling/Pages/cera.aspx

City and Town Population Totals: 2010-2019 (Annual Estimates of the Resident Population for Incorporated Places: April 1, 2010 to July 1, 2019). (2015). [Geodatabase]. U.S. Bureau of the Census. https://www.census.gov/data/tables/time-series/demo/popest/2010s-total-cities-and-towns.html

Collection And Recycling Of Electronic Devices, Vermont General Assembly, Chapter 166 10 (2010). https://legislature.vermont.gov/statutes/fullchapter/10/166

Collector's Electronic Products Collection & Transportation Reports. (n.d.). Illinois Environmental Protection Agency.

Consumer Electronics Recycling Act, SB1417, 100th Illinois General Assembly, Public Act 100-0433 (2017). https://www.ilga.gov/legislation/publicacts/100/PDF/100-0433.pdf

Covered Device Recycling Act, no. 108, General Assembly of the Commonwealth of Pennsylvania (2010).

Deck, A. (2016, March). The Dell Reconnect program provides solutions to e-waste. Dell Technologies Blog. https://www.dell.com/en-us/blog/the-dell-reconnect-program-provides-solutions-to-e-waste/

Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE) Text with EEA relevance, CONSIL, EP, 197 OJ L (2012). http://data.europa.eu/eli/dir/2012/19/oj/eng

Domina, T., & Koch, K. (2002). Convenience and Frequency of Recycling: Implications for Including Textiles in Curbside Recycling Programs. *Environment and Behavior*, *34*(2), 216–238. https://doi.org/10.1177/0013916502342004

Durable Goods: Product-Specific Data (Facts and Figures about Materials, Waste and Recycling). (2022). United States Environmental Protection Agency. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/durable-goods-product-specific-data#Electronics

Electronic Waste Management Act, S981, P.L.2016, Chapter 87 (2017). https://pub.njleg.gov/bills/2016/PL16/87_.PDF

Electronic Waste Management Act, S981, Senate and General Assembly of the State of New Jersey, P.L.2016, Chapter 87 (2017). https://pub.njleg.gov/bills/2016/PL16/87_.PDF

ESRI. Light Gray Canvas Base. [basemap] November 26, 2017. https://basemaps.arcgis.com/arcgis/rest/services/World_Basemap_v2/VectorTileServer

Credits: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

E-Waste Program Plan for 2022. (2021). Electronics Recycling Representative Organization. https://epa.illinois.gov/content/dam/soi/en/web/epa/topics/waste-management/electronics-recycling/manufacturers/program-plans/documents/2022-erro-clearinghouse-manufacturer-e-waste-program-plan.pdf

E-Waste Program Review. (2016). [Report to the Illinois Governor and General Assembly]. State of Illinois Environmental Protection Agency. https://www2.illinois.gov/epa/Documents/iepa/waste-management/electronics-recycling/2016-ewaste-program-review.pdf

Fu, X., Beatty, D. N., Gaustad, G. G., Ceder, G., Roth, R., Kirchain, R. E., Bustamante, M., Babbitt, C., & Olivetti, E. A. (2020). Perspectives on Cobalt Supply through 2030 in the Face of Changing Demand. Environmental Science & Technology, 54(5), 2985–2993. https://doi.org/10.1021/acs.est.9b04975

Grant, K., Goldizen, F. C., Sly, P. D., Brune, M.-N., Neira, M., van den Berg, M., & Norman, R. E. (2013). Health consequences of exposure to e-waste: A systematic review. *The Lancet Global Health*, *1*(6), e350–e361. https://doi.org/10.1016/S2214-109X(13)70101-3

Hickle, G. T. (2014). Moving beyond the “patchwork:” a review of strategies to promote consistency for extended producer responsibility policy in the U.S. *Journal of Cleaner Production*, *64*, 266–276. https://doi.org/10.1016/j.jclepro.2013.08.013

Illinois Counties by Rural/Urban Classification. (2020). [Map]. Illinois Primary Health Care Association. http://www.idph.state.il.us/RuralHealth/Rur_Urb_2021.pdf

Illinois Electronics Recycling Program: 2019 Collection Summary Report. (n.d.). Illinois Environmental Protection Agency. https://epa.illinois.gov/content/dam/soi/en/web/epa/topics/waste-management/electronics-recycling/documents/iepa-2019-e-waste-summary-collection-report.pdf

Illinois Electronics Recycling Program: 2019 Collection Summary Report. (n.d.). Illinois Environmental Protection Agency. https://epa.illinois.gov/content/dam/soi/en/web/epa/topics/waste-management/electronics-recycling/documents/iepa-2019-e-waste-summary-collection-report.pdf

Illinois Electronics Recycling Program: 2020 Collection Summary Report. (n.d.). Illinois Environmental Protection Agency. https://epa.illinois.gov/content/dam/soi/en/web/epa/topics/waste-management/electronics-recycling/documents/iepa-2020-e-waste-summary-collection-report.pdf

