A SPATIAL ANALYSIS OF GREEN ALLEY INFRASTRUCTURE IN CHICAGO

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UNDERGRADUATE THESIS

The University of Chicago, Class of 2021

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1. Introduction

The industrial revolution and the rise of cities transformed the relationship between humanity and the environment (Harvey 1989). Urban spaces became a primary driver of environmentally destructive practices due to their function as a locus for market-driven consumption and industrial production (Spirn 2012; Newell et al. 2012; Harvey 1989). As anthropogenic climate change exacerbates weather conditions worldwide, most academics and planners have come to agree that minimizing ecologically harmful development practices is critical to preventing future catastrophes (City of Chicago Green Stormwater Infrastructure Strategy 2014; Newell et al. 2012; First Street Foundation 2021). The idea of sustainable urbanism has been proposed as a mechanism to minimize environmental destruction by transforming urban spaces from epicenters of industrialization into the frontline of a new system which balances the relationship between people and the planet (Newell et al. 2012; Steffen et al. 2015). Sustainable urbanism is the idea of a resilient urban space that promotes economic development, social justice, and environmental protection, or what has become known as the three 'E's of sustainability: economy, equity, and ecology (Newell et al. 2012). Many scholars now consider the development of green infrastructure an essential part of this new urban space (Newell et al. 2012). Green infrastructure accesses the intersection of the three E's, providing opportunities for building projects which help local economies while constructing structures which promote resilient urban ecosystems and abandon toxic modes of production which disproportionately affect the marginalized in society (Newell et al. 2012; Spirn 2012).

Worldwide, municipalities have created sustainable development plans establishing urban sustainability through green infrastructure. In certain U.S. cities green alleyways are critical to the strategy of developing green infrastructure, taking advantage of massive already existing alley networks (Newell et al. 2012). In 2006, Chicago became the first city in the United States to establish a green alley program, taking advantage of over 1900 miles of alley space (City of Chicago Green Stormwater Infrastructure Strategy 2014).

Green alleys are alley spaces which include green tech innovations, such as permeable pavement, which redirect rainwater away from local sewer systems (City of Chicago Green Stormwater Infrastructure Strategy 2014). By redirecting water away from local sewers green alley infrastructure operates as an auxiliary urban flood management system, reducing the likelihood of sewer overflow or backup which can release pollutants into the environment and disproportionately affects low-income communities of color (City of Chicago Green Stormwater Infrastructure Strategy 2014; Newell et al. 2012; Song and Briscoe 2020). Urban flood rates depend on factors related to local infrastructure, in contrast with riverine and shoreline flooding, making localized green infrastructure, such as green alleys, more important for mitigating the effects of urban flooding (Keenan, Shankar, and Haas 2019; First Street Foundation 2020). In Chicago, variability in local infrastructure quality result in more severe urban flooding effects in lower income neighborhoods and neighborhoods of color (Keenan, Shankar, and Haas 2019; Song and Briscoe 2020). As climate change exacerbates flood conditions throughout the Chicago area, green alleys become more critical for creating resilient urban space and addressing environmental injustices perpetuated through the disparate impact of urban flooding (City of Chicago Green Stormwater Infrastructure Strategy 2014; First Street Foundation 2021).

Since the start of the program, little research has been done covering its development. Most research on green alleys has focused on their significance within the broader context of green infrastructure, but few studies have evaluated their efficacy or progress (Newell et al. 2012; Finewood 2019). No research has been done on the spatial distribution of green stormwater infrastructure, and more specifically green alleys, across Chicago (Illinois Department of Natural Resources 2015; City of Chicago Green Stormwater Infrastructure Strategy 2014). This is significant as evaluation of sustainability programs, such as the green alley program, is critical to ensuring their success at transforming the urban space (Portney 2003). Common criticisms of sustainability plans call out their purely discursive commitment to sustainability, arguing that they frequently fail to engender actual changes in urban policy or the built environment (Portney 2003; Whitehead 2012). As well, all infrastructure development brings up questions of environmental justice as variations in infrastructure distribution frequently manifest in disparate adverse health effects between lower income neighborhoods of color and higher income communities and majority white neighborhoods (Campbell 2013; Keenan, Shankar, and Haas 2019). Spatial analysis provides important insights into the distribution patterns of infrastructure, which are important for modeling their efficacy and evaluating disparities in regional impacts (Illinois Department of Natural Resources 2015).

This paper aims to start the process of assessing Chicago's green infrastructure development through an analysis of the spatial distribution of Chicago's green alleys, and the relationship between this spatial distribution and other environmental and demographic indicators. As is the case with most green infrastructure in Chicago, the development of green alleys was promoted gradually without a centralized infrastructure plan and targeted citywide completion dates, in contrast to grey infrastructure, which has resulted in a deficit of holistic evaluations of green alley development (City of Chicago Green Stormwater Infrastructure Strategy 2014; Chicago Green Alley Handbook 2010). Spatial distribution analyses of infrastructure are useful for city management as they allow for future planning projects to contextualize the current state of infrastructure and determine areas for improvement (Hou 2018).

This thesis set out to characterize the spatial distribution of green alleys and to identify correlations between this distribution and the distributions of socioeconomic and environmental phenomena which could play a causative role in variations of green alley clustering across the city of Chicago. Although correlation cannot confirm causation, dependence of green alley distribution on another variable would most likely result in a spatial correlation between their distributions.

Based on an understanding of existing socioeconomic and infrastructure disparities in Chicago one would expect that a decentralized development process, such as the green alley program, would most likely result in a spatial distribution of infrastructure which reflected these disparities. A decentralized development process, which occurs gradually and involves multiple distinct projects over time, in contrast with centralized processes which aim for a particular end goal with an established completion timeline, would most likely be more dependent on, and more readily reflect, regional disparities in material wealth or environmental conditions, which could affect infrastructure distribution patterns. Existing structural factors, which predispose the urban core and northeast side of the city to newer development and more frequent maintenance, might result in clustering of green alley sites within these regions. The urban core is a rough geographic region based on the historic development of Chicago, which includes the loop and adjacent neighborhoods, which tend to include older buildings, greater economic activity, and higher population density (Conzen 2004). As well, the structural factors which predispose the south and west side of the city to disinvestment may result in a lack of green alley density or spatial clustering in these regions. This distribution would be significant because flooding disproportionately affects neighborhoods outside of the urban core and across the south and west side of Chicago, a deficit in green alleys across these parts of Chicago could indicate a limitation to the overall effectiveness of the green alley program and outline a possible future direction for further green alley development (Keenan, Shankar, and Haas 2019).

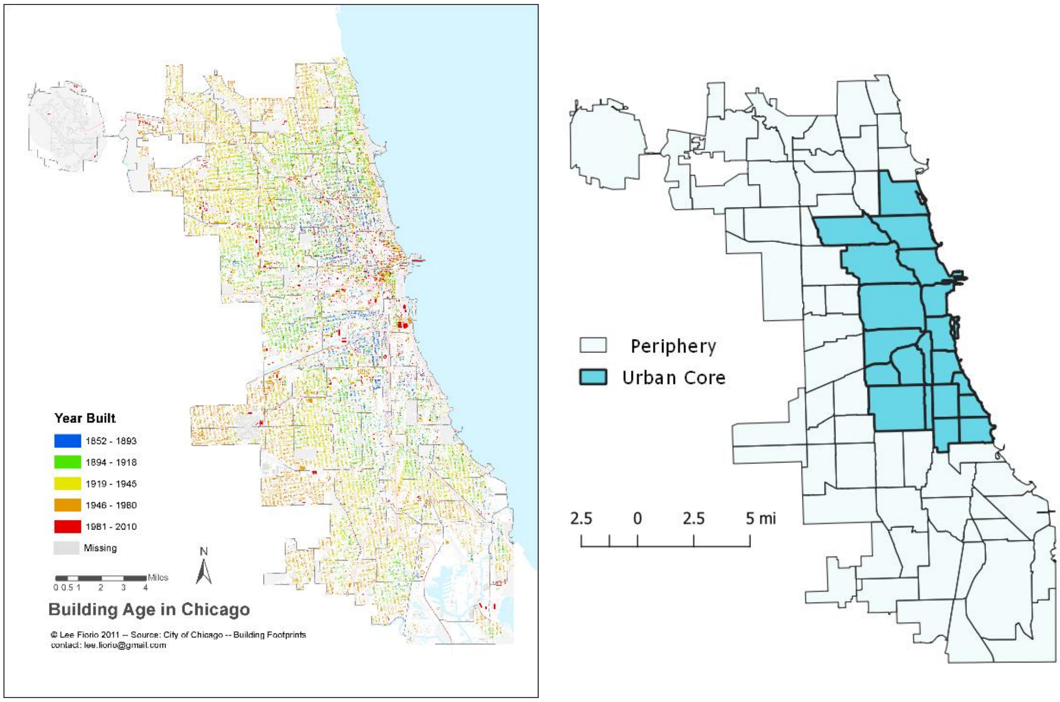

Figure 1 (Left) Map of building footprints categorized by age across the city, indicating expansion of the city of Chicago over time. Source: Geographic Society of Chicago. (Right) the urban core of Chicago.

Spatial analysis can quantitatively characterize the distribution of green alleys through measurements of density and clustering. Spatial density measurements relate the concentration of green alley sites to the total land area around them. Clustering measurements relate the concentration of green alley sites in terms of their proximity to other green alley sites. Combined these two measurements can define regions with higher numbers of green alleys and identify distribution patterns which can be used to evaluate the potential effectiveness of the green alley program.

Furthermore, spatial analysis can be used to assess correlation between two variables across the city. Correlations between green alley distribution will be used to identify possible explanations for variations in green alley density. Correlation will also be used to quantitatively characterize the relationships between green alley distribution and systemic disparities between the urban core and urban periphery, which perpetuate environmental injustice.

In doing this spatial analysis, this thesis hopes to set up future research questions to determine an explanation for the clustering of green alleys in the urban core and the deficit of alleys in the urban periphery. As well, through spatial analysis, this thesis aims to help elucidate possible future directions for green alley development in community areas currently lacking green alleys.

This thesis is subdivided into six sections, including this introduction. The second section, the literature review, will explain the history and significance of green infrastructure in the context of broader trends in sustainability, and will elaborate on the importance of spatial analysis in evaluating infrastructure. The third section, the background, will describe in depth the problem of urban flooding in Chicago, the significance of green alleys as a part of green infrastructure, and the role of green alleys in mitigating stormwater flooding in Chicago. The background will also describe green alley technology and its limitations, and the existing infrastructure disparities across Chicago. The fourth section, methodology, will discuss the methods used to measure green alley spatial density and multivariable spatial correlations. The fifth section, discussion and results, will present and analyze the data. The sixth section, the conclusion, will relate the analysis of the data to the broader context of future green alley development and green infrastructure in Chicago.

2. Literature Review

2.1 Sustainability

The idea of sustainable urbanism comes from a long history of theorizing on the relationship between humanity and the natural world (Spirn 2012). The idea of a more ecologically friendly urban space gained currency in the 1960s and 1970s as environmentalist movements spread awareness of the destructive impacts unregulated industry has on the health of communities and ecosystems in urban spaces (Spirn 2012; Whitehead 2012). During the 1990s, the term sustainability gained currency, defined as a descriptor of alternative systems which reduced overconsumption and environmental destruction while also meeting economic development goals and improving social systems (Whitehead 2012). To researchers, activists, and some politicians meeting these goals implied that sustainable development occupied an intersection between social policies, economic policies, and environmental policies. Sustainable policies would promote community engagement, reduce health issues, and create economic opportunities while simultaneously reducing toxic waste, greenhouse gas emissions, and the loss of biodiversity (Whitehead 2012, Newell et al. 2012). This intersection became commonly summarized as the three “E”s of sustainability: Ecology, Equity, and Economy (Newell et al. 2012).

Over the next decades, academics, city planners, activists, and engineers argued further over the definition of sustainability (Whitehead 2012). Public awareness grew of the disastrous effects of greenhouse gas-induced climate change, increasing interest in changing how humanity interacts with the natural world (Whitehead 2012). Discourse about sustainability began to focus on the idea of sustainable urbanism, which applied previously defined principles of sustainability to the specific problem of transforming the city, the center of capitalist consumption and production, into an ecologically friendly and socially inviting space (Whitehead 2012, Newell et al. 2012; Harvey 1989).

The vagueness of the sustainability concept caused debate over its application and drew criticism over its usage (Whitehead 2012; Portney 2003). Some critics lamented the fact that sustainability plans frequently did not live up to their ambitions, and that sustainability was used as a discursive tool to rebrand the same set of wasteful projects (Portney 2003). Other critics claim that sustainability, in its current usage, has operated more as branding than as effective policy and does little to challenge the underlying assumptions of the market systems which drive unsustainable consumption and production in the first place (Whitehead 2012). This was the case in Mesa Arizona, where sustainability programs focused on economic revival and did little to reign in sprawl despite the strain urban sprawl has on the desert environment (Whitehead 2012).

Proponents of sustainable urbanism have attempted to resolve these criticisms through developing concrete mechanisms for the establishment of an urban space that directly challenges current unsustainable practices (Newell et al. 2012). Advocates for sustainability recognize the need for continual project evaluation and the establishment of concrete long-term goals as a means of determining which sustainability projects are effective and which are just marketing (Portney 2003; Newell et al. 2012). Green infrastructure has become a central component of sustainable urbanism as it presents a concrete visualization of how the systems which underly urban space can be made to materially counter wasteful consumption and promote environmental conservation (Newell et al. 2012).

2.2 Green Infrastructure

Researchers have come to define green infrastructure around a set of characteristics. Green infrastructure includes infrastructure which tends to emphasize the characteristics of "multifunctionality and connectivity" (engaging with a network of built and natural systems); and includes structural elements which create conditions for environmental improvement (Newell et al. 2012).

Green infrastructure aligns with principles of sustainability, accomplishing goals emphasizing the three E's (Newell et al. 2012). Structural elements of the infrastructure projects directly benefit local ecology, while also supporting economic systems which depend on resilient infrastructure (Newell et al. 2012). Through an ecosystem services framework green infrastructure can be contextualized as a mechanism for correcting inequities within urban systems which occur due to environmental injustice (McPhearson 2014). The ecosystem services framework emphasizes how biodiversity promotion and environmental spaces can affect social benefits, such as cleaner air and healthier environments as well as social spaces for community building (McPhearson 2014).

Green infrastructure also operates as a practical application of the concept of ecological urbanism. Ecological urbanism is framework which promotes sustainable urbanism through the synthesis of natural ecosystem functions with the function of urban spaces (Spirn 2012). Ecological urbanism promotes the incorporation of the natural environment with the built environment for the accomplishment of broader sustainable development goals (Spirn 2012).

Green infrastructure, through presenting concrete steps and material solutions which can be implemented through urban spaces, resolves concerns around the vagueness of sustainable urbanism (Newell et al. 2012; Portney 2003). It imagines a new system which materially changes the conditions which create ecological hazards throughout urban spaces, transforming the platitudes of sustainability plans into tangible changes in the built environment (Spirn 2012).

2.3 The Importance of Spatial Analysis

Critics of sustainability have pointed out that sustainability plans have on occasion served more as marketing strategies than as tangible actions which foster change in urban systems (Portney 2003; Whitehead 2012). One way sustainability programs can be tested to ensure they go beyond just discursive commitments to sustainability is through project evaluation which uses concrete metrics to assess progress and failure occurring with regards to a program's stated goals (Portney 2003). One type of project evaluation is spatial analysis (Hou 2018). No research has been done yet on the spatial distribution of green stormwater infrastructure throughout Chicago. A spatial analysis of infrastructure looks at the distribution of a type of infrastructure across geographic space and makes quantitative and qualitative claims regarding the density, clustering, and correlation of that variable (Hou 2018). Comparison between spatial analyses of multiple variables can be used to provide further context for the significance of a variable's presence or absence in a specific location (Hou 2018). This quantifiable absence or presence can later be used to make claims regarding the local effectiveness of infrastructure in an area, allowing for future evaluation of sustainability (Hou 2018).

Spatial analysis of stormwater infrastructure is critical for improving management and planning of future infrastructure projects (Illinois Department of Natural Resources 2015). Detailed information on the spatial distribution of GSI can help planners and city management model its functionality (Hou 2018). Presently, there have been no studies into the spatial distribution of green stormwater infrastructure across Chicago (Illinois Department of Natural

Resources 2015). Understanding the current distribution of green alleys can improve decision making with regards to the development of future green alleys. Spatial analyses can contribute to a more wholistic understanding of the effectiveness of GSI, as GSI arises through decentralized planning (City of Chicago Green Stormwater Infrastructure Strategy 2014). Models based on spatial distribution can be used to determine weaknesses and strengths of the stormwater infrastructure system, enabling the prioritization of resources which address deficits in infrastructure efficacy (City of Chicago Green Stormwater Infrastructure Strategy 2014; Illinois Department of Natural Resources 2015). Specifically, quantification of spatial density and clustering is essential to model the efficacy of green alley infrastructure in reducing basement flooding, as basement flooding is the result of local sewer back ups and thus its effects are dependent on variations in local sewer infrastructure and the cumulative effects of local green stormwater infrastructure (City of Chicago Green Stormwater Infrastructure Strategy 2014; Illinois Department of Natural Resources 2015).

3. Background

3.1 Names and Places in Chicago

For reference this section will include these maps the names of Chicago's community areas. These names will be mentioned in the discussion of spatial variation across Chicago.