Illinois Electronics Recycling Program: 2020 Collection Summary Report. (n.d.). Illinois Environmental Protection Agency. https://epa.illinois.gov/content/dam/soi/en/web/epa/topics/waste-management/electronics-recycling/documents/iepa-2020-e-waste-summary-collection-report.pdf

Illinois EPA Beyond the Bin Map. (n.d.). [Map]. ESRI. https://illinois-epa.maps.arcgis.com/apps/webappviewer/index.html?id=1e86d9a5913a4ca49fb0cfd64f1c2

Knussen, C., Yule, F., MacKenzie, J., & Wells, M. (2004). An analysis of intentions to recycle household waste: The roles of past behaviour, perceived habit, and perceived lack of facilities. *Journal of Environmental Psychology*, *24*(2), 237–246. https://doi.org/10.1016/j.jenvp.2003.12.001

Miafodzyeva, S., Brandt, N., & Andersson, M. (2013). Recycling behaviour of householders living in multicultural urban area: A case study of Järva, Stockholm, Sweden. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, *31*(5), 447–457. https://doi.org/10.1177/0734242X13476746

Mouw, S. (2020). State of Curbside Recycling Report. The Recycling Partnership.

Ongondo, F. O., & Williams, I. D. (2011). Greening academia: Use and disposal of mobile phones among university students. *Waste Management*, *31*(7), 1617–1634. https://doi.org/10.1016/j.wasman.2011.01.031

Ryen, E. G., Babbitt, C. W., Tyler, A. C., & Babbitt, G. A. (2014). Community Ecology Perspectives on the Structural and Functional Evolution of Consumer Electronics: Evolving Community of Consumer Electronics. Journal of Industrial Ecology, 18(5), 708–721. https://doi.org/10.1111/jiec.12130

Saphores, J.-D. M., Nixon, H., Ogunseitan, O. A., & Shapiro, A. A. (2006). Household Willingness to Recycle Electronic Waste: An Application to California. *Environment and Behavior*, *38*(2), 183–208. https://doi.org/10.1177/0013916505279045

Saphores, J.-D. M., Ogunseitan, O. A., & Shapiro, A. A. (2012). Willingness to engage in a pro-environmental behavior: An analysis of e-waste recycling based on a national survey of U.S. households. *Resources, Conservation and Recycling*, *60*, 49–63. https://doi.org/10.1016/j.resconrec.2011.12.003

SB585 Bill Information. (2021, April 26). https://www.arkleg.state.ar.us/Bills/Detail

Schumacher, K. A., & Agbemabiese, L. (2019). Towards comprehensive e-waste legislation in the United States: Design considerations based on quantitative and qualitative assessments.

Resources, Conservation and Recycling, *149*, 605–621. https://doi.org/10.1016/j.resconrec.2019.06.033

Shahana Althaf. (2020). *Data Set for Consumer Electronics MFA in Althaf et al 2020 JIE manuscript* [Data set]. Zenodo. https://doi.org/10.5281/ZENODO.3986935

Shevchenko, T., Laitala, K., & Danko, Y. (2019). Understanding Consumer E-Waste Recycling Behavior: Introducing a New Economic Incentive to Increase the Collection Rates. Sustainability, 11(9), 2656. https://doi.org/10.3390/su11092656

Shittu, O. S., Williams, I. D., & Shaw, P. J. (2022). Prospecting reusable small electrical and electronic equipment (EEE) in distinct anthropogenic spaces. *Resources, Conservation and Recycling*, *176*, 105908. https://doi.org/10.1016/j.resconrec.2021.105908

Sidique, S. F., Lupi, F., & Joshi, S. V. (2010). The effects of behavior and attitudes on drop-off recycling activities. *Resources, Conservation and Recycling*, *54*(3), 163–170. https://doi.org/10.1016/j.resconrec.2009.07.012

The Electronic Products Recycling and Reuse Act, SB2106, 97th General Assembly, 415 ILCS (2011). https://www.ilga.gov/legislation/fulltext.asp?DocName=&SessionId=84&GA=97&DocTypeId=SB&DocNum=2106&GAID=11&LegID=58299&SpecSess=&Session=

TIGER/Line with Selected Demographic and Economic Data (Census Tract: Illinois). (2015). [Geodatabase]. U.S. Bureau of the Census. https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-data.2015.html#list-tab-1656998034

Tonglet, M., Phillips, P. S., & Read, A. D. (2004). Using the Theory of Planned Behaviour to investigate the determinants of recycling behaviour: A case study from Brixworth, UK. *Resources, Conservation and Recycling*, *41*(3), 191–214. https://doi.org/10.1016/j.resconrec.2003.11.001

Tran, C. D., & Salhofer, S. P. (2018). Analysis of recycling structures for e-waste in Vietnam. *Journal of Material Cycles and Waste Management*, *20*(1), 110–126. https://doi.org/10.1007/s10163-016-0549-1

United States Environmental Protection Agency. (2022, December 3). Durable Goods: Product-Specific Data. epa.gov. Retrieved from https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/durable-goods-product-specific-data

Vining, J., & Ebreo, A. (1990). What Makes a Recycler?: A Comparison of Recyclers and Nonrecyclers. *Environment and Behavior*, *22*(1), 55–73. https://doi.org/10.1177/0013916590221003

Wagner, T. P. (2013). Examining the concept of convenient collection: An application to extended producer responsibility and product stewardship frameworks. *Waste Management*, *33*(3), 499–507. https://doi.org/10.1016/j.wasman.2012.06.015

Wang, Z., Guo, D., & Wang, X. (2016). Determinants of residents' e-waste recycling behaviour intentions: Evidence from China. *Journal of Cleaner Production*, *137*, 850–860. https://doi.org/10.1016/j.jclepro.2016.07.155

Wilson, G. T., Smalley, G., Suckling, J. R., Lilley, D., Lee, J., & Mawle, R. (2017). The hibernating mobile phone: Dead storage as a barrier to efficient electronic waste recovery. *Waste Management*, *60*, 521–533. https://doi.org/10.1016/j.wasman.2016.12.023

Wyoming: 2020 Census. (2021). [Map]. United States Census Bureau. https://www.census.gov/library/stories/state-by-state/wyoming-population-change-between-census-decade.html

Zaharudin, Z. A., Brint, A., Genovese, A., & Piccolo, C. (2021). A spatial interaction model for the representation of user access to household waste recycling centres. *Resources, Conservation and Recycling*, *168*. https://doi.org/10.1016/j.resconrec.2021.105438

Zeng, X., Mathews, J. A., & Li, J. (2018). Urban Mining of E-Waste is Becoming More Cost-Effective Than Virgin Mining. *Environmental Science & Technology*, *52*(8), 4835–4841. https://doi.org/10.1021/acs.est.7b04909

Appendix

Mapping Illinois' Covered Electronic Devices to CTA Categories

In determining the corresponding Consumer Technology Association category for each covered electronic device, several decisions and assumptions were made. The CTA survey data includes ownership rates for desktop, notebook, and laptop computers, but not computer monitors. In its definition of desktop computers, CERA notes that "a desktop computer is not designed for portability and generally utilizes an external monitor" (Consumer Electronics Recycling Act, 2017). CERA also defines notebook and tablet computers as containing a screen and video display within the device, therefore not requiring an external monitor (Consumer Electronics Recycling Act, 2017). To estimate the number of computer monitors in Illinois, a one-to-one ratio of computer monitors to desktop monitors was used.

Similarly, the CTA report does not include ownership data on electronic keyboards or electronic mice. For the electronic keyboard category, it was assumed a one-to-one ratio of desktop and tablet computers to keyboards. Under this assumption, the sum of desktop and tablet computers will be equivalent to the number of electronic keyboards. CERA defines notebook computers as containing a keyboard within the device and therefore is not used as a proxy for the number of electronic keyboards. For the electronic mouse category, a one-to-one ratio of desktop and notebook computers was assumed. Both desktop and notebook keyboards are defined in Illinois' electronic waste recycling law as using an electronic mouse to interact with, while tablet computers are described as touch-screen devices, and therefore are excluded from the ratio.

Satellite and cable receivers are both listed as covered electronic devices under CERA (Consumer Electronics Recycling Act, 2017). There are no exact corresponding categories in the

CTA report, so for cable receivers, we used the ownership rates for cable modems. It is assumed that each household with a cable modem will have one of that device, so a one-to-one ratio was used. The CTA report contains data on internet connections, including the percentage of households in each income bracket that obtain internet through satellite connection. For satellite receivers, we assumed a one-to-one ratio of households with satellite internet to satellite receivers.

Multi-function printers are defined in the CTA report as printers with scanning and faxing capabilities (18th Annual Consumer Technology Ownership and Market Potential Study, 2016). Therefore, the CERA categories of printer, facsimile machine, and scanner, are combined in the Illinois device calculations, using the CTA ownership rates for multi-function printers to represent the combined ownership rate of these three devices.

The Consumer Technology Association also combines DVD/Blu-Ray players and recorders, which corresponds to the separate CERA categories of digital video disc players and digital video disc recorders. As they are combined in the CTA ownership rates, the calculation quantifying these devices in Illinois is done once, with the resulting value representing the combined number of digital video disc recorders and players. Conversely, Illinois lists video game consoles as a covered electronic device type, while the CTA report contains two categories of video game consoles: home and portable. Using the ownership rates listed in the CTA report, the number of home video game consoles and portable game devices are calculated separately and later summed to obtain the number of video game consoles in Illinois.

The Illinois Consumer Electronics Recycling Act (CERA) lists “television” as a covered electronic device and defines the television category as including both cathode ray tube (CRT) televisions and flat panel televisions (2017). The CTA data provides ownership rates for flat panel televisions but not CRT televisions. CERA also defines “computer monitor” as including both CRT and flat panel monitors. As noted, before, a one-to-one ratio of desktop computers to computer monitors is used because the CTA report does not include any ownership data for computer monitors.