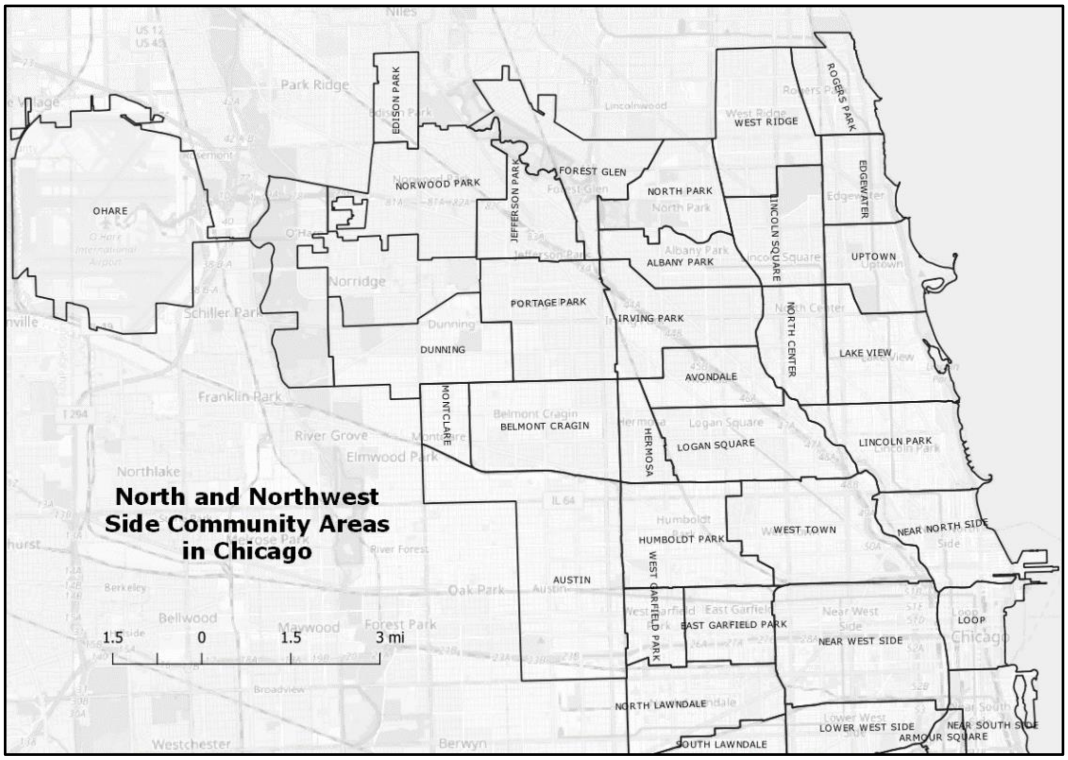

Figure 2 Shows the names of community areas across the north and northwest side of Chicago

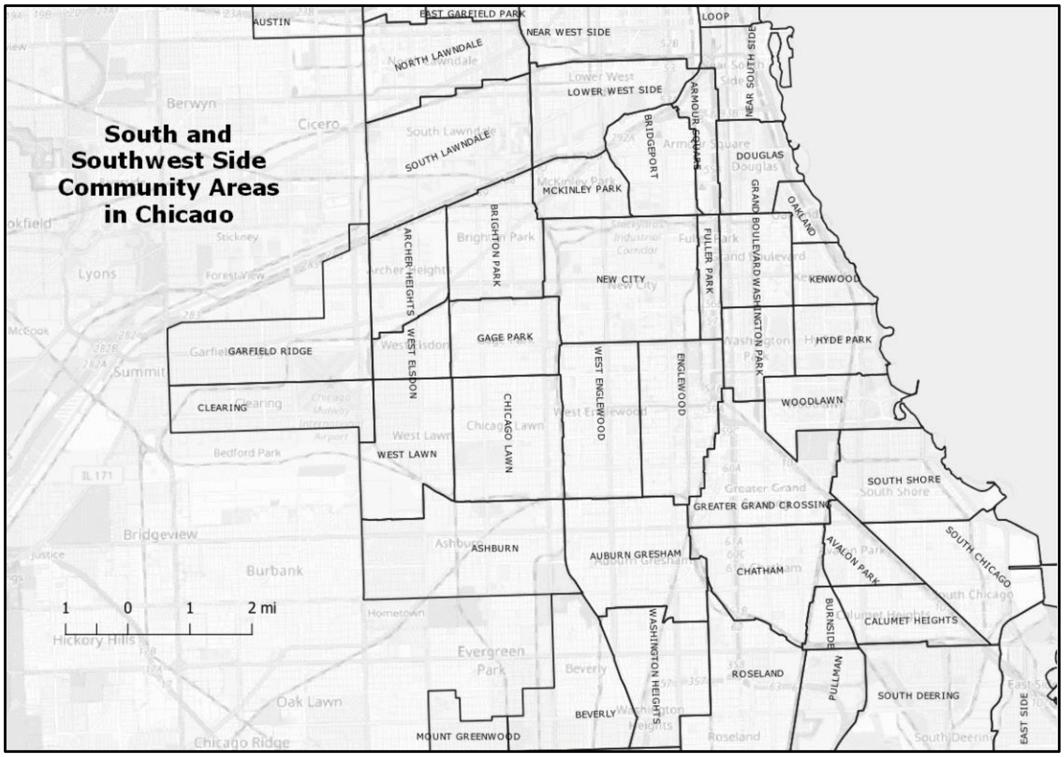

Figure 3 Shows the names of community areas across the south and southwest side of Chicago.

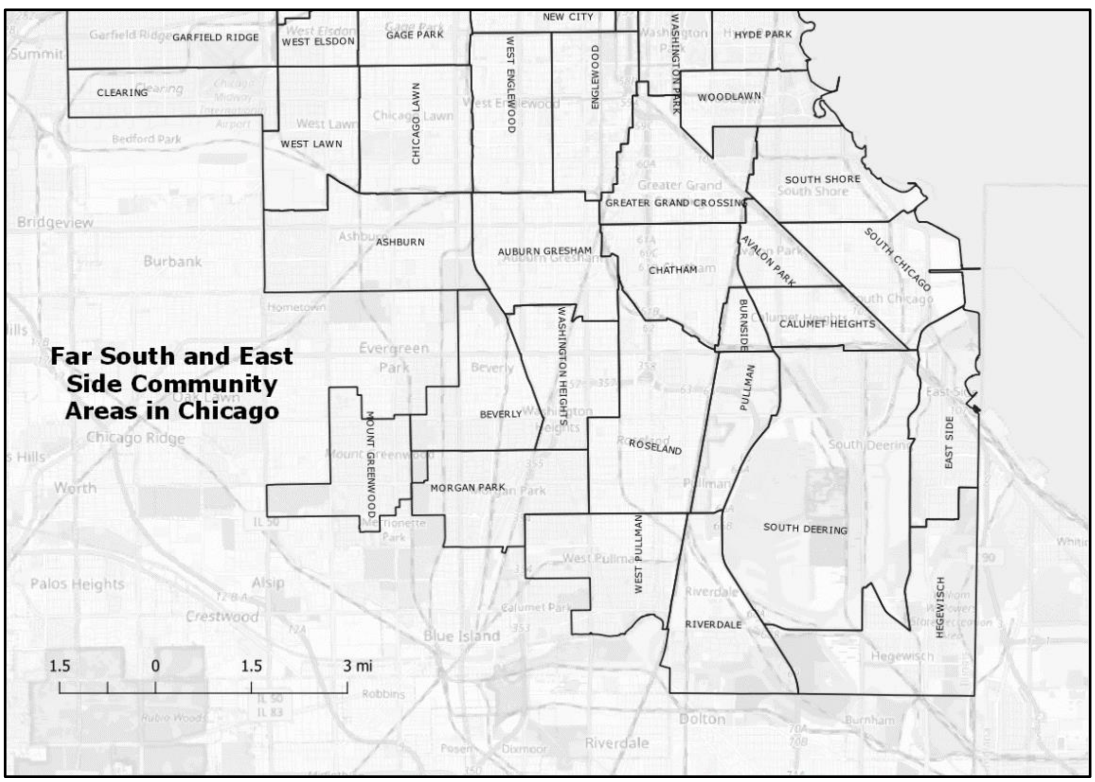

Figure 4 Shows the names of community areas across the far south, south west, and east side of Chicago.

3.2 Chicago's Stormwater Infrastructure

In 2014, the city of Chicago published a comprehensive report on the state of green stormwater infrastructure projects throughout the city. Green stormwater infrastructure (GSI) was presented as an auxiliary system to larger projects developing grey stormwater infrastructure to confront the issue of stormwater flooding in Chicago (City of Chicago Green Stormwater Infrastructure Strategy 2014).

3.2.1 Stormwater Flooding

In Chicago, one inch of rain citywide results in approximately 4 billion gallons of stormwater (City of Chicago Green Stormwater Infrastructure Strategy 2014). Between the years 2006 and 2011, the city of Chicago received around 45 inches of rainfall annually (City of Chicago Green Stormwater Infrastructure Strategy 2014). This annual average rainfall had only increased since the 1990s due to climate change (City of Chicago Green Stormwater Infrastructure Strategy 2014). A 2008 report commissioned by the city of Chicago revealed that climate change would further increase the frequency and severity of rainfall. Estimates suggest that Chicago's annual precipitation could increase by 20-30% by the end of the century (City of Chicago Green Stormwater Infrastructure Strategy 2014). This would increase the instances of stormwater flooding citywide. Stormwater flooding is a significant issue in the city of Chicago, rooted in the development of the city upon historic swampland (City of Chicago Green Stormwater Infrastructure Strategy 2014). The swamps of Chicago served an environmental niche as a natural filter and absorbent space for rainfall in the Chicago river and Calumet river basins (Joyce 2019; City of Chicago Green Stormwater Infrastructure Strategy 2014). During the construction of the city significant portions of the swamp and marshland were made impervious to rainfall. Approximately 60% of Chicago's land today is paved or covered by buildings (City of Chicago Green Stormwater Infrastructure Strategy 2014).

Figure 5 Map of Chicago river systems. Source: Active Transportation Alliance.

As climate change increases the severity of storms, stormwater flooding will increase, as has been the case in recent years. Climatologists have stated that based on historic trends a 4.96 inch rainfall over a 2-day period would classify as a "ten-year storm," implying a weather event likely to occur once every ten years (City of Chicago Green Stormwater Infrastructure Strategy 2014). Between 2008 and 2014, four storms have occurred which have exceeded the rainfall of the predicted “ten-year storm.” This has resulted in an uptick in urban flood damage and complaints of basement flooding.

According to a study by the Illinois Department of Natural Resources, urban flooding has caused $2.319 billion in documented property damage throughout Illinois over 2007-2014 (Illinois Department of Natural Resources 2015). In Cook County alone, over $773 million in urban flood damage was recorded from 2007-2011 (Song and Briscoe 2020). On top of this damage, urban flood victims frequently lose emotionally significant personal property and as well can experience negative health effects due to flood damage; especially in warm weather, flooding can increase asthma cases and risk of contracting West Nile virus (Joyce 2019; Keenan, Shankar, and Haas 2019). The Federal Emergency Management Agency (FEMA) estimates that after flooding nearly 40% of small businesses are unable to recover (Joyce 2019). Flooding also significantly reduces property values in an area, with estimates of values lowering from 10-25% their original value (Joyce 2019).

Urban flooding occurs due to many local factors, making it difficult to measure and map. On top of riverine and shoreline flooding, back-ups in local sewer infrastructure and rainwater or ground water seepage also contribute to urban flooding (Keenan, Shankar, and Haas 2019). These latter phenomena are more difficult to track and measure and can be dependent on variations in infrastructure, such as building age, permeable surface area, cracks in basement walls, sewer system elevation, and neighborhood depressional areas (Keenan, Shankar, and Haas 2019).

In response to damages incurred by flooding, FEMA mandated flood insurance in areas where flood risk was high, these areas are known as special flood hazard areas. Recent studies have revealed that FEMA flood coverage is incomplete and fails to cover many instances of urban flooding in the Chicago area as FEMA flood risk maps model flooding based on limited inputs at broader scales, resulting in higher risk thresholds, unlike newer flood risk models which consider more locally specific flood risks (Song and Briscoe 2020; First Street Foundation 2021; First Street Foundation 2020). Over 90% of the insurance and disaster assistance claims relating to urban flooding occurred in properties outside FEMA's special flood hazard areas (Joyce 2019; Song and Briscoe 2020). By not being included in FEMA special flood hazard areas, many houses are not mandated to have flood insurance and as a result do not have access to recovery funding from the National Flood Insurance Program (NFIP) (Song and Briscoe 2020; Joyce 2019).

Research by the First Street Foundation, evaluating flooding using probabilistic flood modeling at the scale of individual properties, providing a precursory analysis of flooding in areas not covered by FEMA (First Street Foundation 2020). The difficulty in measuring urban basement flooding, due to the relation between basement flooding and local infrastructure as well as local precipitation, leaves significant parts of Chicago's flood zones still unknown. A lack of studies into the effects of urban flooding have created a deficit in urban flood data, leaving areas with significant basement flooding unmapped (Illinois Department of Natural Resources 2015).

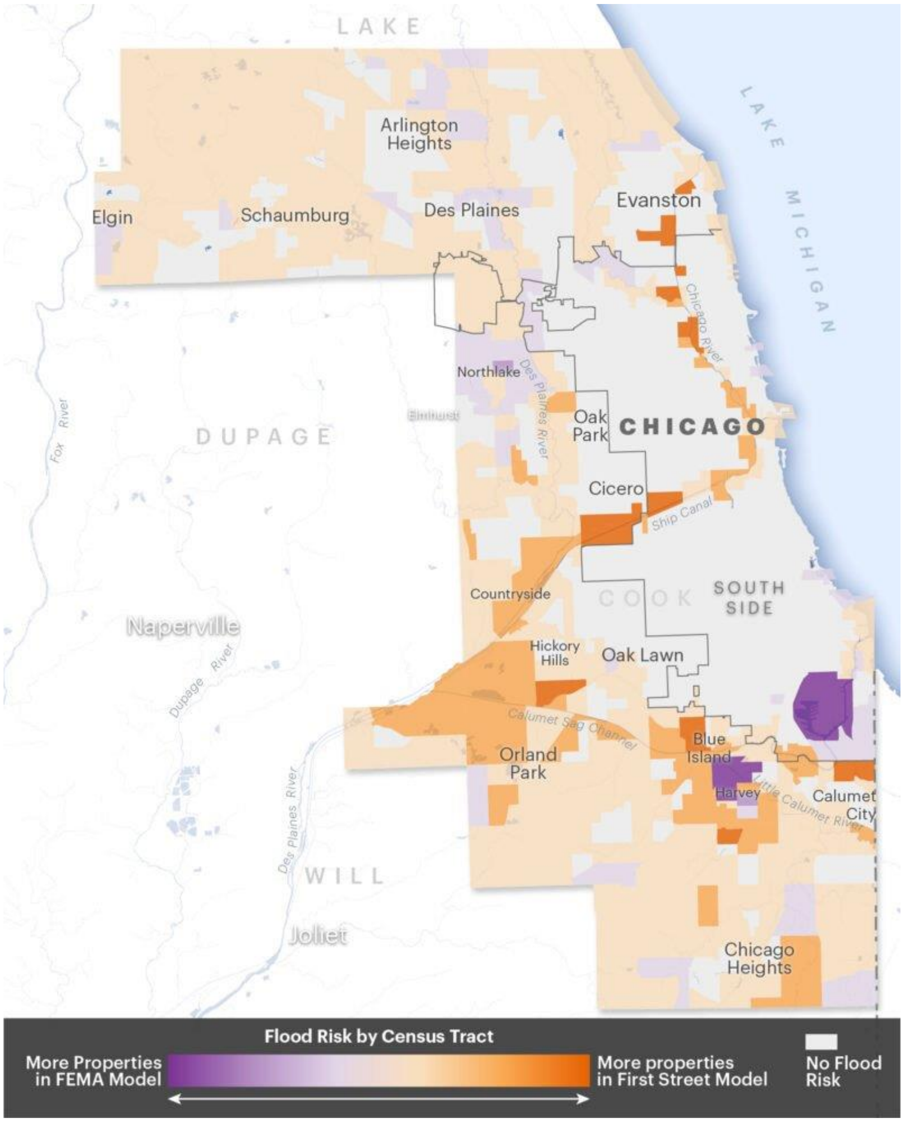

Figure 6 Map of urban flood risk throughout Cook County. Areas in Orange have significantly more at-risk properties than are included in FEMA urban flooding prediction. Source: Propublica (Song and Briscoe 2020).

The effects of urban flooding are felt across the entire Chicago area, but disproportionately affect marginalized communities in predominantly lower-income communities of color, which are less likely to have flood insurance (Song and Briscoe 2020; Joyce 2019). Between 2007 and 2016, there were nearly 230,000 flood-related claims, of which 87% of claims were in communities of color (Song and Briscoe 2020). Many communities with high flood claim payouts were found along the south and west side of Chicago. Eight out of ten of the top ten census tracts with properties at risk outside of FEMA flood hazard areas are majority nonwhite (Song and Briscoe 2020).

Much more research is needed on the issue of urban flooding across Chicago. Numerous factors can increase the likelihood of basement flooding (such as soil type, impervious surface coverage, rainfall data, age of infrastructure, etc.) making the identification of basement flood zones more difficult to spatially correlate (Illinois Department of Natural Resources 2015). Further research using GIS software is needed to fully assess the extent of flood risk throughout the City of Chicago (Illinois Department of Natural Resources 2015). This research is significant as it will allow for more accurate stormwater infrastructure planning, especially concerning the development of green stormwater infrastructure which can more directly address the problem of basement flooding (Illinois Department of Natural Resources 2015).