To obtain an ownership rate for CRT TVs, the ratio of CRT to flat panels in 2015 waste flow was calculated from the Supplemental Information for Althaf et al., 2020. The document used was “MFAOUTPUT_Product level flows_kg.xlsx”. A snapshot of the relevant data used from this dataset is shown in Table 1. This column displays product waste flow in the US in units of devices. The rows correspond to the year 2015 for CRT monitors, CRT TVs, LED monitors, LED TVs, LCD monitors, LCD TVs, respectively. For televisions, LED and LCD TVs were combined to represent “Flat Panel TVs” and for monitors, LED and LCD monitors were combined to represent “Flat Panel Monitors.” In 2015, the ratio of CRT to Flat Panel TVs in the waste flow was 0.89 and the ratio of CRT to Flat Panel monitors was 0.94. In a separate sheet for TVs and monitors, the corresponding ratio was multiplied by the flat panel totals for each income bracket and census tract.

Table A 1. Product waste flow data for CRTs and Flat Panels, found in the Supplemental Information for Althaf et al., 2020 (Shahana-Althaf, 2020).

ProductName	**Year**	**Product_Wasteflow_US_units**
CRT monitor	2015	7,852,653.61
CRT TV	2015	21,518,366.15
LED Monitor	2015	981,701.01
LED TV	2015	2,816,662.66
LCD monitor	2015	7,355,280.83
LCD TV	2015	21,404,276.61

Validation of Model Using Real Collection Data from Illinois

The collection totals for eight electronic waste collection sites in Illinois were obtained for the year 2021. This data was obtained from the Illinois Environmental Protection Agency (*Collector's Electronic Products Collection & Transportation Reports*, n.d.). These collection values were compared to the estimated potential e-waste mass located within three or five miles of the real site location. The closest modeled site under the Illinois convenience standard was also identified, and the estimated potential e-waste mass within three or five miles of the modeled site was tabulated as well. The results for the eight sites are displayed in the tables and figures below.

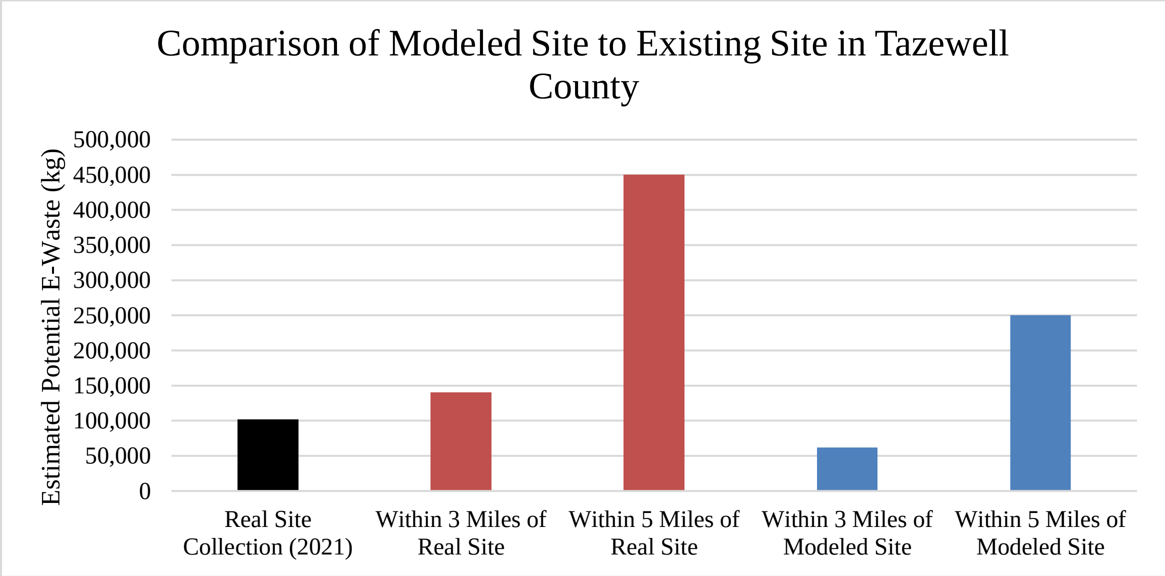


Figure A 1. Tazewell County: 2021 collection total for a real Illinois site, compared to the potential estimated e-waste mass around the real site and closest modeled site.

Table A 2. Tazewell County: Comparison of estimated potential electronic waste within three and five miles of a real site and the closest modeled site.

Scenario	**Estimated Potential E-Waste (kg)**
Real Site Collection (2021)	101,493
Within 3 Miles of Real Site	140,000
Within 5 Miles of Real Site	450,000
Within 3 Miles of Modeled Site	62,000
Within 5 Miles of Modeled Site	250,000

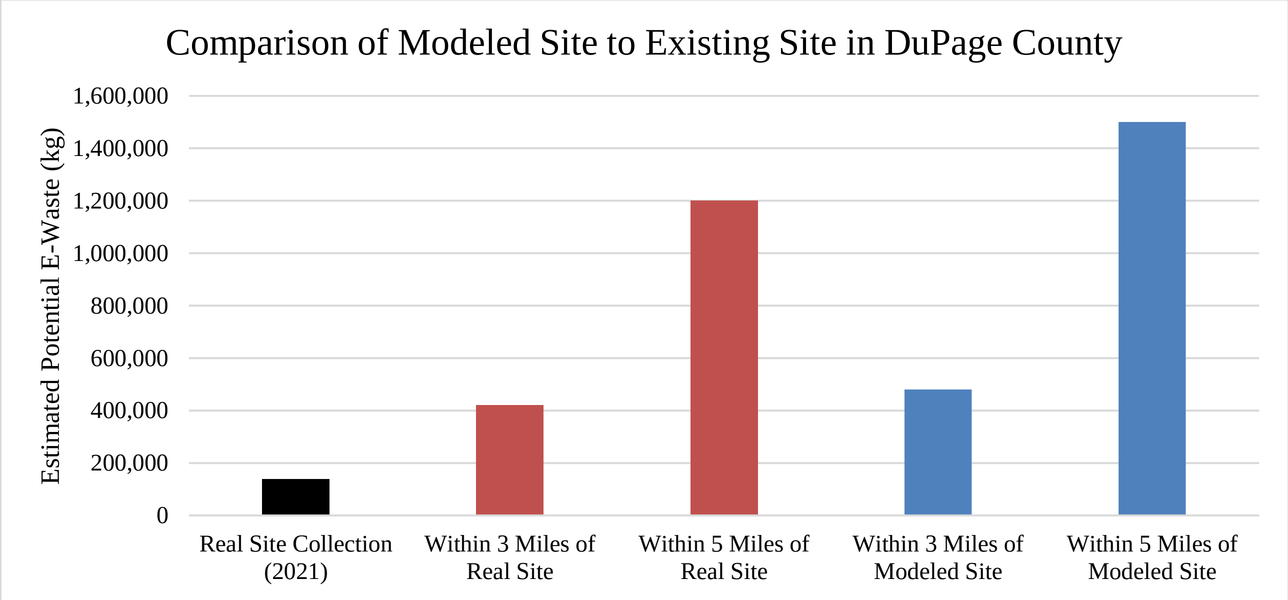


Figure A 2. DuPage County: 2021 collection total for a real Illinois site, compared to the potential estimated e-waste mass around the real site and closest modeled site.

Table A 3. DuPage County: Comparison of estimated potential electronic waste within three and five miles of a real site and the closest modeled site.

Scenario	**Estimated Potential E-Waste (kg)**
Real Site Collection (2021)	137,329
Within 3 Miles of Real Site	420,000
Within 5 Miles of Real Site	1,200,000
Within 3 Miles of Modeled Site	480,000
Within 5 Miles of Modeled Site	1,500,000

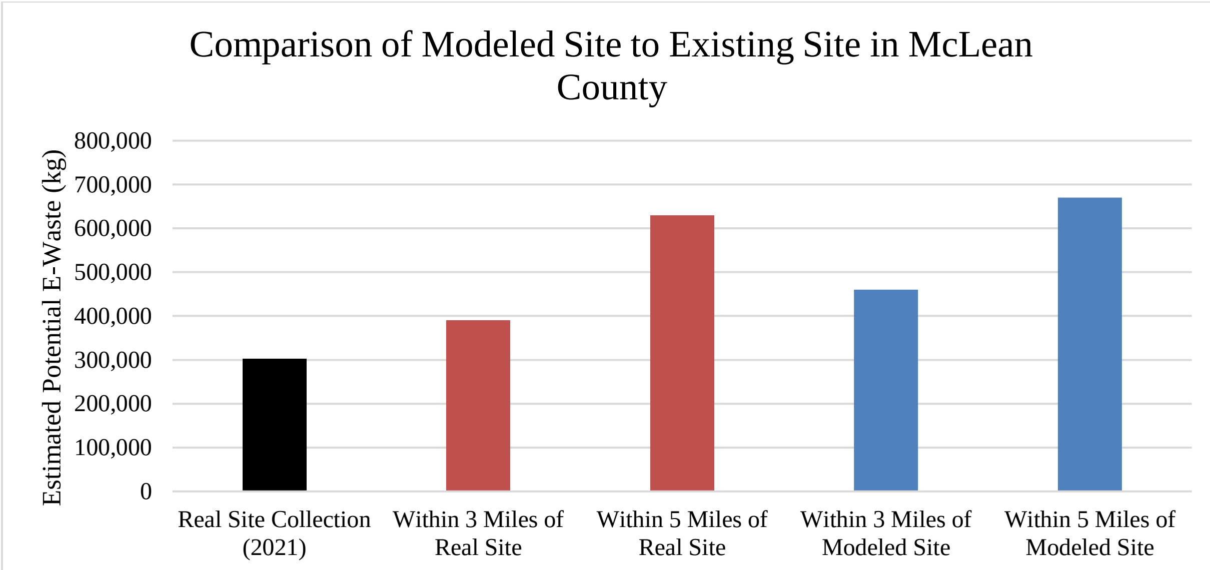


Figure A 3. McLean County: 2021 collection total for a real Illinois site, compared to the potential estimated e-waste mass around the real site and closest modeled site.