3.2.2 Chicago's Grey Stormwater Infrastructure

Grey infrastructure, in contrast to green infrastructure, has been the traditional means for addressing the problems of stormwater induced flooding in Chicago. Chicago has a network of approximately 5000 miles of sewers which collect both stormwater and sanitary sewage (City of Chicago Green Stormwater Infrastructure Strategy 2014). This stormwater and sanitary sewage are sent to the city's wastewater treatment plants where it is treated and discharged. During storm conditions when sewer capacity exceeds the capacity of wastewater treatment plants, water is emptied into tunnels and reservoirs which are commonly referred to as Chicago's "Deep Tunnel" (City of Chicago Green Stormwater Infrastructure Strategy 2014). If capacity is exceeded in the reservoirs, then water is emptied back into the rivers. This is commonly known as a "Combined Sewer Overflow" (CSO). In Chicago as little as 0.67 inches of rain over a period of 24 hours can trigger a CSO. From 2007-2012 CSO events occurred on 314 days, or approximately once a week. CSOs can release significant pollution from the sewers into the city's rivers, raising environmental concerns. If rivers are overflowing due to stormwater, to prevent mass flooding, engineers can reverse the flow of water in the rivers towards Lake Michigan, resulting in sewage and rainwater entering the lake polluting drinking water and beaches. Since 1985 this has occurred a total of 27 times. During heavy rainfall events, when water cannot access the Deep Tunnel and CSO systems, it becomes backed up in sewers, triggering basement flooding. (City of Chicago Green Stormwater Infrastructure Strategy 2014)

Since 1972 the City of Chicago has invested in construction of the Tunnel and Reservoir Plan (TARP) as a means of expanding grey infrastructure for managing greater volumes of stormwater. Phase 1 of TARP was completed in 2006, but phase 2 of TARP is not expected to be completed until 2029. Phase 1 expanded TARP to include over 109 miles of tunnels and 2.3-billion-gallon capacity. Phase 2 is expected to expand TARP capacity to 20 billion gallons. (City of Chicago Green Stormwater Infrastructure Strategy 2014)

TARP operates by redirecting excess stormwater into a series of deep tunnels and reservoirs around the city, preventing CSO incidents by taking on excess capacity that cannot be taken on by the water treatment plants. TARP remains a critical central component to the city's plan for mitigating stormwater overflow flooding, but with the deadline for the complete expansion of TARP still years into the future, and climate change expected to increase severe rainfalls, it is critical the city invests into the construction of auxiliary, green stormwater infrastructure (GSI) for mitigating urban flooding by addressing the root problem of Chicago's urban flooding: the development of impervious surfaces (roofs, roads, sidewalks, non-permeable pavements) over Chicago's wetland ecosystems. (City of Chicago Green Stormwater Infrastructure Strategy 2014)

As well, even after the completion of TARP, basement flooding will remain an issue as it is caused by local rainfall excesses which are unable to reach TARP and CSO systems. This makes the development of GSI an essential component to Chicago's stormwater management plan as GSI can be used to mitigate local rainfall effects and reduce the overall runoff volume entering the sewer system. (City of Chicago Green Stormwater Infrastructure Strategy 2014)

3.2.2 Chicago's Green Stormwater Infrastructure Projects

The goal of Chicago's GSI programs is to develop infrastructure which addresses the root of the problem of stormwater induced flooding through the integration of ecological systems with urban spaces. This is in contrast with grey stormwater infrastructure which focuses more on mitigating the symptoms of flooding through redirecting water flows. The City of Chicago has proposed and promoted GSI projects alongside policies managing the development of green and sustainable infrastructure. GSI programs throughout Chicago include the green roofs program, green alleys program, green streets program, downspout disconnections, and sustainable backyard program. (City of Chicago Green Stormwater Infrastructure Strategy 2014)

The downspout disconnections and sustainable backyard program focus on educating communities on how to establish greener rainwater practices on their own properties, disconnecting downspouts from sewers into rain barrels, rain gardens, or yards and distributing rebates for developing compost bins and planting native flora. (City of Chicago Green Stormwater Infrastructure Strategy 2014)

The green streets program plants trees along major streets to provide shade which mitigates the urban heat island effect. The green roofs program promotes the establishment of green rooftops that absorb rainwater into vegetation, reduce energy expenditure per building by insulating against heat loss, and reduce pollution levels by increasing vegetation in an area. The green alleys program, which is the focus of this paper, promotes the construction of a variety of permeable pavement alleys which allow for stormwater to absorb into the ground and provide a variety of co-benefits such as reduction of urban heat island effect, improving Chicago's worn-down alleys, and establishing potential social spaces. (City of Chicago Green Stormwater Infrastructure Strategy 2014)

Chicago has also implemented several policies, guidelines, and ordinances which encourage sustainable practices and regulate the development of green stormwater infrastructure. The Chicago Stormwater Ordinance provides standards and restrictions on developments and renovations which connect to the sewer system. It mandates that buildings larger than 15,000 square feet and parking lots larger than 7,500 square feet must retain the first half inch of rain during a storm on site. Requirements for this can also be met through reducing impervious land cover which generates runoff. The Chicago Stormwater Ordinance has resulted in a reduction of 3 million square feet of impermeable surfaces in the city since 2008. Chicago's green stormwater guidelines and policies mandate steps that should be taken for a better on-site storm water management in new developments (City of Chicago Green Stormwater Infrastructure Strategy 2014). This could create a structural reason explaining disparities in the effects of urban flooding as older neighborhoods become more likely to experience greater degrees of flooding than newer neighborhoods which build according to updated guidelines.

It is estimated that as of 2014 green roof and green alley infrastructure captures over 85 million gallons of water per year (City of Chicago Green Stormwater Infrastructure Strategy 2014). Further data is needed to fully understand the efficacy of GSI in the Chicago area. Few analyses have been done on the wholistic effects of larger GSI systems on stormwater management and most data regarding the effects of GSI are based on pilot demonstration projects (City of Chicago Green Stormwater Infrastructure Strategy 2014; Illinois Department of Natural Resources 2015). In contrast with the central planning that coordinates the development of grey stormwater infrastructure, GSI is built gradually by decentralized actors, frequently on private property (City of Chicago Green Stormwater Infrastructure Strategy 2014). The full effectiveness of GSI systems depends on the gradual aggregation of a significant GSI presence over a longer time-period (City of Chicago Green Stormwater Infrastructure Strategy 2014). As a result, little research has been done in terms of project evaluation of green stormwater infrastructure in Chicago. Studies in New York City have indicated that green stormwater infrastructure could eventually be used as a long-term cost-saving alternative to traditional grey infrastructure, but similar studies have not been conducted in Chicago to determine if a full transition to green stormwater infrastructure could be accomplished (City of Chicago Green Stormwater Infrastructure Strategy 2014).

3.3 Chicago's Green Alley Program

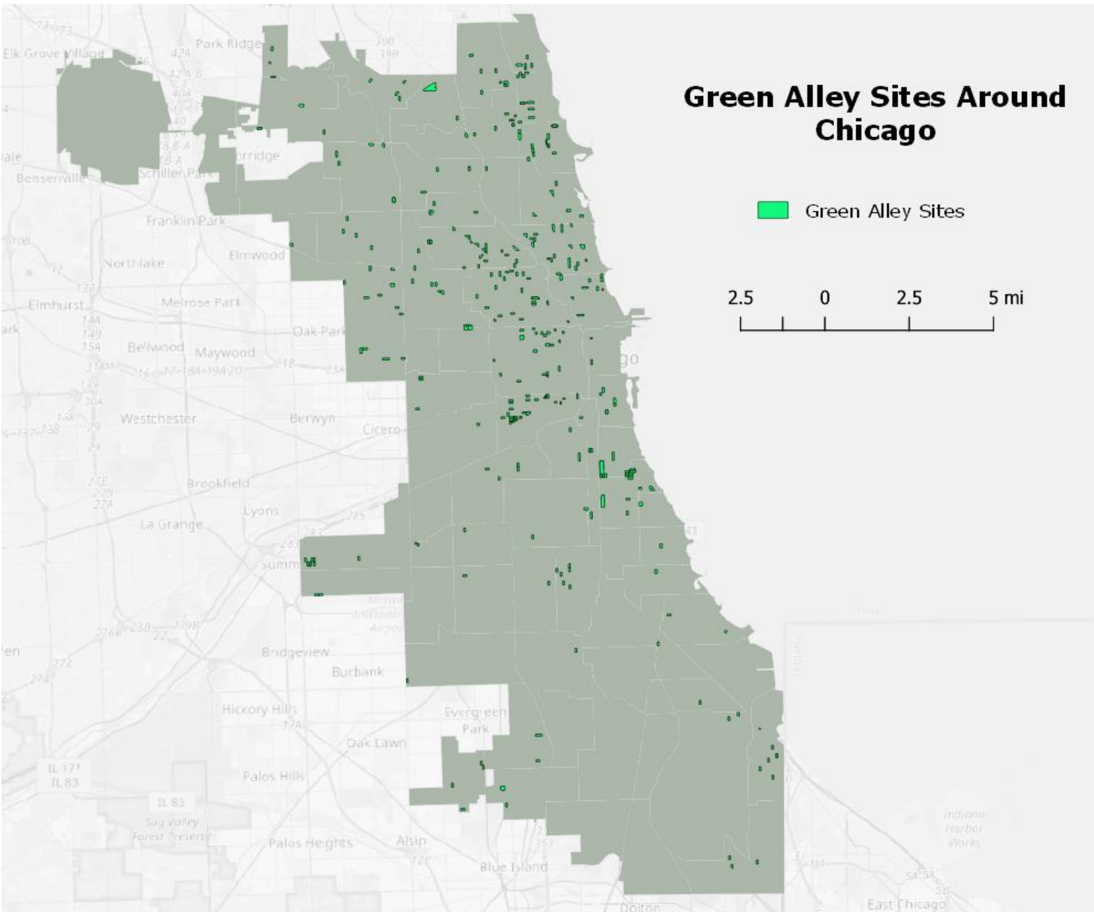

Figure 7 Green alley sites around Chicago.

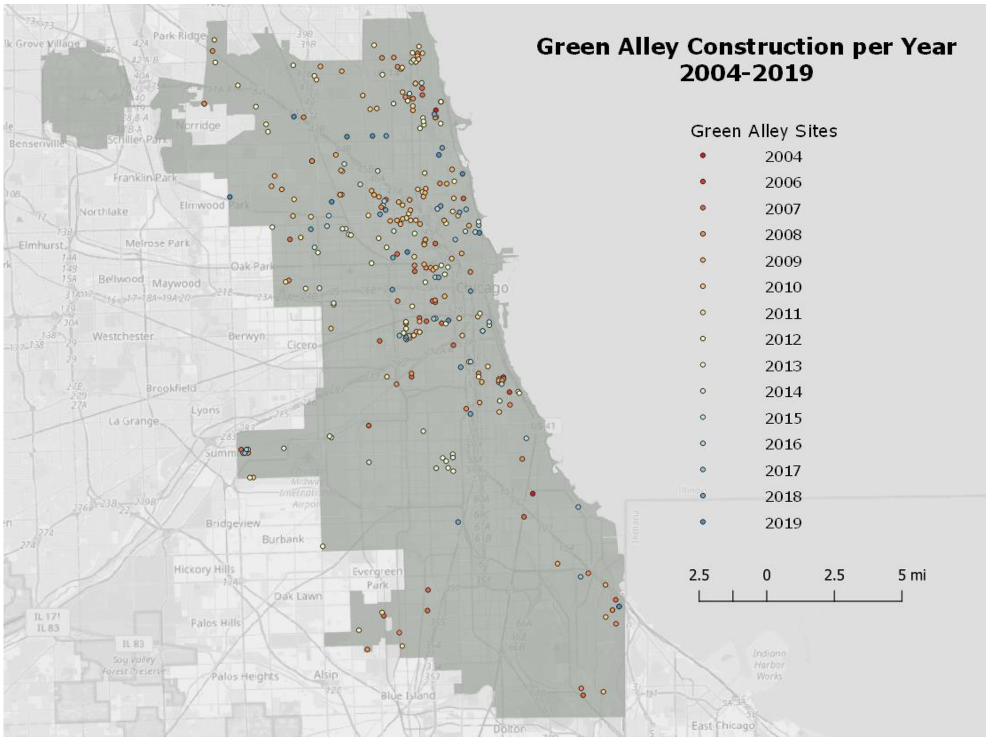

Figure 8 Green alley sites classified by year of development from 2004-2019. The 2004 site was a pilot project for the start of the green alley program in 2006.

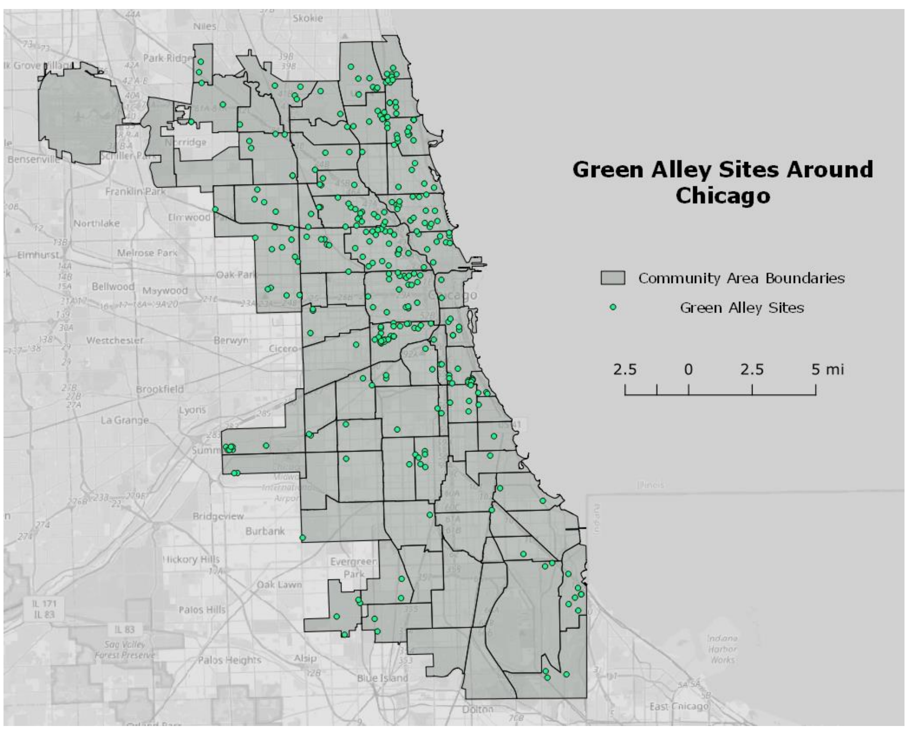

Figure 9 Green alley centroids shown in relation to Chicago's community area boundaries.

The Green Alley Program is central to Chicago's GSI strategy (Newell et al. 2012). In 2006, Chicago became the first city to announce such a program, pioneering the early implementation of green alleyways in the United States (Newell et al. 2012; City of Chicago Green Stormwater Infrastructure Strategy 2014). Green Alleys are alley spaces which include green tech innovations, such as permeable pavements, which divert rainwater runoff away from the Chicago sewer system (City of Chicago Green Stormwater Infrastructure Strategy 2014). Green alleys increase permeable surfaces, which is integral to mitigating urban flood risk as there is an inverse relationship between increased permeable surfaces and flood risk (Keenan, Shankar, and Haas 2019).

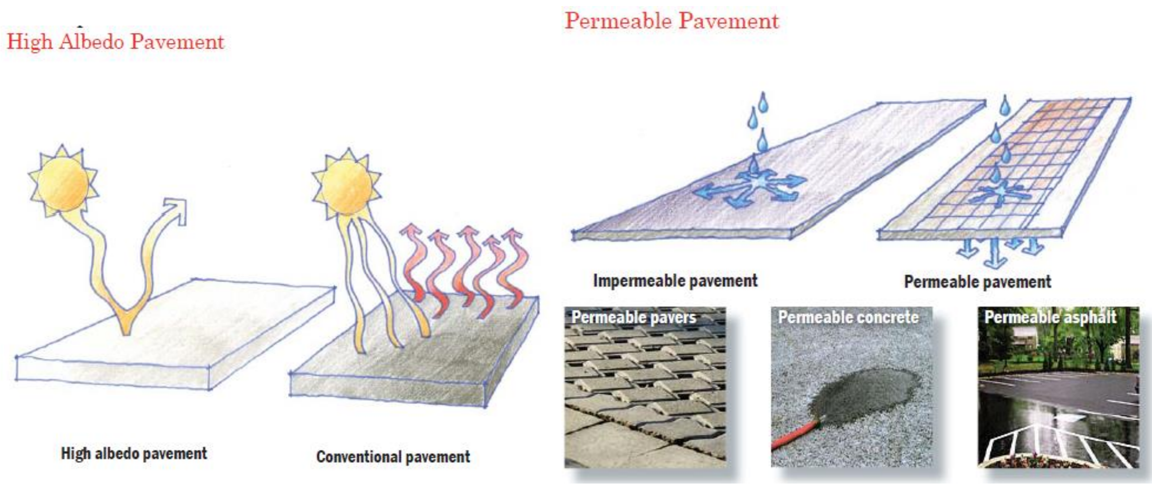

Figure 10 (Left) How high Albedo pavement reflects sunlight and reduces absorbed heat. Source: Chicago's Green Alley Handbook 2010. (Right) Depiction of how permeable pavement functions to percolate water into the ground. Source: Chicago's Green Alley Handbook 2010.

Not all green alleys incorporate permeable pavements. Alleys with French drains and storm sewers are classified in Chicago as green alleys because they redirect water into drainage systems which do not enter the main Chicago sewer system (Chicago Green Alley Handbook 2010). French drains are perforated drains situated beneath gravel instead of permeable pavement (City of Chicago Green Stormwater Infrastructure Strategy 2014). Storm sewers are separate sewer systems which direct rainwater into local bodies of water without mixing with sanitary sewer systems. Both French drains and storm sewers redirect rainwater runoff back into the ground or into nearby bodies of water without mixing with sanitation waste (City of Chicago Green Stormwater Infrastructure Strategy 2014).

Green alleys which use permeable pavements incorporate multiple techniques for redirecting stormwater runoff. One technique is to incorporate high-infiltration soil layers underneath permeable pavement which allows rainwater to percolate into the ground (Chicago Green Alley Handbook 2010; City of Chicago Green Stormwater Infrastructure Strategy 2014). Another technique is to have green alleys serve as rainwater detention spaces. During storms rainwater percolates underneath the alley and later evaporates after the storm has passed (City of Chicago Green Stormwater Infrastructure Strategy 2014). Finally, some green alleys incorporate French drain or other drainage systems underneath which then redirect rainwater runoff away from the main Chicago sewer system. It is estimated that as of 2014, Chicago's combined green alley infrastructure captures 17 million gallons of storm water per year (City of Chicago Green Stormwater Infrastructure Strategy 2014).