Table A 4. McLean County: Comparison of estimated potential electronic waste within three and five miles of a real site and the closest modeled site.

Scenario	**Estimated Potential E-Waste (kg)**
Real Site Collection (2021)	302,736
Within 3 Miles of Real Site	390,000
Within 5 Miles of Real Site	630,000
Within 3 Miles of Modeled Site	460,000
Within 5 Miles of Modeled Site	670,000

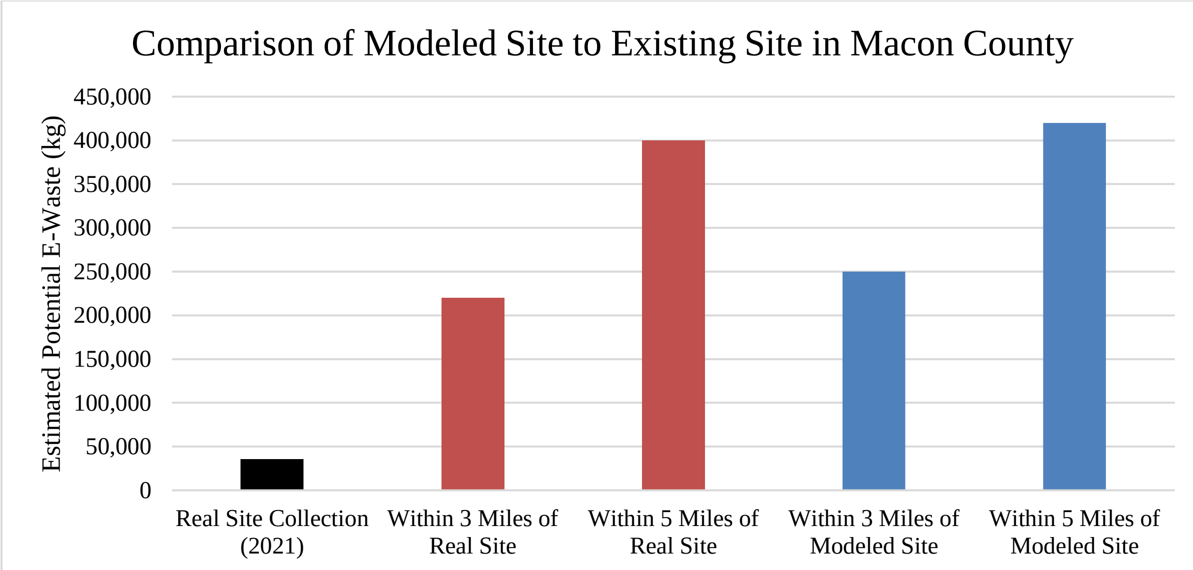


Figure A 4. Macon County: 2021 collection total for a real Illinois site, compared to the potential estimated e-waste mass around the real site and closest modeled site.

Table A 5. Macon County: Comparison of estimated potential electronic waste within three and five miles of a real site and the closest modeled site.

Scenario	**Estimated Potential E-Waste (kg)**
Real Site Collection (2021)	35,762
Within 3 Miles of Real Site	220,000
Within 5 Miles of Real Site	400,000
Within 3 Miles of Modeled Site	250,000
Within 5 Miles of Modeled Site	420,000