Green alleys incorporate several green tech innovations not directly related to mitigating stormwater runoff (Chicago Green Alley Handbook 2010; Center for Neighborhood Technologies 2020). Several incorporate recycled, slag-based concretes in their paving (Chicago Green Alley Handbook 2010). This reduces emissions waste during concrete production and saves energy by reducing total concrete usage (Chicago Green Alley Handbook 2010). Green alleys can also incorporate high albedo surfaces which are lighter and more reflective than traditional pavements, minimizing heat absorption which causes urban heat island effect (Chicago Green Alley Handbook 2010). The urban heat island effect occurs when extensive pavements absorb more heat from the sun than natural ground cover, resulting in a raised overall temperature for an area and exacerbating the effects of climate change (Center for Neighborhood Technologies 2020). It is estimated that incorporating high reflect surfaces can reduce peak temperatures by 2-9° F (Center for Neighborhood Technologies 2020). Some green alleys may also include adjacent vegetation which provides green space for communities and as well helps to clean air pollution (Chicago Green Alley Handbook 2010; Center for Neighborhood Technologies 2020).

Permeable pavements are generally used on surfaces which are subject to low-speed, low-impact vehicle usage, which has made its implementation optimal for alley settings instead of busier streets (City of Chicago Green Stormwater Infrastructure Strategy 2014). However, innovations in technology are expanding the possibilities for permeable pavement usage around the city. As of 2014 the city has developed plans to expand permeable pavement usage which has been used in green alleys to parts of Chicago’s streets as well (City of Chicago Green Stormwater Infrastructure Strategy 2014).

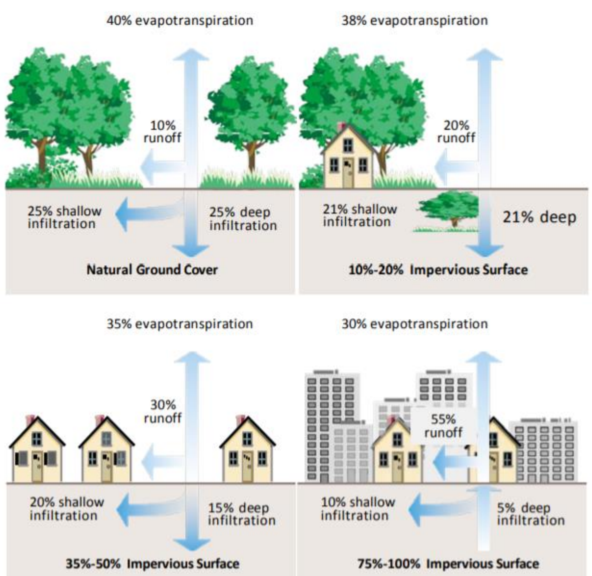

Figure 11 The effects of impervious surfaces on total runoff. Source: Illinois Department of Natural Resources 2015

Green alleys exist as part of a larger system of green infrastructure, shifting urban development practices to encourage sustainability. They accomplish this shift through promoting several goals across the intersection of the three E's (Newell et al. 2012). Green alleys benefit local economies by redirecting stormwater runoff into the ground, in turn preventing basement flooding which creates significant costs for residents and businesses. By redirecting stormwater runoff green alleys improve regional ecology, reducing the likelihood of CSO events which can pollute surrounding ecosystems (Newell et al. 2012; City of Chicago Green Stormwater Infrastructure Strategy 2014). Depending on the incorporation of specific technologies, green alleys offer several social and ecological co-benefits. Technologies such as high albedo pavement reflect greater amounts of sunlight, reducing the urban heat island effect which threatens urban ecology and disproportionately affects lower income neighborhoods, exacerbating existing inequities in urban systems (Center for Neighborhood Technologies 2020; Chicago Green Alley Handbook 2010; Anderson and McMinn 2019). As well, the implementation of green alleys replaces older, more worn-down alley infrastructure, creating spaces for easier transportation as well as social space for community congregation (City of Chicago Green Stormwater Infrastructure Strategy 2014).

3.4 Infrastructural Disparities Across Chicago

Proponents of sustainable urbanism and green infrastructure tend to emphasize the overlap between the goals of sustainability plans and social justice movements which both advocate for programs which advance general equity (Campbell 2013). Researchers such as Scott Campbell argue that the convergence of the goals of sustainability and social justice might not be inherent to sustainability planning and green infrastructure (Campbell 2013). Campbell argues that social justice must be advocated throughout the sustainability process to avoid exacerbating and entrenching existing inequity (Campbell 2013). This is especially critical when it comes to green infrastructure development (Keenan, Shankar, and Haas 2019). Campbell notes that middle class environmental interests tend to overrule the environmental interests of the poor and marginalized, often leading to exclusionary sustainability which perpetuates existing structural inequity (Campbell 2013; Finewood 2019). Sustainability and social justice must be further negotiated so that sustainable development projects do not perpetuate existing structural inequalities. Project evaluations can be used as a means of managing the risks and identifying flaws in a project's negotiation between sustainability and social justice (Campbell 2013).

In Chicago especially there is a long history of targeted disinvestment and redlining in communities on the South and West sides of the city. This has resulted in significant segregation throughout the city between income levels and ethnicities (Liu 2021). This segregation has further manifested in structural issues with regards to infrastructure throughout the city which in turn has perpetuated instances of environmental injustice (Bullard 2001; Liu 2021; Finewood 2019). Environmental injustice can be seen clearly through variations in pollution levels throughout cities across the country, as lower-income communities of color tended to be in closer proximity to industrial plants and toxic waste (Bullard 2001).

A report by the Center for Neighborhood Technology recommends that urban flooding specifically should be viewed as an environmental justice issue, and that stormwater infrastructure should be developed in partnerships with community organizations to best address existing disparities in the effects of flooding. This report showed a correlation in higher rates of flood damage claims and lower income communities (Keenan, Shankar, and Haas 2019). The communities most at risk for urban flooding tend to be lower-income communities of color

(Song and Briscoe 2020; Joyce 2019). These communities occur primarily across the south and west side of Chicago, which would make a negative spatial correlation between green alleys and the south and west side particularly notable, as permeable surfaces can mitigate flood risk (Keenan, Shankar, and Haas 2019). These communities also frequently have no FEMA mandated flood insurance and are thus subject to greater damage due to urban flooding (Song and Briscoe 2020).

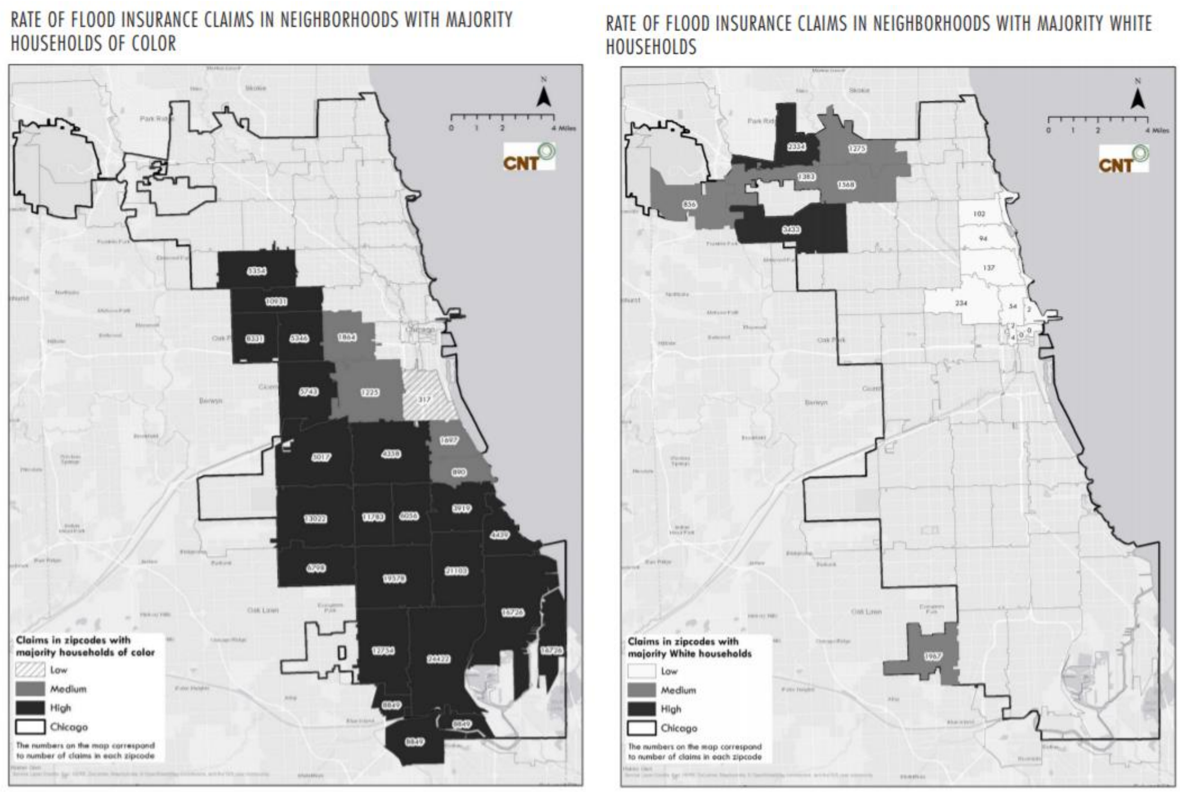

Figure 12 (Left) Depicts rates of flood damage claims in majority communities of color. In comparison with rates of flood damage claims in majority white neighborhoods (Right). Source: Center for Neighborhood Technology (Keenan, Shankar, and Haas 2019)

One reason for these disparities might be aging buildings and poorly maintained sewer infrastructure (Keenan, Shankar, and Haas 2019). Another reason might be that neighborhoods that increase their property values and in turn attract higher-income communities may also tend to be newer and include more updated stormwater infrastructure innovations mandated by city policy in 2008 (City of Chicago Green Stormwater Infrastructure Strategy 2014). Older neighborhoods might be more at risk due to already aging infrastructure and the relationship between property value, flood risk, and income level needs to be further explored (Song and Briscoe 2020; City of Chicago Green Stormwater Infrastructure Strategy 2014).

Understanding the structural factors which perpetuate infrastructure disparities throughout the city is critical to maintaining and promoting equity in sustainability planning and avoiding perpetuation of injustice. Green stormwater infrastructure, due its relationship with sustainability, can serve as a catalyst for broader consideration of environmental justice in mitigating urban flood risk (Keenan, Shankar, and Haas 2019).

4. Methodology

Studies have been planned by the city to evaluate the full costs and benefits of green stormwater infrastructure in comparison to alternative innovations in sustainability (such as a reduction in impervious surfaces), but no research has yet been released to the public (City of Chicago Green Stormwater Infrastructure Strategy 2014). The goal of this thesis is to begin the process of assessing the spatial distribution of Chicago's green alleys. Several methods of spatial analysis were performed on a map obtained from the Chicago Department of Transportation (CDOT), via the Freedom of Information Act, specifying the locations and sizes of green alley sites across the city. The size of green alleys was given via a polygon shapefile which defined the area of a green alley by the size of the city blocks around a green alley. In this study the area of blocks which includes a green alley is defined as the green blocks area. The block size operated as a proxy measurement for defining green alley area across the city because green alleys are built across the city by city blocks due to the inherent structural relationship between blocks and alleys (Martin 2020). Alleys developed as strategic assets in early urban planning by helping to organize urban space by blocks (Martin 2020). As a result, blocks inherently include proportionately sized alley space as right of way transit and for waste disposal (Martin 2020). If green blocks area was larger than another it offered a larger green alley space and thus comparative block area had a proportionate ratio to comparative alley area.

Figure 13 Satellite imagery of green alley site (source: Google Maps).

Figure 14. Visualization of Alleys in Block of Green Alley Polygon used to calculate Green Alley area. Note larger blocks of space contain greater alleys, indicating approximately proportionate ratio of alley space to block space.

This research aims to characterize the spatial distribution of green alleys throughout the city by density, identifying clusters of green alleys, and determining any spatial autocorrelation of green alley sites. The density of green alley spatial distribution is then further contextualized by comparing the density of green alleys across community areas with the distribution of other climatic, environmental, and demographic variables across the city. Namely, this paper compares the distribution of green alleys with the variation in precipitation across the city, variation in per capita income across the city, and variations in impervious surface coverage, water coverage, and green space/ vegetation coverage throughout the city. Data sets for per capita income, precipitation levels, coarse particle pollution, grey index, green index, blue index, road index, and vegetation index were all obtained from the Chicago Health Atlas.

4.1 Density

Spatial analysis was done using QGIS, GeoDa, and Microsoft Excel. Analysis of the density of green alleys was done via two methods. The first was through the creation of a green alley score for comparing densities between community areas. The second was a kernel density estimate (KDE) using QGIS' Kernel Density Heatmap plug in. The unit of the community area was chosen for the scale of analysis because of the ease of comparison with multiple public data sources. Most data obtained from the Chicago Data Portal and Chicago Health Atlas was done at the scale of the community area. The community area is also a significant sociopolitical unit in Chicago. Historically, community areas have developed their own cultural attributes and distinct neighborhood characters and are involved with city government and planning.

The green alley score was devised for two reasons. The estimates for relative densities of community areas would need to be compared with other variables, which requires a common spatial unit for comparison. The second reason is because the green alley score corrects for flaws in the Kernel Density Estimate with regards to available space for green alleys. KDE is a non-parametric way of modeling the probability of a variable appearing in a specific space based on the current locations of that variable. KDE gives weight to the distance between variables in space and then interpolates probable density of locations across continuous space. Where there are more alley sites in closer proximity to one another there will be greater density. The KDE estimates density entirely based on spatial metrics of proximity and concentration. This can be problematic when assessing the density of green alleys because not all available space can be turned into green alley space. KDE was still done for this study so that a visual analysis of density at a scale smaller than the community area could be started, and to compare and confirm the density patterns depicted by the green alley score maps.

4.1.1 Devising the Green Alley Score

Some city blocks inherently cannot have green alleys built upon them. Blocks primarily zoned for conservation space, wetland space, waterways, rail, and highways cannot develop green alleys. As a result of technical restrictions on green alley development, blocks which are zoned to include underground utilities or near facilities which could put permeable pavement in contact with chemical toxins cannot develop green alleys. Green alleys with permeable pavement are also best situated on spaces which interact with low-impact, low-speed traffic, and thus could not be placed on highways or transportation centers for larger vehicles.

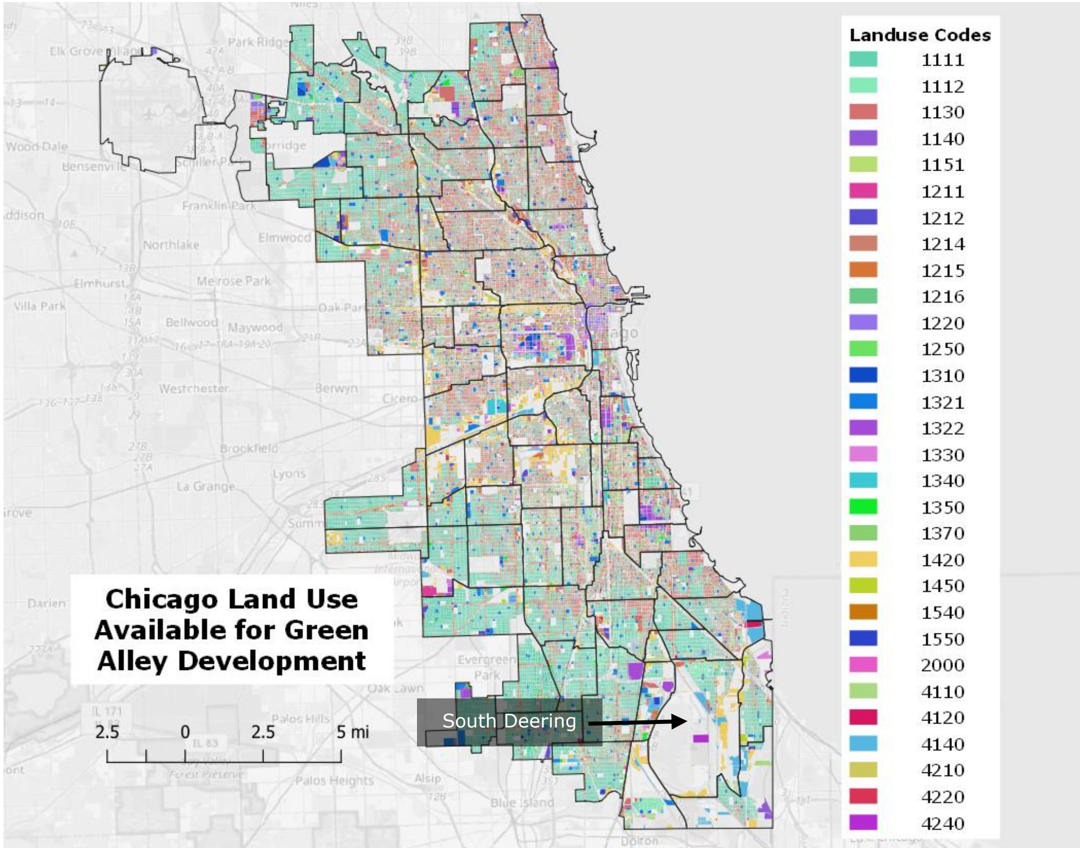

Figure 15 The total area per community area available for alley space. Block spaced zoned for land use which cannot include green alleys was deleted from this map. Note the noticeable disparity in available space between neighborhoods such as South Deering versus the space within its community area boundaries..

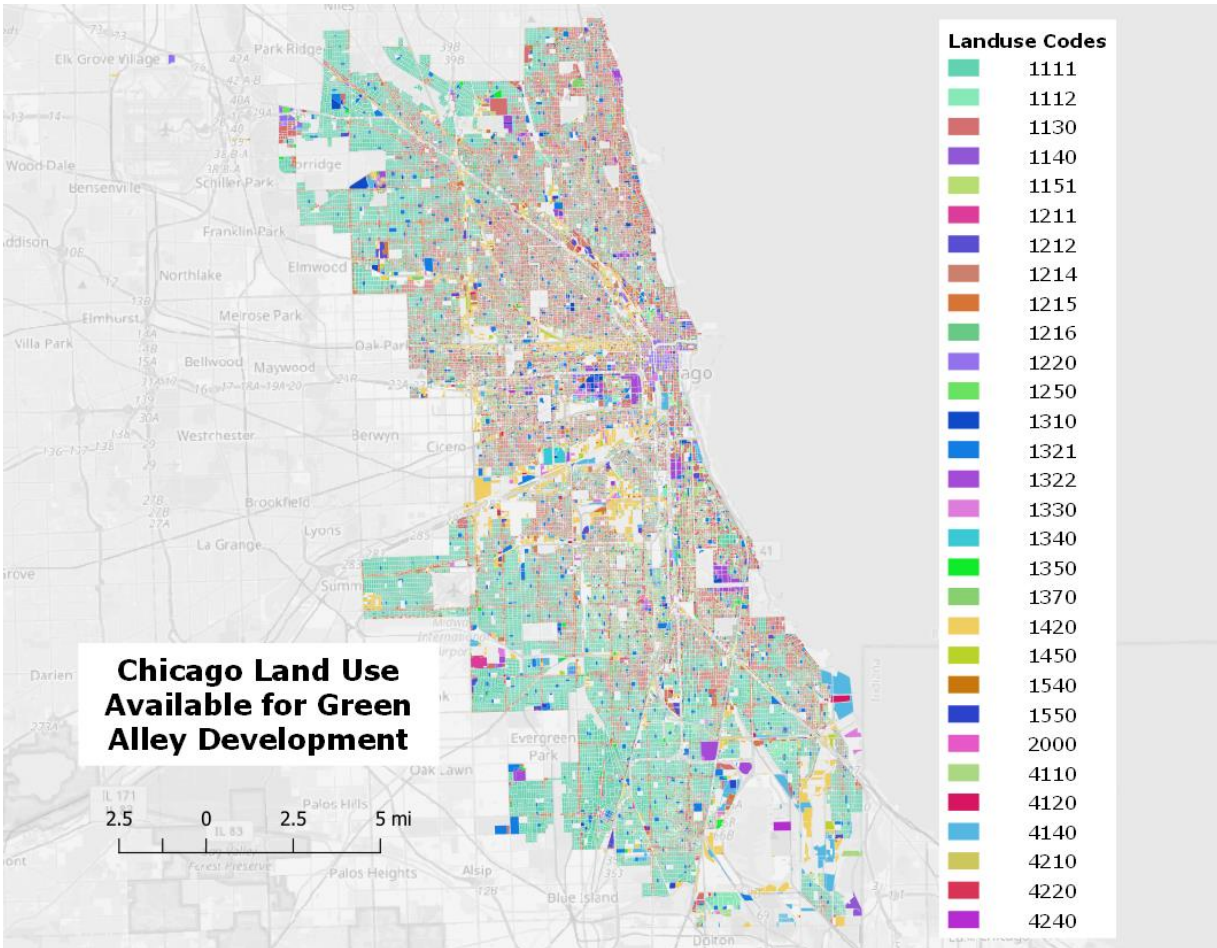

Figure 16 The entire city if zoning unable to host green alley sites were taken out.

These restrictions mean that there is varying space available between neighborhoods for the development of green alleys. It would be inaccurate then to suggest that there is higher green alley density in a neighborhood that is entirely residential in comparison to one that is primarily conservation space or waterways (ie: South Deering), because the neighborhood with more highway space, conservation space, or rail space would have significantly less area available for developing green alleys. Highway space, railways, and vegetative space would all serve as confounding explanatory variables for the lack of green alleys that would not necessarily indicate variability in green alley spatial density between community areas.

To control for confounding variables the Green Alley Score (GAS) was devised to account for zoning codes which could not host green alley space. GAS is a ratio measuring the percentage of available space in a community area covered by green alleys. It is defined as the sum of estimated green block area within a community area, divided by the estimated total available block area in a community zoned such that it could potentially include green alleys. The GAS value would reflect a measure of green alley density which accounts for disparities in available surfaces throughout neighborhoods. It should be noted that the GAS score is a rough estimate that is still functionally useful for making comparisons of the degree of green alley concentration and density across the city of Chicago.

$$GAS = \frac{\sum_{i=1}^{n} A_{block,i}}{\sum_{i=1}^{k} A_{block,i}}$$

Figure 17 Equation for the Green Alley Score where A is the area of a block, n is the last block in a community area including a green alley in a set of green blocks 1 to n, and k is the last block able to host a green alley in a community area, including the set of blocks 1 to n and including additional available blocks n to k.

The total green block area was obtained from CDOT data. This block area is not actually equivalent to the total area of green alleys in a community because certain blocks frequently have variable alley area, but because the goal of this spatial analysis was comparison of density across the city, and alley repair is done on a block by block basis, only the comparative ratio of green blocks per neighborhood mattered. Larger block sizes would result in larger community areas which would in turn mitigate the variation in ratios between green alley density due to error in alley area measurements.

An example of how only block area could still be used as a functional measurement of green alley density is demonstrated by the scenario in which two blocks have equivalent alley space, but varying block space. If both blocks had green alleys then both of their green alley densities would appear at 100%, which would be verified by the GAS as the block area would be divided by itself. Although there is error when the green alley coverage is less than complete, this study assumed that variance between green alley area for equivalent block size was negligible because of the sample size of green alley sites and total alley sites being compared across the city, and because block size and alley development was standardized within the city of Chicago in 1830 to approximately 660’ x 330’ (Street and Site Plan Design Standards 2007). As well, alternative density measurements (such as KDE and density clustering) when coupled with the rough GAS estimate could be used to validate density comparisons where the margin of error was suspect.

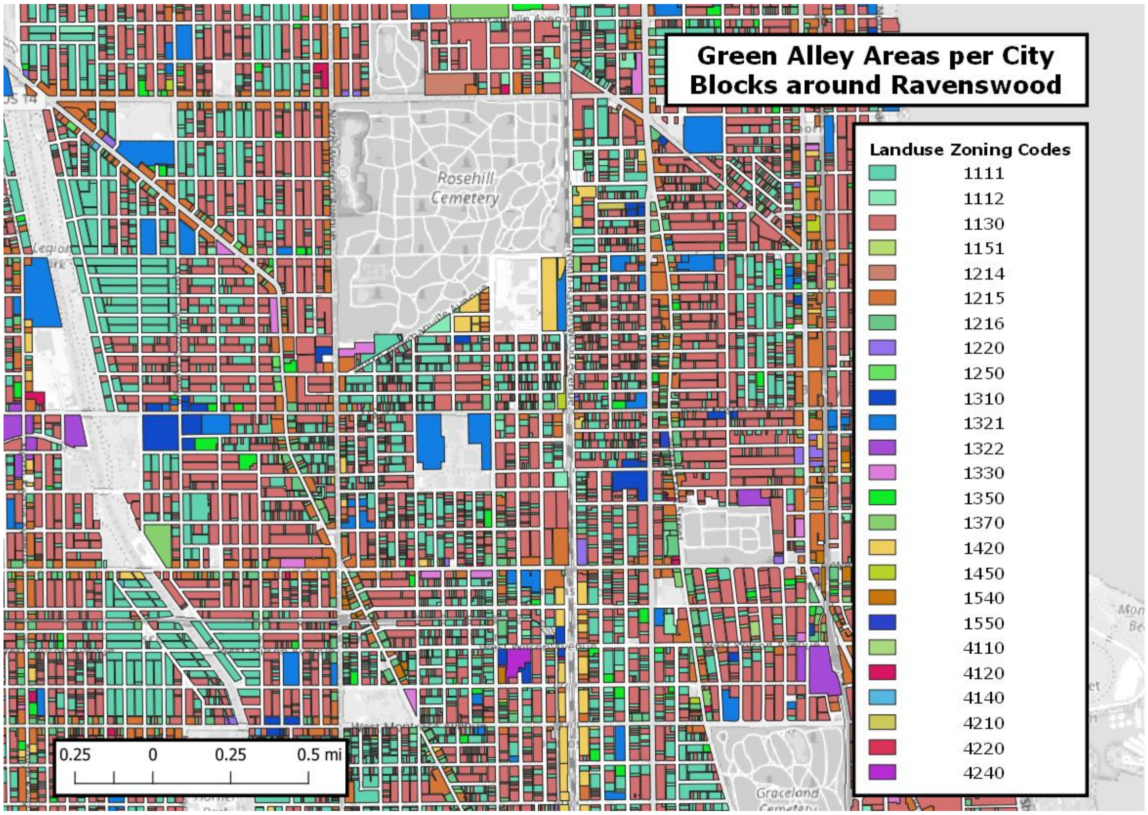

Figure 18 Close up view of land parcels included in total area. Note how larger block parcels include proportionally larger alley space across the length of the parcel.

The total available area in a community area zoned to potentially host green alleys was calculated through taking a sum of all space in a community area which could potentially host a green alley. This was done by using the Chicago Metropolitan Agency for Planning's (CMAP) map of Chicago divided by land use codes. An analysis of the intersection of the green alley polygon shapefile and the land use map revealed a list of land use codes which could potentially host green alleys. Further assumptions were made regarding the restrictions of green alley placement to determine a list of land use codes which could not host green alley space. When a land use code was determined to be unable to host a green alley it was deleted from the land use map. The remaining spaces were then summed per community area to determine a total available community area space value. Codes for green space and water space were deleted as well as codes identifying the location of underground utilities. Several other codes dealing with roads and rail transportation were deleted as well as codes which specified the locations of cemeteries, park land, landfills, and water treatment facilities. A full list of land use codes, their significance, and their reason for inclusion and exclusion can be found in the appendix of this paper.

Zoning for small scale industrial spaces (industrial spaces under 100,000 square feet) were kept as potential spaces for green alley development, but larger industrial spaces were not. This was ultimately decided because land use on the west side included several green alley sites around small-scale industrial spaces, but none around larger industrial spaces. It was assumed that larger industrial spaces presented several potential hazards (toxic waste, pollution, high-impact vehicles) which would disincentivize (or make impossible) green alley development. Land zoned as vacant space set aside for industrial usage was also deleted from the map for similar reasons, as the spaces were all significantly larger than 100,000 square feet.

There was uncertainty over the exclusion of certain land use codes which included both area that could not be turned into green alley space and area which could be turned into green alley space, such as the land use code 6000 and the larger scale industrial land use. To resolve this debate four GAS scores which included different land use zoning were calculated. These scores are referred to as Green Alley Score 0 (GAS 0), Green Alley Score 1 (GAS 1), Green Alley Score 2 (GAS 2), and Green Alley Score 3 (GAS 3). GAS 0 assessed the maximum extent of available community area space by continuing to include land use coded 6000 and land use coded for large scale industrial space. GAS 1 eliminated land use coded 6000 but continued to use land use coded for large scale industrial space. GAS 2 eliminated land use coded 6000 and land use coded for large scale industrial space. GAS 3 eliminated 6000 zoning codes, large scale industrial zoning codes, and codes zoned for cultural spaces (such as Soldier Field and Cellular

Field). These scores were averaged to determine an average GAS (the average Green Alley Score), and the range of plausible GAS scores was used to assess the spread of possible GAS values and identify community areas in need for further assessment. Comparisons between the choropleth maps of the different GAS scores indicated the maximum and minimum possible GAS for community areas. Each GAS score was evaluated during correlation tests to note any differences between community areas depending on the inclusion of certain land use codes during GAS calculation. This allowed for better comparison between community areas with close GAS values and identified areas which would require further research for more detailed spatial analyses.

Community areas which contained no green alley space had their summed green alley area values each adjusted by 10,000 square feet when calculating GAS. 10,000 square feet was a value 10 orders of magnitude less than the smallest green alley resulting in a noticeably smaller GAS value that was still large enough to allow GAS comparison between community areas which lacked green alleys. This controlled for variations in community area size between community areas without green alleys, indicating a greater green alley deficit for larger community areas. If summed green alley area was left equal to zero for empty community areas, these comparisons would not have been apparent as all empty community areas would have GAS values equal to zero.

After determining the GAS of each neighborhood, choropleth maps of Chicago's community areas were created. The first separated GAS scores by quantile into 10 equivalent bins of community areas. The second separated GAS scores into 10 bins using Jenks natural breaks optimization. Each map emphasized a different aspect of the data visually, which will be discussed further in the results and discussion section.

4.1.2 Kernel Density Esimation

A Kernel Density Estimate (KDE) was used to assess density at a scale smaller than the community area and confirm the spatial density of green alleys depicted in the GAS maps. KDE is a non-parametric method of determining the spatial density of a phenomenon. KDE determines density by evaluating the probability of a random spot being a phenomena site based on the current spatial distribution. The probability estimate is made to reflect the decay of likelihood of a location further from one of the known sites and emphasizes that having multiple sites in proximity increases the probability of a potential site nearby. To perform KDE this paper took the centroids of each green alley polygon and weighted those points by the green alley site area.

Three KDE maps were developed for this thesis. Each map used a quartic kernel shape at varying radii. The first map used a radii of 1000 meters. The second map used a radii of 2000 meters. The third map used a radii of 3000 meters. Each estimate was weighted by the area of a particular green alley site to reflect differences in permeable pavement coverage across a space.

4.2 Correlation

4.2.1 Spatial Weights

Spatial weights quantify the spatial relationship between two shapes/points on a map based on the distance between them and their adjacency (Anselin 2014). Spatial weights were set for the green alley site map via distance weighting using a non-parametric uniform kernel function shape. The coordinates for the distance weighting were set at the centroids of the green alley spaces, and the distance between two points was determined via Euclidean distance. For the GAS choropleth map the weights were set using contiguity weights using queen contiguity.

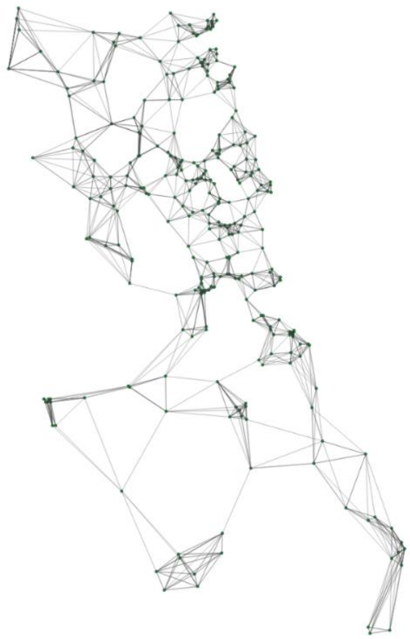

Figure 19. Kernel distance spatial weighting for green alley sites across Chicago

4.2.2 Clustering and Autocorrelation

Analysis of autocorrelation and clustering was done using GeoDa. It is important to note the distinction between green alley site clustering and green alley score distribution clustering (GAS distribution clustering), as the two phrases are similar but refer to different measurements. Green alley site clustering refers to the density clustering of the centroid points of green alley spaces. GAS distribution clustering refers to the statistically significant clustering of community areas with close GAS scores.

Autocorrelation was assessed by determining the Global and Local Univariate Moran's I. The Local Moran's I was also used to determine potential clustering and autocorrelation by year for green alley areas. The Moran's I is a common method for determining autocorrelation which involves comparing the distribution of a set of values across space to a null value of spatial randomness (Anselin 1995). The global Moran's I determines a statistical measure of correlation for the entire distribution set via the Moran's I scatterplot (Anselin 1996). The scatterplot produces the Moran's I statistic to describe the spatial correlation of a distribution of values by comparing the spatial lag between similar values (Anselin 1996). The Moran's I statistic is between 0 and 1, with values closer to one indicating greater degrees of correlation (Anselin 1996). Values greater than .7 indicate statistically significant correlation between the distribution (Anselin 1996). The local Moran's I assesses the correlation of individual spaces' values with their adjacent spaces, describing statistically significant clustering patterns (Anselin 1995).

Clustering for the distribution of green alley spaces overall was determined using GeoDa's DBScan* density clustering tests. DBScan* uses similar inputs to the Kernel Density Estimation (Anselin 2020). DBScan* connects a core green alley centroid with other adjacent centroids (Anselin 2020). If the number of connections to the core centroid exceeds a specified minimum this centroid becomes part of a cluster (Anselin 2020). All centroids in a cluster must meet the minimum number threshold, functioning as their own core centroids (Anselin 2020). Centroids which do not reach the minimum connection threshold are considered noise (Anselin 2020). The number of clusters can be adjusted by adjusting the distance threshold, which adjusts the number of centroids considered adjacent (Anselin 2020). Clusters can be joined under DBScan* if centroids within one cluster meet the minimum cluster threshold by connecting to centroids in a separate core's clusters (Anselin 2020). Analyses of green alley site clustering were measured using minimum point connection requirements of 5 and 7. Each of these minimum point requirements was analyzed at radii of .1 and .2 epsilon distance, totaling four separate clustering results.

DBScan* was chosen over alternative density clustering measurements such as DBScan and HDBScan because of the flexibility offered in choosing the epsilon distance value to compare varying scales of clustering and because DBScan* does not include border centroids (Anselin 2020). Border centroids are centroids connected to core centroids, but which do not form cores of their own (Anselin 2020).

4.2.3 Comparative Correlation

A global and local bivariate Moran's I was used to analyze comparisons between green alley distribution and other variables around the city. All variables were correlated against the average Green Alley Score. All variable data was obtained from the Chicago Data Portal and Chicago Health Atlas. All variable data was collected for the scale of the community area and thus could be joined to the community area map of Chicago to create a choropleth map depicting the spatial distribution of a variable. Variables were chosen for their specific contextualization offered in terms of environmental and socioeconomic indicators throughout the city.