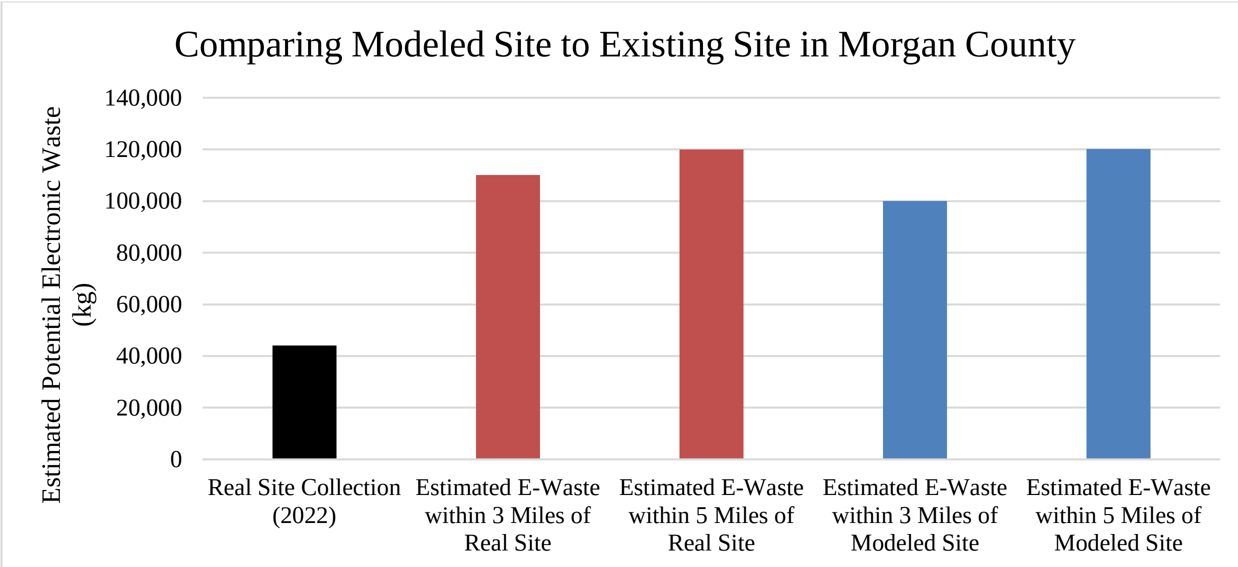


Figure A 5. Morgan County: 2021 collection total for a real Illinois site, compared to the potential estimated e-waste mass around the real site and closest modeled site.

Table A 6. Morgan County: Comparison of estimated potential electronic waste within three and five miles of a real site and the closest modeled site.

Scenario	**Estimated Potential Electronic Waste (kg)**
Real Site Collection (2022)	44,048
Within 3 Miles of Real Site	110,000
Within 5 Miles of Real Site	120,000
Within 3 Miles of Modeled Site	100,000
Within 5 Miles of Modeled Site	120,000

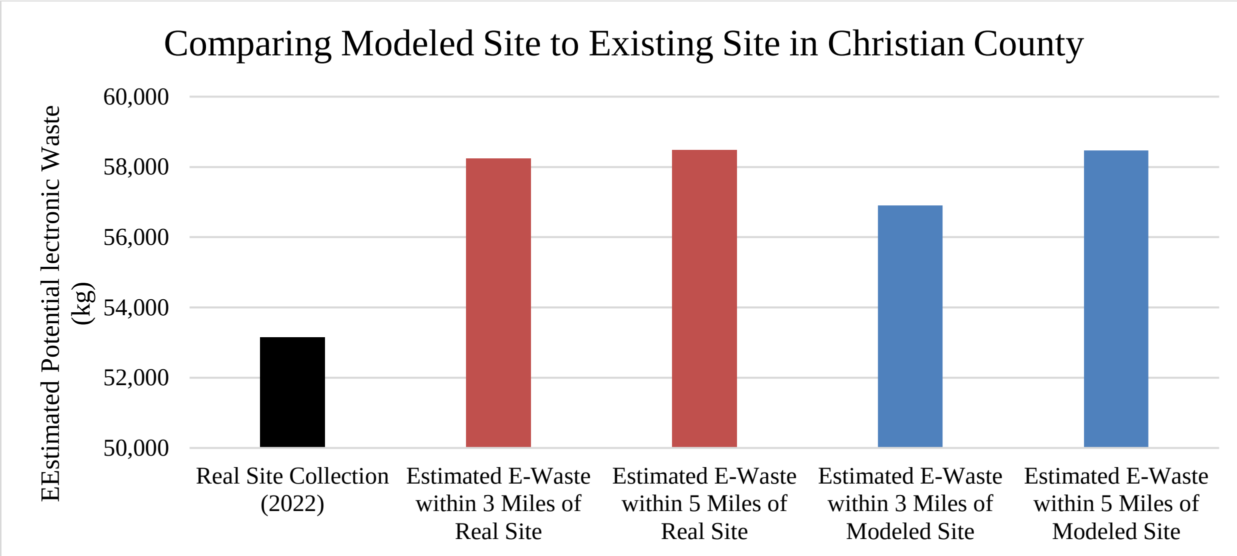


Figure A 6. Christian County: 2021 collection total for a real Illinois site, compared to the potential estimated e-waste mass around the real site and closest modeled site.

Table A 7. Christian County: Comparison of estimated potential electronic waste within three and five miles of a real site and the closest modeled site.

Scenario	**Estimated Potential Electronic Waste (kg)**
Real Site Collection (2022)	53,144
Within 3 Miles of Real Site	58,000
Within 5 Miles of Real Site	58,000
Within 3 Miles of Modeled Site	57,000
Within 5 Miles of Modeled Site	58,000