Certain variables were based on statistics devised by the city to measure indicators such as vegetation coverage per community area and developed surface coverage per community area. These variables are referred to as the grey index, green index, vegetation index, blue index, and road index. The grey index is the total measurement of developed land area as a percentage of total community area space. The green index is the measurement of total vegetation land cover (as defined by the National Land Cover Database) as a percentage of total community area space. The vegetation index is like the green index but evaluates "greenness" via satellite imagery as total numbers of green pixels as a percentage of the total community area averaged over discrete units of time. The blue index is the measurement of total open water coverage (as determined by assessing blue pixels in satellite imagery) in a community area as a percentage of total community area space. Finally, the road length index assesses an estimate of traffic emissions per community area by evaluating the density of roads over an area. (Chicago Data Portal 2020)

The remaining variables assessed were average precipitation levels per community area, average per capita income per community area, and coarse pollution levels per community area. These were assessed to further contextualize the spatial distribution of green alleys throughout the city in relation to socioeconomic and environmental indicators.

To determine the spatial correlation between these variables and the GAS values this study used a local and global bivariate moran's I. The bivariate moran's I applies the principles of the univariate moran's I to two variables, standardizing two sets of variables and assessing the spatial lag between approximately equivalent variables in each set (Anselin 2019). The global bivariate Moran's I statistic indicates the degree of correlation between the entirety of both data sets, comparing their relationship to a null hypothesis of random values across space (Anselin 2019). Even in instances of no global correlation, the local Moran's I can still provide insights into relationships between two variables across space (Anselin 2020). The significance of clustering using the local moran's I is subjective and based on an assessment of variables (Anselin 2020). For this paper, instances of local clustering were compared to larger patterns of GAS distribution and the larger distribution patterns of specific variables to determine if clustering reflected significant spatial patterns.

5. Discussion and Results

5.1 Density Assessment

A combination of density and clustering measurements revealed several common patterns which defined the distribution of green alleys across the city. The core of the city, consisting of near west side, near north side, and near south side community areas (from Lincoln Park down to Grand Boulevard and out west to Near West Side) had a higher green alley density than the northwest, southwest, and far south side. Green Alley Score (GAS) distribution maps revealed community areas in this core region had larger green alley site clustering and higher Kernel Density Estimates (KDE) than community areas outside of the core region, except for the far northeast side which had similar green alley site clustering and KDE values.

When controlling for unavailable space in community areas, GAS values revealed comparisons not made visible in clustering and KDE maps, such as distinctions between community areas within the core of the city and comparisons between neighborhoods with low green alley density. GAS values also revealed a higher green alley density in East Side and Hegewisch than was depicted on KDE maps. GAS distribution revealed East Side and Hegewisch had green alley density comparable to community areas on the northwest side of the city, greater than adjacent community areas across the south side which had few to no green alleys. GAS distribution also revealed that South Deering, which appears to have low green alley density on KDE maps is not as low density as neighboring community areas on the south side, such as Roseland and Pullman, due to large percentages of unavailable space.

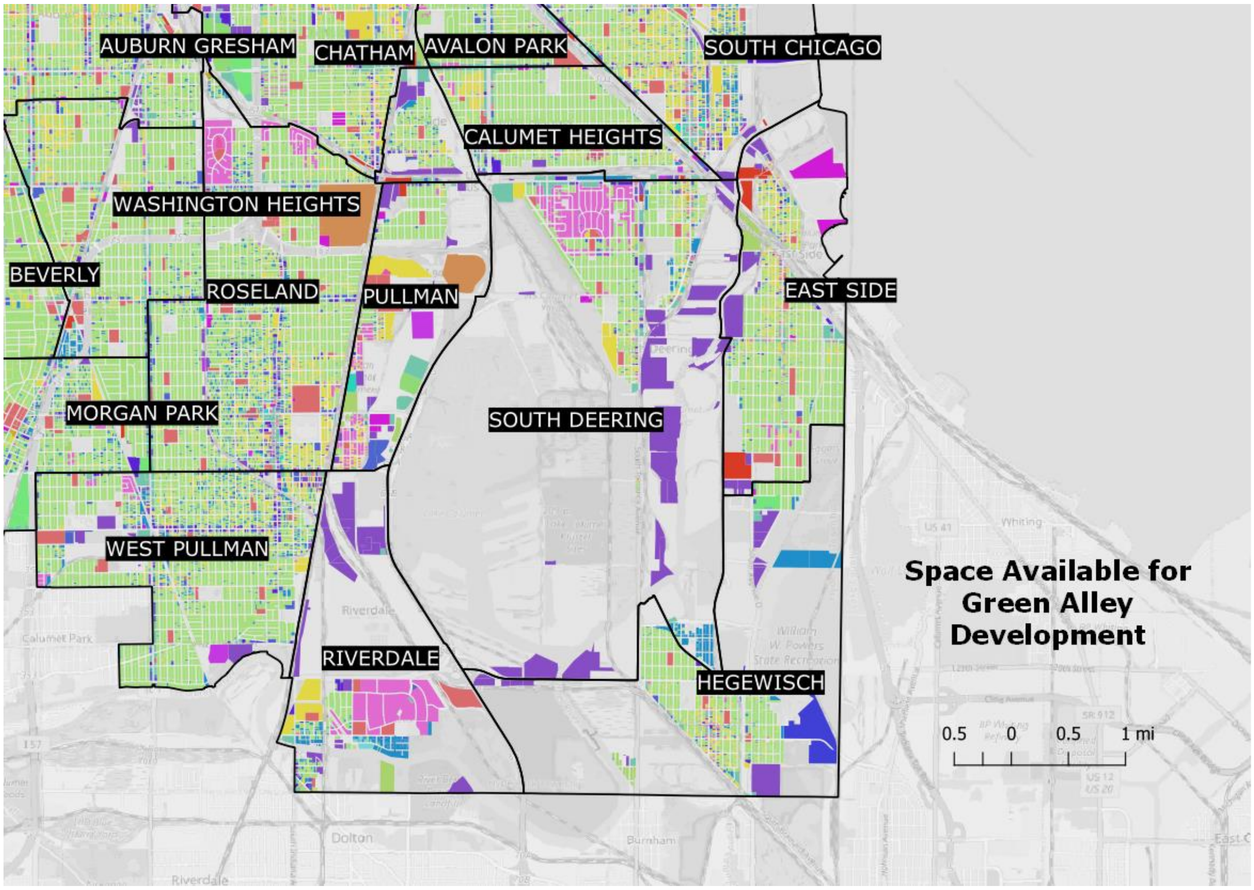

Figure 20 Map of available land (bright colors) in South Deering and adjacent neighborhoods, which can have green alleys developed. Note the size of South Deering as a community area in comparison to the available land which can host a green alley.

GAS values also confirmed that when controlling for unavailable space in community areas the disparity in green alley density between the north and south side was still apparent. GAS distribution on the north side of Chicago included most of the community areas in the top 50% of green alley scores. There was a statistically significant cluster of low-density community areas across the southside around South Deering, Pullman, Roseland, and Chatham. This low-density clustering included several community areas with a p value less than .01 indicating statistically significant correlation between the central far southside of Chicago and a lack of green alleys. GAS distribution clustering also indicated statistically significant correlation of high green alley density with near south loop neighborhoods.

Every analysis produced maps which indicated a statistically significant clustering of green alleys around near south loop neighborhoods. The community area of Oakland had a significantly denser green alley presence than all other neighborhoods on Green Alley Score (GAS) distribution maps, GAS clustering maps, green alley site clustering maps, and Kernel Density Estimate (KDE) maps. Its GAS value was in the 99^{th} percentile of all GAS values. This is most likely due to the statistically significant clustering of larger alleys within Oakland as indicated by green alley site clustering maps using DBScan* and higher density depicted on KDE maps. The fact that Oakland had a higher GAS than all other community areas is also likely due to its size, as GAS values were determined by dividing alley space by available community area space. A large percentage of Oakland's area is predominantly lakefront which cannot be turned into green alley space. As an already small area, this leaves Oakland likely to have a comparatively higher alley score as it would take less green alley space to cover the entirety of Oakland than other community areas.

Another important aspect of the green alley density across the north side is the decrease in green alley density on the northwest side in comparison to the northeast side. Although there is no statistically significant correlation of GAS distribution, the KDE map and GAS distribution map both show a decrease in green alley density on the northwest side in comparison to the northeast side, which has comparable density to the urban core. Figures 33-36 show clustering patterns along the northeast side of the city that do not appear on the northwest side. Figure 27 shows more community areas on the northwest are in the bottom 50% of GAS scores than on the northeast side (five community areas in comparison to two).

As permeable surface presence is inversely correlated with urban flooding, and a comparative deficit in green alleys would indicate significantly less flood risk mitigation across the periphery in comparison to the urban core. As the south and west side of Chicago are majority neighborhoods of color, this disparity in green alley infrastructure, could indicate a racial and ethnic disparity in green alley benefits. This disparity could have broader implications for health disparities across the city and raises environmental justice concerns, begging the question of sustainability for who?

As well, disparities in green alley development between the urban core and urban periphery could have implications for the overall effectiveness of the green alley program at mitigating urban flood risks. The periphery experiences higher rates of urban flooding as indicated by the disparate flood damage claims filed by communities of color across the south and west side (see figure 12). Urban flooding depends on local infrastructure quality and thus an absence of green alleys in proximity to high flood risk areas would likely mean green alley development has minimal effect on urban flooding in areas most at risk. This further implies the clustering of green alleys across the urban core is most likely mitigating most risk in the urban core, leaving flood risk in the periphery, where it is highest, the least mitigated.

5.1.1 GAS Maps

5.1.1.1 Jenks Natural Breaks

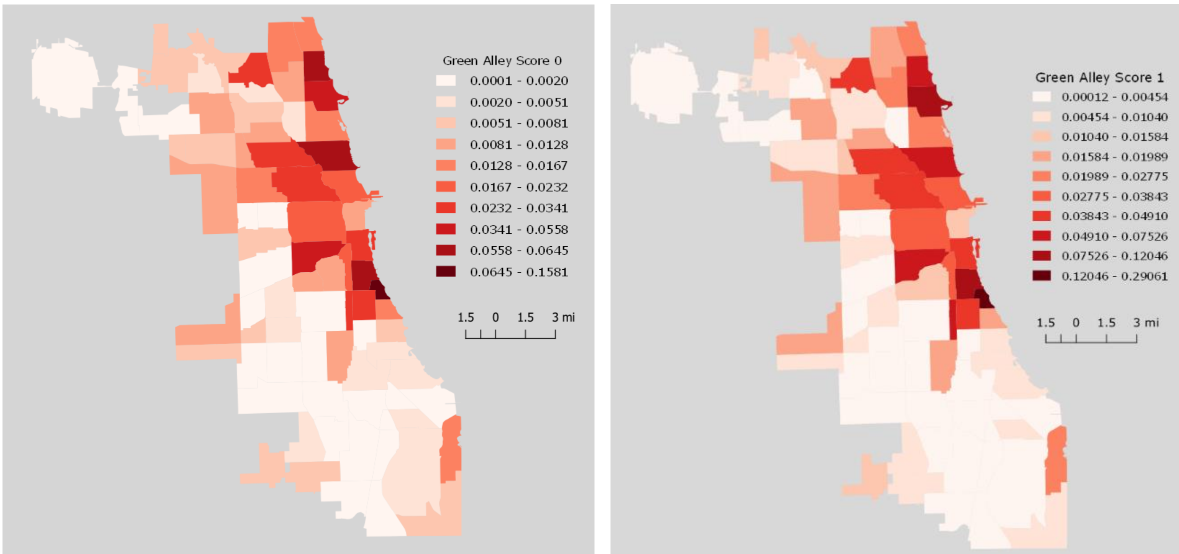

Figure 21 (Left) GAS 0 distribution across Chicago community areas, classified by Jenks natural breaks. GAS 0 included land use coded 6000 when determining the total area. (Right) GAS 1 distribution across Chicago community areas separated by Jenks natural breaks. GAS 1 excluded land use coded 6000 when determining total area.

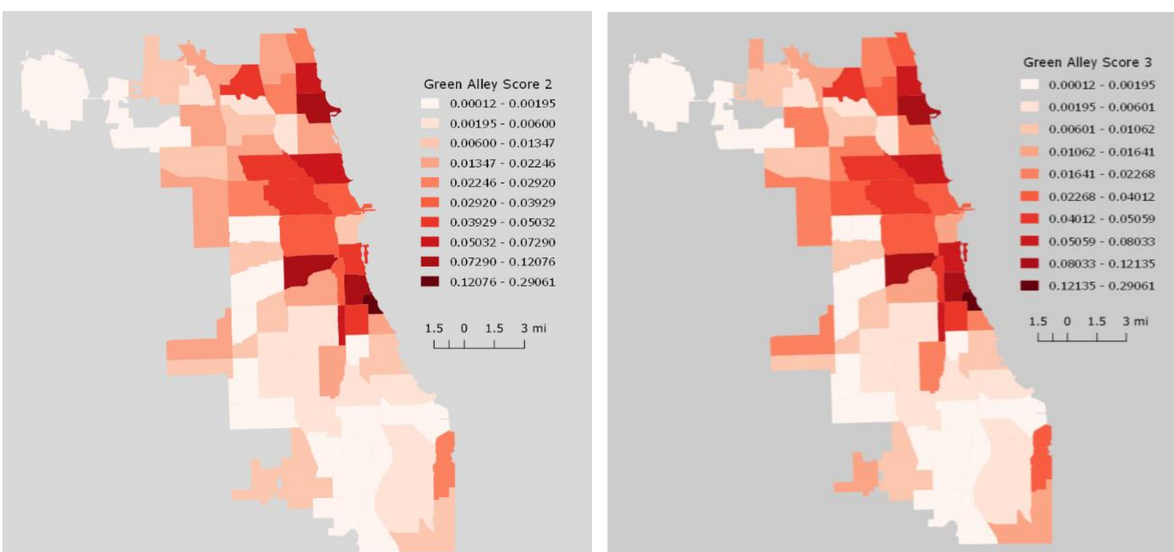

Figure 22 (Left) GAS 2 distribution across Chicago community areas classified by Jenks natural breaks. GAS 2 excluded land use coded 6000 and land use coded for large industrial sites when determining total area. (Right) GAS 3 distribution across Chicago community areas. GAS 3 excluded 6000 land use, large scale industrial land use, and land use zoned for cultural sites.

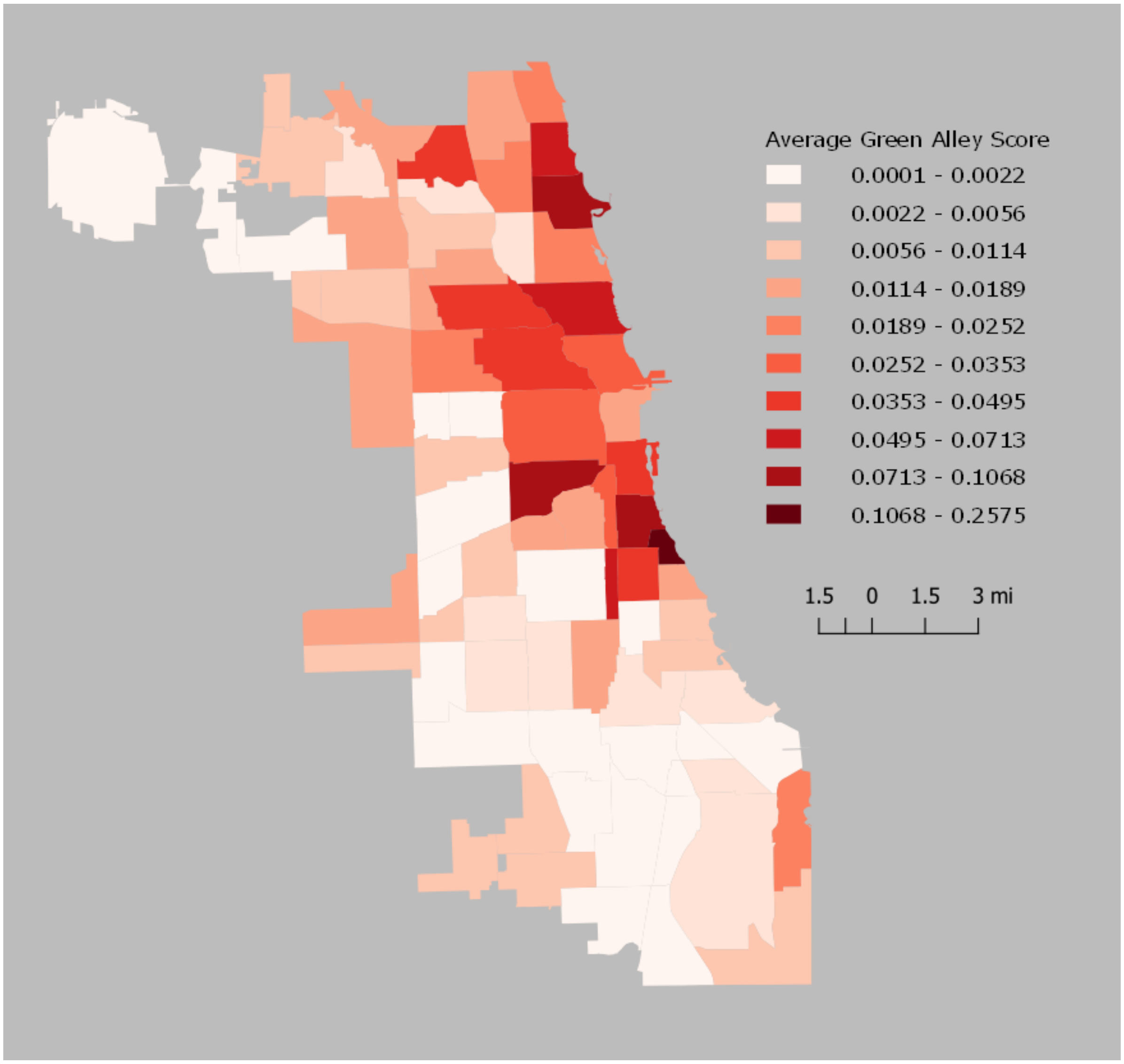

Figure 23 Distribution of Average Green Alley Scores (Average GAS) across the city of Chicago by community area.classified by Jenks natural breaks. Average GAS took the average of the other four GAS values.

GAS values control for land unable to be developed into green alley space. GAS distribution maps provide insights not readily available on KDE maps or clustering maps. By controlling for unavailable land, GAS distribution maps rule out land use variability as a confounding explanation for the distribution of green alley scores. The GAS distribution maps allow for more insight into comparison between areas of comparable density. Classifying GAS values into bins divided by Jenks Natural Breaks reveals differences in density between community areas in the urban core. Classifying by Jenks Natural Breaks also further reinforces data suggesting a greater density of green alleys across the north side than the south side.

Notably the green alley density of the loop is less than the density of the surrounding core community areas, with a lower green alley score. Lower West Loop is much denser than Near West Side and the near northside community areas. The near southside community areas are more green-alley dense than the near northside community areas as indicated by GAS distribution clustering on the near southside but not the near northside. This disparity within the core may be due to less available land in the smaller near southside community areas, resulting in greater green alley density with less green alleys. The community areas of Edgewater and Uptown have comparable GAS values to the urban core. This is reflective of larger green alley clusters on the far north side and emphasizes the disparity in green alley distribution between the north, south, and west sides of the city, as Edgewater and Uptown are not within the urban core. The green alley site clustering around Edgewater and Uptown is the only clusters outside of the core comparable in GAS and KDE values to parts of the urban core.

5.1.1.2 Quantile

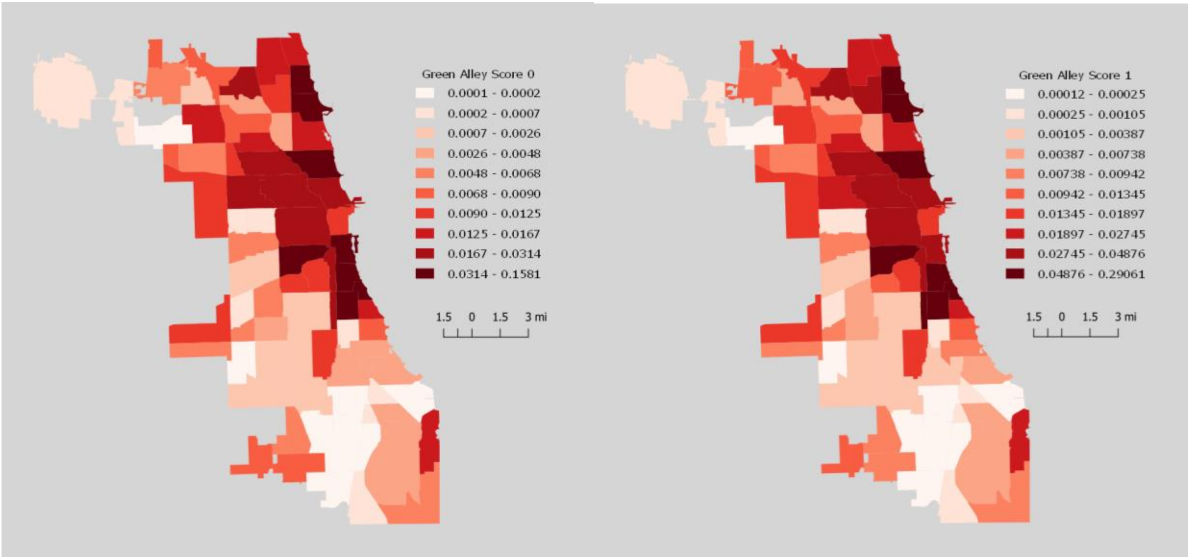

Figure 24 (Left) GAS 0 distribution across Chicago community areas, classified by quantile. GAS 0 included land use coded 6000 when determining the total area. (Right) GAS 1 distribution across Chicago community areas separated by quantile. GAS 1 excluded land use coded 6000 when determining total area.

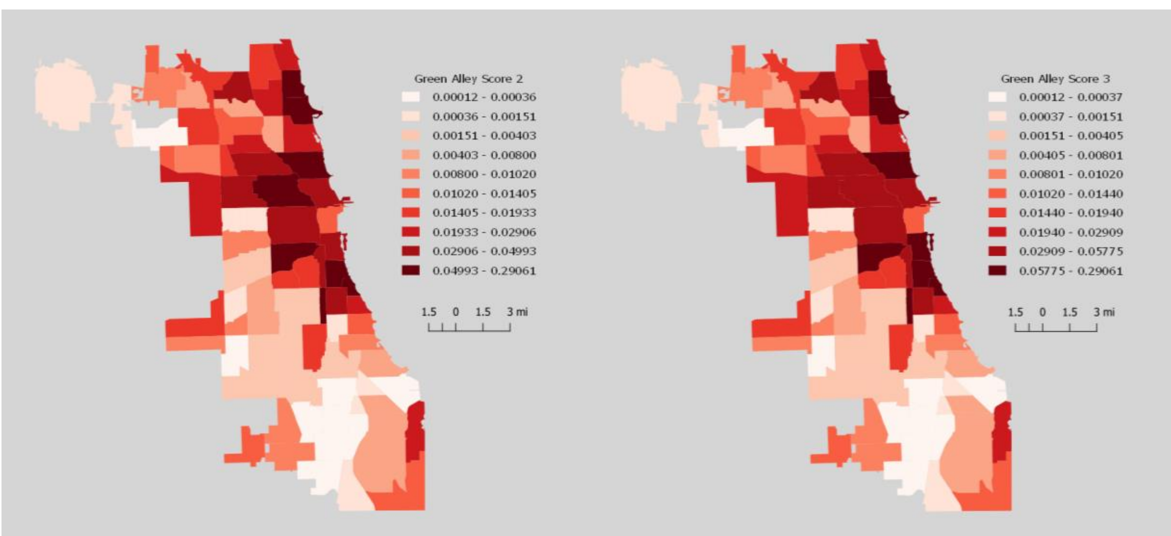

Figure 25 (Left) GAS 2 distribution across Chicago community areas, classified by quantile. GAS 2 excluded land use coded 6000 and land use coded for large industrial sites when determining total area. (Right) GAS 3 distribution across Chicago community areas, classified by quantile. GAS 3 excluded 6000 land use, large scale industrial land use, and land use zoned for cultural sites.

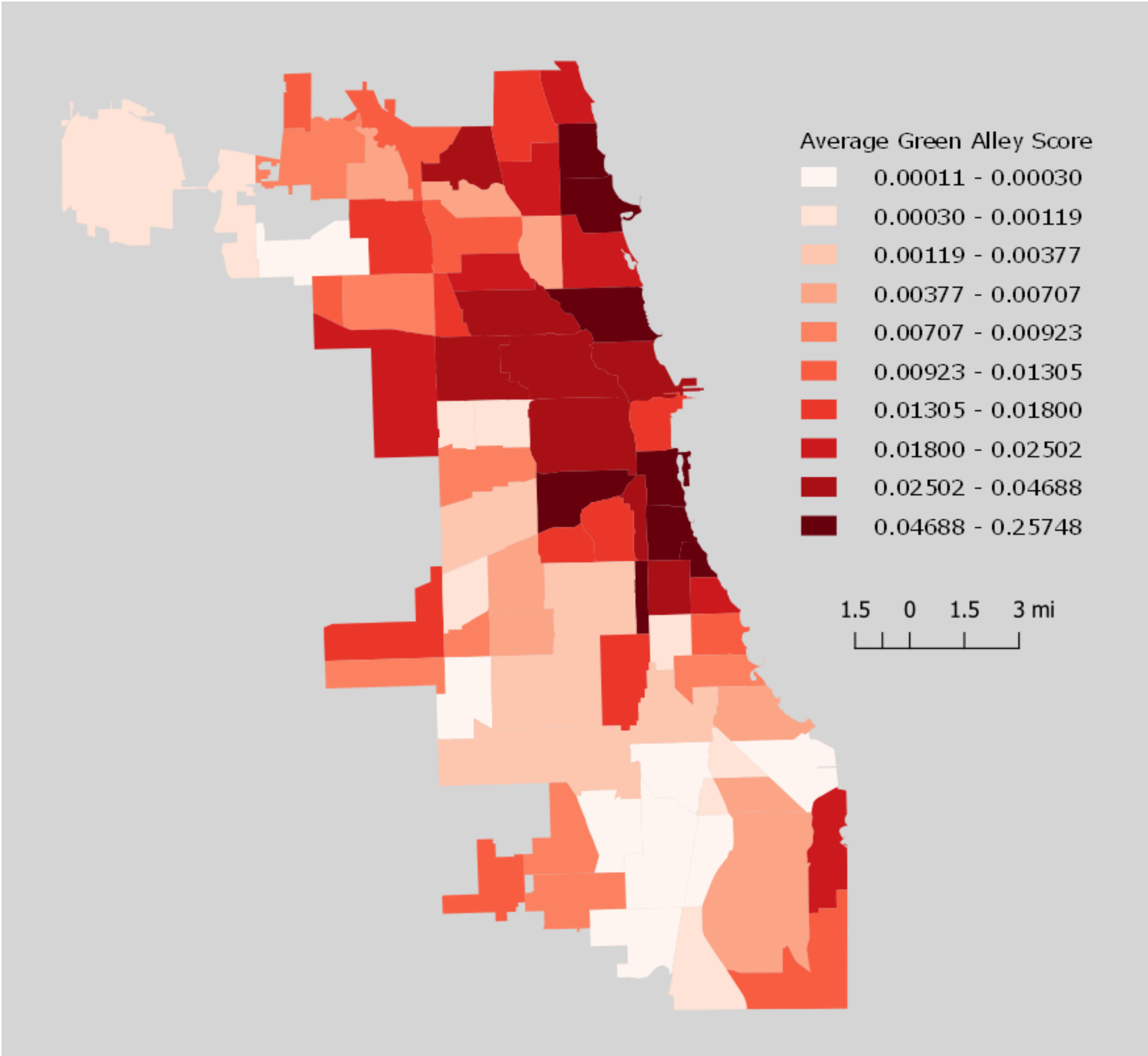

Figure 26 Distribution of Average Green Alley Scores (Average GAS) across the city of Chicago by community area, classified by quantile. Average GAS took the average of the other four GAS values.

In contrast with the GAS maps classified by Jenks Natural Breaks, classification by quantile allows for easier comparison between communities with lower green alley density across the south and west side. Quantile classification also emphasizes the distinction in density between the far south side and the northwest side, with northwest side community areas appearing in higher quantile bins than neighborhoods such as Chatham, Roseland, and Pullman in the southside low green alley density cluster.

The Quantile classification helps to compare community areas with no green alley presence. Community areas such as Riverdale, Burnside, and Avalon Park lack green alleys entirely, but a large portion of their community area space is taken up by unavailable land. By adjusting the numerator of the green alley score by 10,000 the distinction between communities such as Riverdale and Chatham are made apparent. The differences in GAS values of these neighborhoods indicates that less green alley sites would be needed to fully transform impervious surfaces to permeable ones in communities such as Riverdale than in communities such as Chatham.

Another aspect of the quantile classification maps that should be highlighted is the higher value of South Deering which appears on KDE maps as having a very low green alley density. Although South Deering is not comparable to community areas in the urban core, much of the emptiness present in South Deering on the KDE maps is marshland, transit (highways/railways), and wastewater treatment facilities. These spaces cannot be turned into green alley space and thus the area available for green alley development in South Deering is actually much smaller than it appears on the map. It would take less green alley sites to fully convert impervious alley pavement in South Deering than in neighborhoods such as Roseland and Chatham. This is not to say that South Deering has a high green alley density, but in comparison to other areas of low green alley density throughout the south side, low green alley density is most likely due to confounding factors such as the presence of unusable land.

Quantile classification reinforces analyses made concerning the density of south east side neighborhoods, East Side and Hegewisch. The green alley density of these neighborhoods is likely comparable to density on the far northwest side and stands in contrast to the low density of adjacent far south side neighborhoods. This is also shown on green alley site clustering maps.

5.1.1.3 Percentile

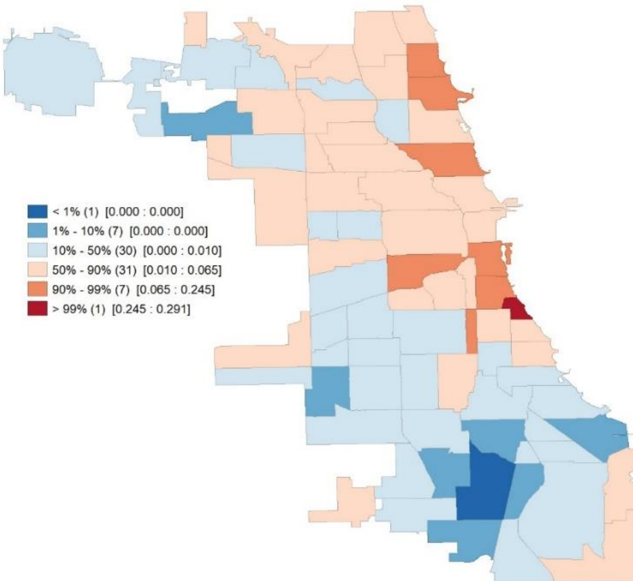

Figure 27 Shows the GAS distribution across Chicago separated into percentiles.

Classifying GAS values by percentile further emphasized the disparity in green alley density between the urban core and city periphery, specifically the south side west of the Calumet river. Only one community area in the bottom 10th percentile occurs on the north side of the city. Except for Edgewater and Uptown on the far north side all community areas above the 90th percentile lie in the urban core.

5.1.2 KDE

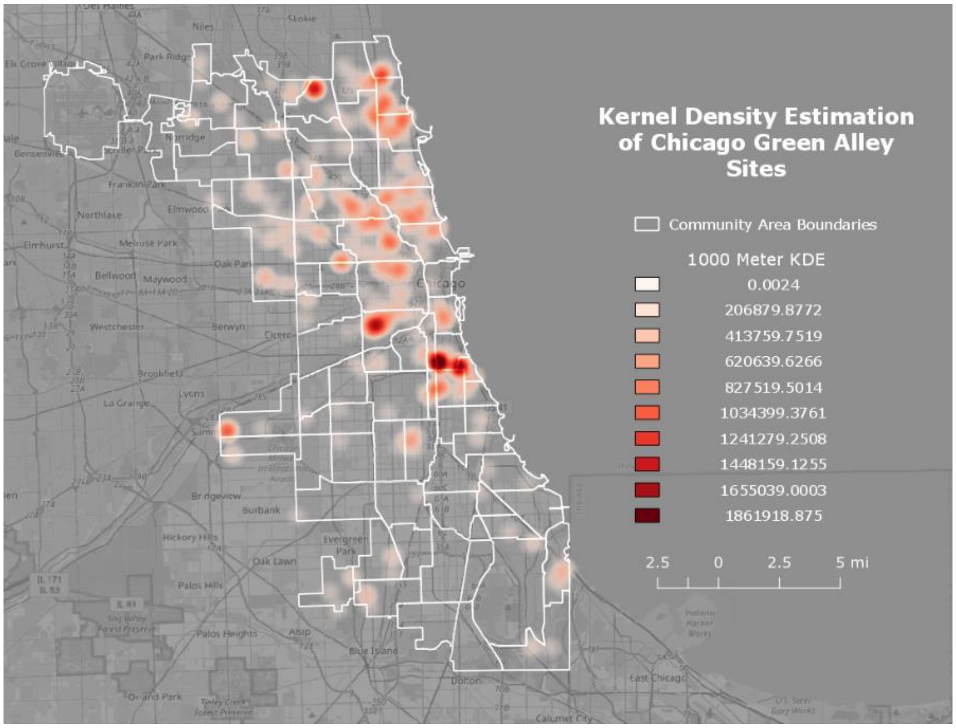

Figure 28 (Top) Kernel Density Map with the radius set at 1000 meters.

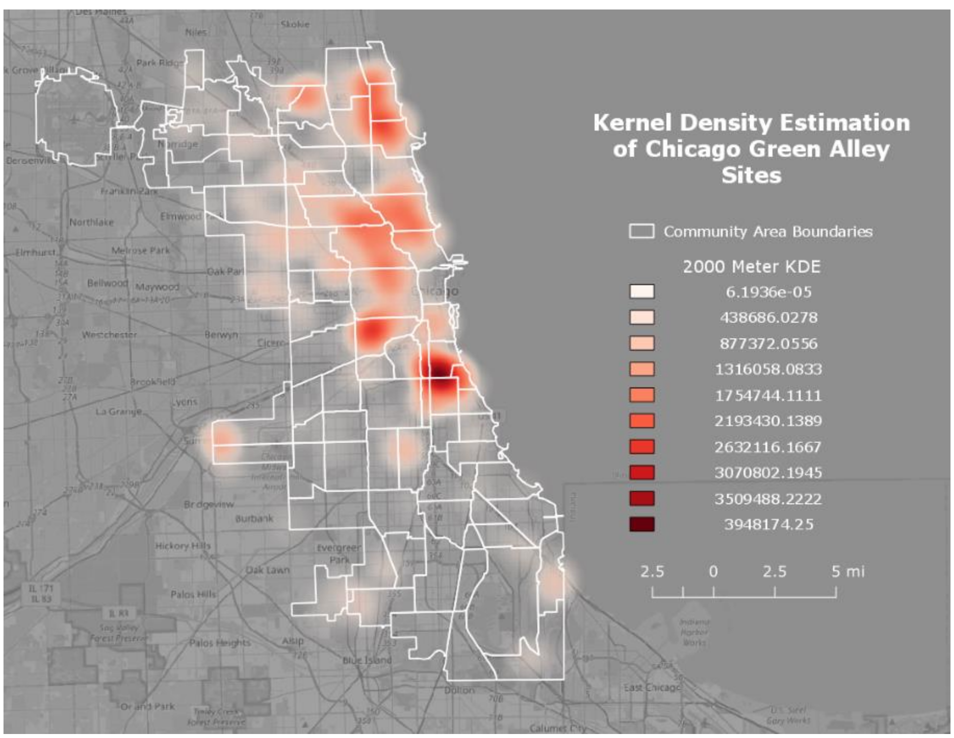

Figure 29 Kernel Density Esimate map with radius of 2000 meters.