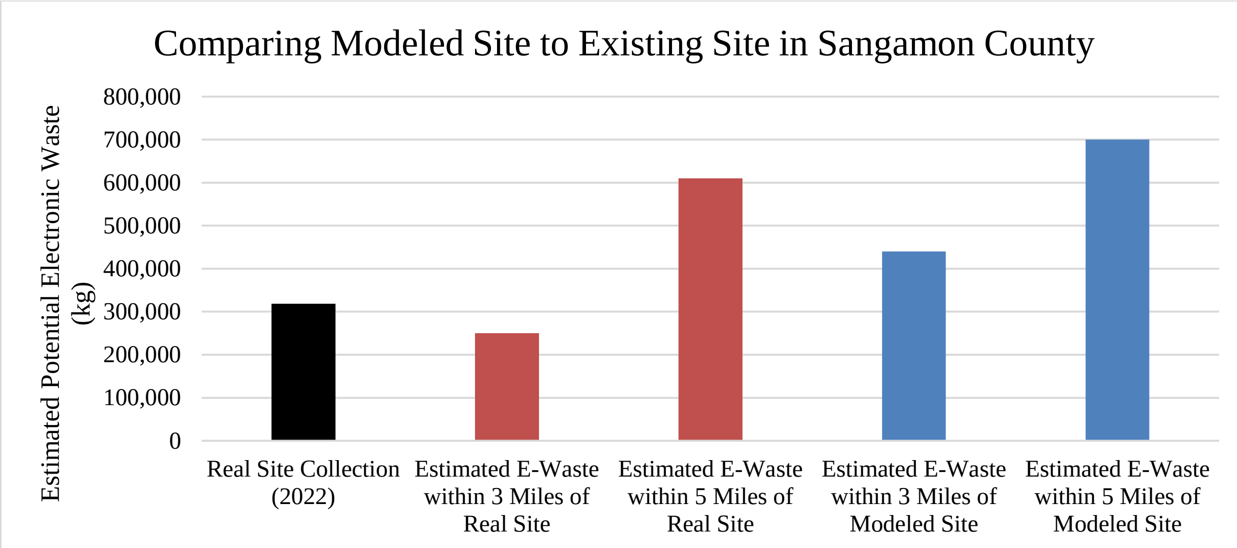


Figure A 7. Sangamon County: 2021 collection total for a real Illinois site, compared to the potential estimated e-waste mass around the real site and closest modeled site.

Table A 8. Sangamon County: Comparison of estimated potential electronic waste within three and five miles of a real site and the closest modeled site.

Scenario	**Estimated Potential Electronic Waste (kg)**
Real Site Collection (2022)	318,192.33
Within 3 Miles of Real Site	250,000
Within 5 Miles of Real Site	610,000
Within 3 Miles of Modeled Site	440,000
Within 5 Miles of Modeled Site	700,000

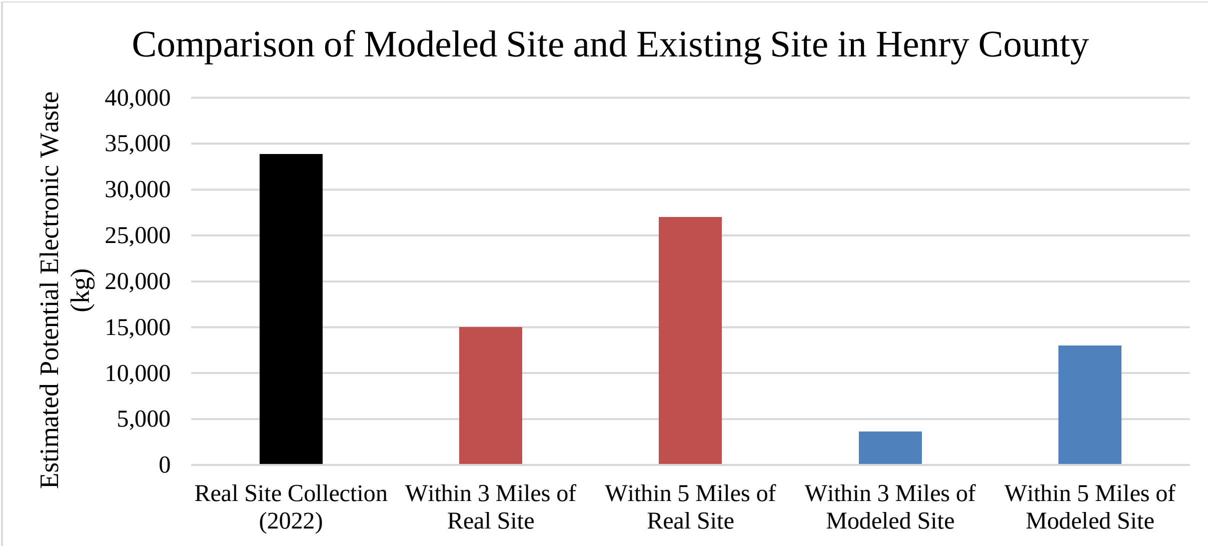


Figure A 8. Henry County: 2021 collection total for a real Illinois site, compared to the potential estimated e-waste mass around the real site and closest modeled site.

Table A 9. Henry County: Comparison of estimated potential electronic waste within three and five miles of a real site and the closest modeled site.

Scenario	**Estimated Potential E-Waste (kg)**
Real Site Collection (2022)	33,860
Within 3 Miles of Real Site	15,000
Within 5 Miles of Real Site	27,000
Within 3 Miles of Modeled Site	3,600
Within 5 Miles of Modeled Site	13,000