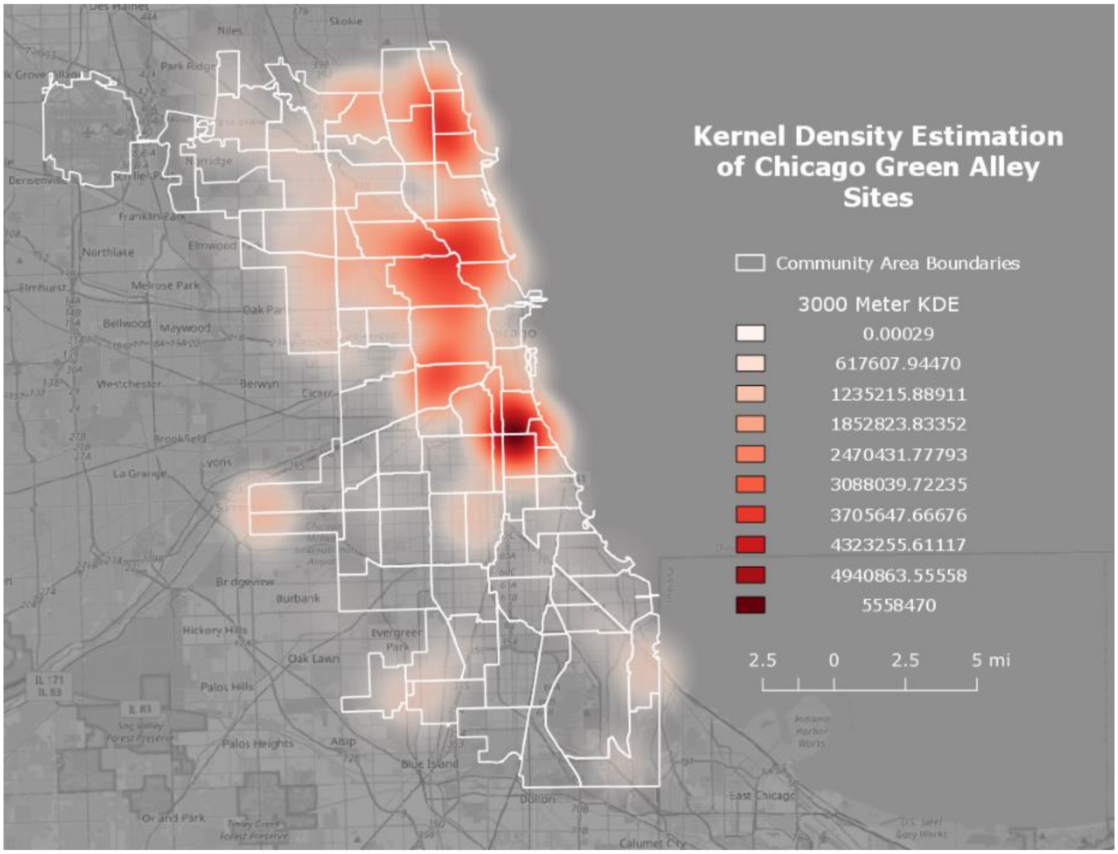

Figure 30 Kernel Density Estimate map with radius of 3000 meters. Notice how at 3000 meters the variations in green alley density across the city become more apparent, while the inability of the KDE to account for unavailable land is more pronounced as reflected by the visually equivalent density of Lower West Loop and West Town.

The KDE maps depicted the raw spatial density of green alleys around Chicago, assuming a continuously available surface space throughout the city. Although this assumption is erroneous, when paired with analysis of Green alley scores (which adjust for unavailable surfaces in community areas) and their clustering, patterns can be observed within certain community areas. These patterns strengthen observations made when assessing the clustering patterns of green alleys and GAS values per community area.

The KDE maps help to emphasize that community areas with significant green alley density may be in proximity to other community with green alley density due to clustering of green alley development around community area boundaries. Clustering patterns of GAS values across community areas indicated significant clustering around the Near South Loop and Oakland community areas. The KDE maps reveal that this clustering occurs in high density around the border areas between Oakland and Douglas, and Douglas and Armor square. This is further emphasized by the clustering patterns indicated on the DBScan, DBScan*, and HBScan maps of green alley sites.

The KDE maps when compared with the green alley site clustering maps depict how community areas on the south and west side, which have higher GAS values than their comparatively lower GAS scored neighbors, tend to include statistically significant clusters of green alley development. This is the case in Garfield Ridge, Clearing, and Englewood neighborhoods. Each of these neighborhoods have more green alley sites (reflected in higher GAS values) than adjacent southside neighborhoods, such as Auburn Gresham and Greater Grand Crossing, but their green alley sites tend to cluster in only part of the neighborhood (ie: far west side in Garfield Ridge and Clearing, northwest side of Englewood). This indicates a greater green alley deficit space than is depicted on GAS maps, which is shown in the empty areas on the KDE maps.

Smaller radius KDE maps confirm clustering results and indicate patterns of green alley density within community areas, while larger radius KDE maps help to show comparative density across the city. There is significantly greater green alley density on the northeast side of Chicago than on the South and West sides. By expanding the KDE radius the density of the northwest side in comparison to the southeast side can be better compared. Both areas have comparable clustering and density at smaller kernel density radii, but the proximity of more of these clusters on the northwest side lends to a greater density along the northwest side of Chicago than the southeast. The exception to this is the East side community area, which on all maps demonstrates higher levels of green alley density than the surrounding community areas. The green alley density of East side also does not statistically cluster at lower radius value DBScan maps and higher radius DBScan* maps, demonstrating a comparably greater level of green alley dispersion across the East side than in neighboring southside neighborhoods.

Some density comparisons depicted on the KDE maps fail to account for land unavailable to be used for green alley development. Density on the Southeast side neighborhoods of Hegewisch and East Side are visually greater on the GAS distribution maps than on the KDE maps because the KDE maps do not account for the significant presence of land in these areas which cannot be turned into green alley space. Empty space on the KDE maps is not as informative as on the GAS maps because one cannot compare the emptiness of a neighborhood such as South Deering with its neighbors. The KDE maps cannot reflect that a significant amount of space in South Deering is wastewater treatment and marshland. As well, empty space on the smaller radius KDE maps in Lower West Side and Near West Side is mostly due to land around the river and large-scale industrial sites which cannot be converted into green alley space. As a result, the significantly higher green alley density of Lower West Side is not reflected in the larger radius KDE maps, unlike on the GAS maps.

5.1.3 Clustering of GAS Scores

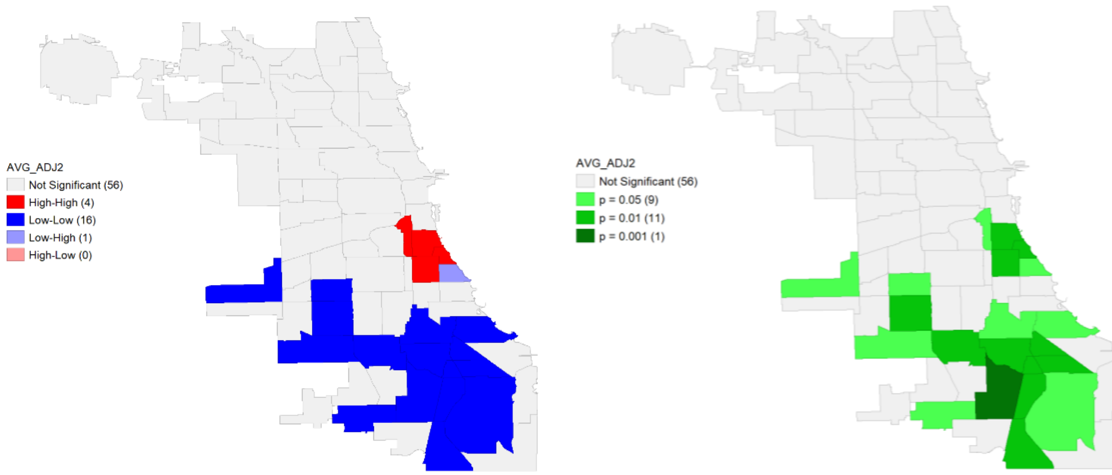

Figure 31 (Left) Map of statistically significant GAS (AVG_ADJ2) distribution clustering. (Right) Map of p values for statistically significant clusters, indicating degree of significance for spatial correlation.

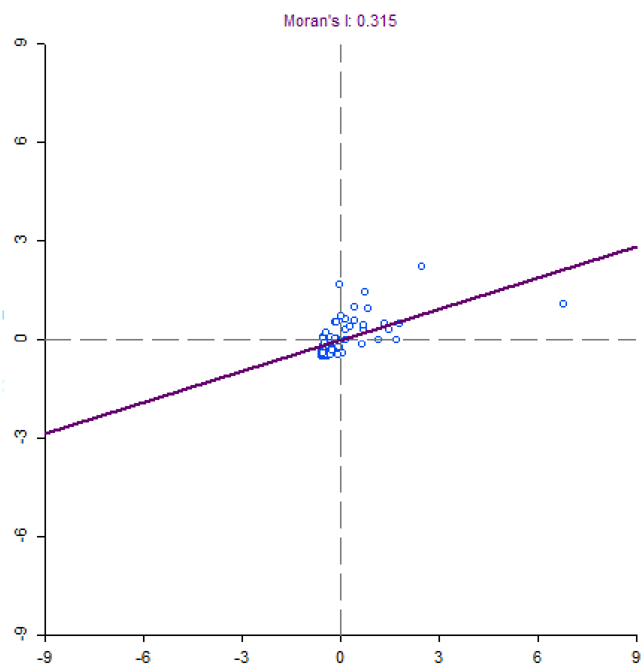

Figure 32 Moran's I scatterplot for the autocorrelation of average GAS distribution across community areas. Standardized GAS scores are on the x axis. Spatially lagged scores are on the y axis.

Using the global and local univariate Moran's I measurements the Moran's I statistic and local clustering was determined for the GAS distribution map. With a Moran's I statistic of .315 there was not enough correlation between GAS distribution to say with certainty that the distribution is not spatially random. However, this does not preclude the possibility of statistically significant in local GAS clustering, as shown on the GAS distribution clustering map above. With a p value less than .01 there is a spatial correlation between low GAS values and the far southside of Chicago, west of the Calumet river. As well, with a p value less than .01 there is a spatial correlation between high GAS values and the near south loop community areas, within the urban core. This further reinforces the evidence for a spatial distinction in green alley density between the far south side and the rest of the city.

5.1.4 Clustering of Green Alley Sites

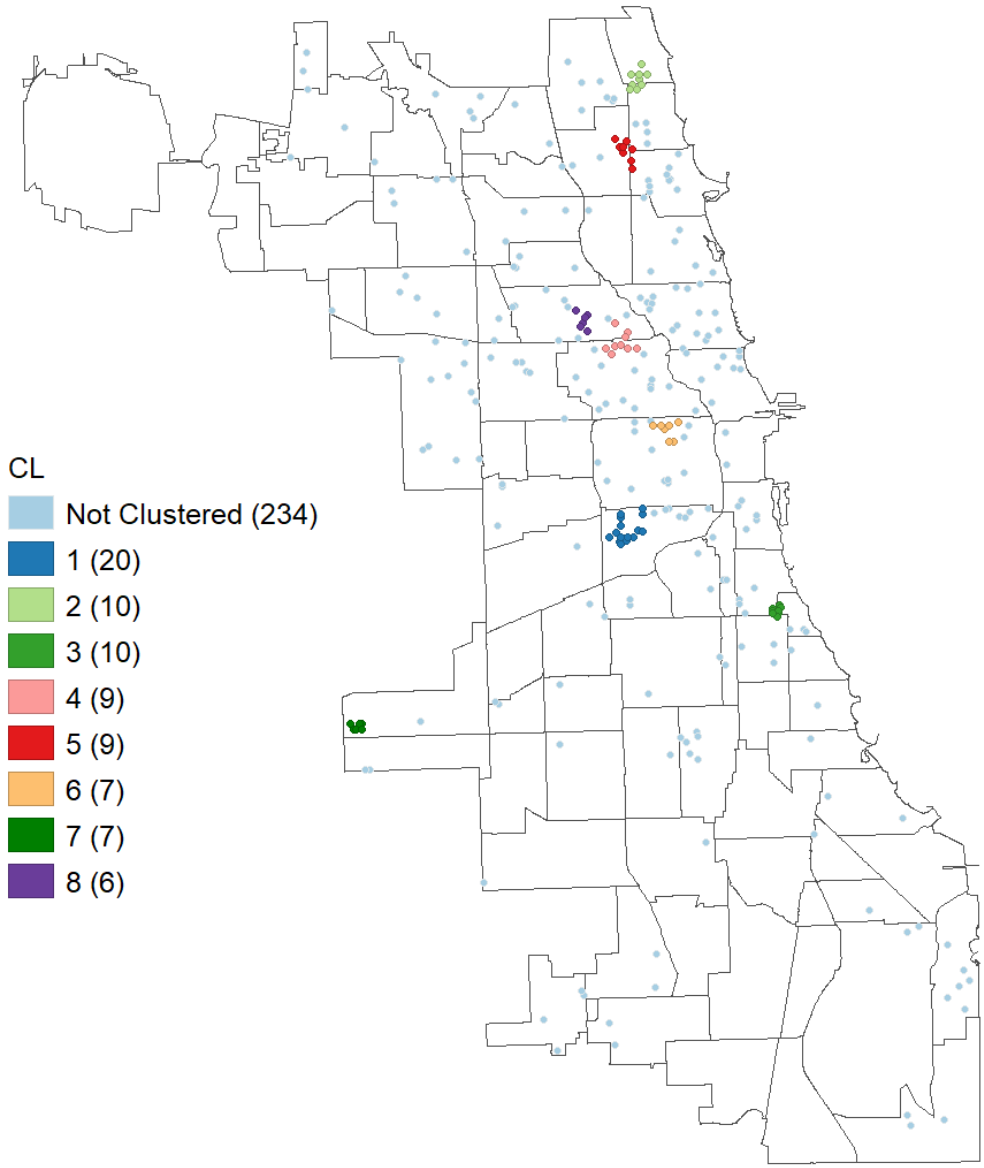

Figure 33 DBScan measurement of density clustering based on a radius of .1 epsilon and minimum cluster size of 5 core connections.*

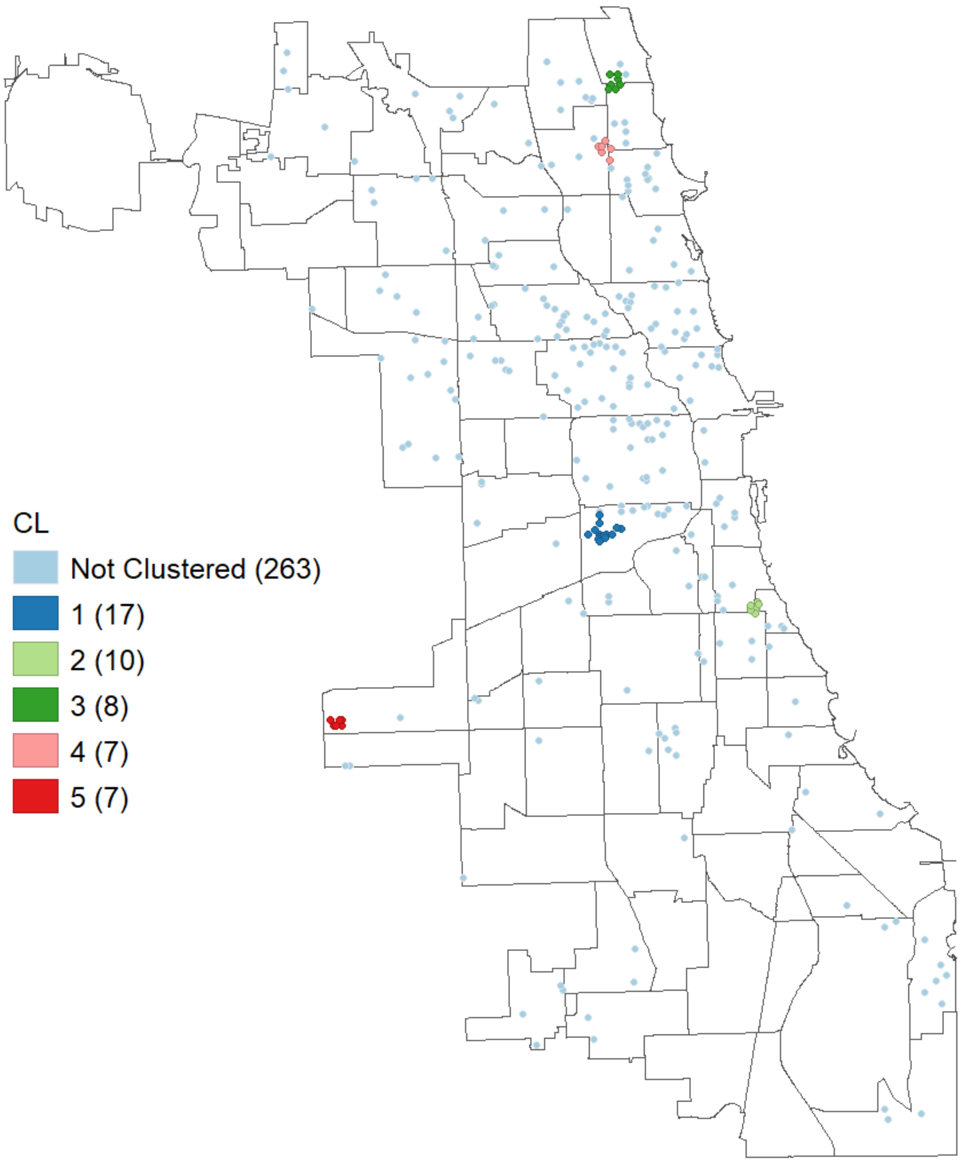

Figure 34 DBScan measurement of density clustering based on a radius of .1 epsilon and minimum cluster size of 7 core connections.*

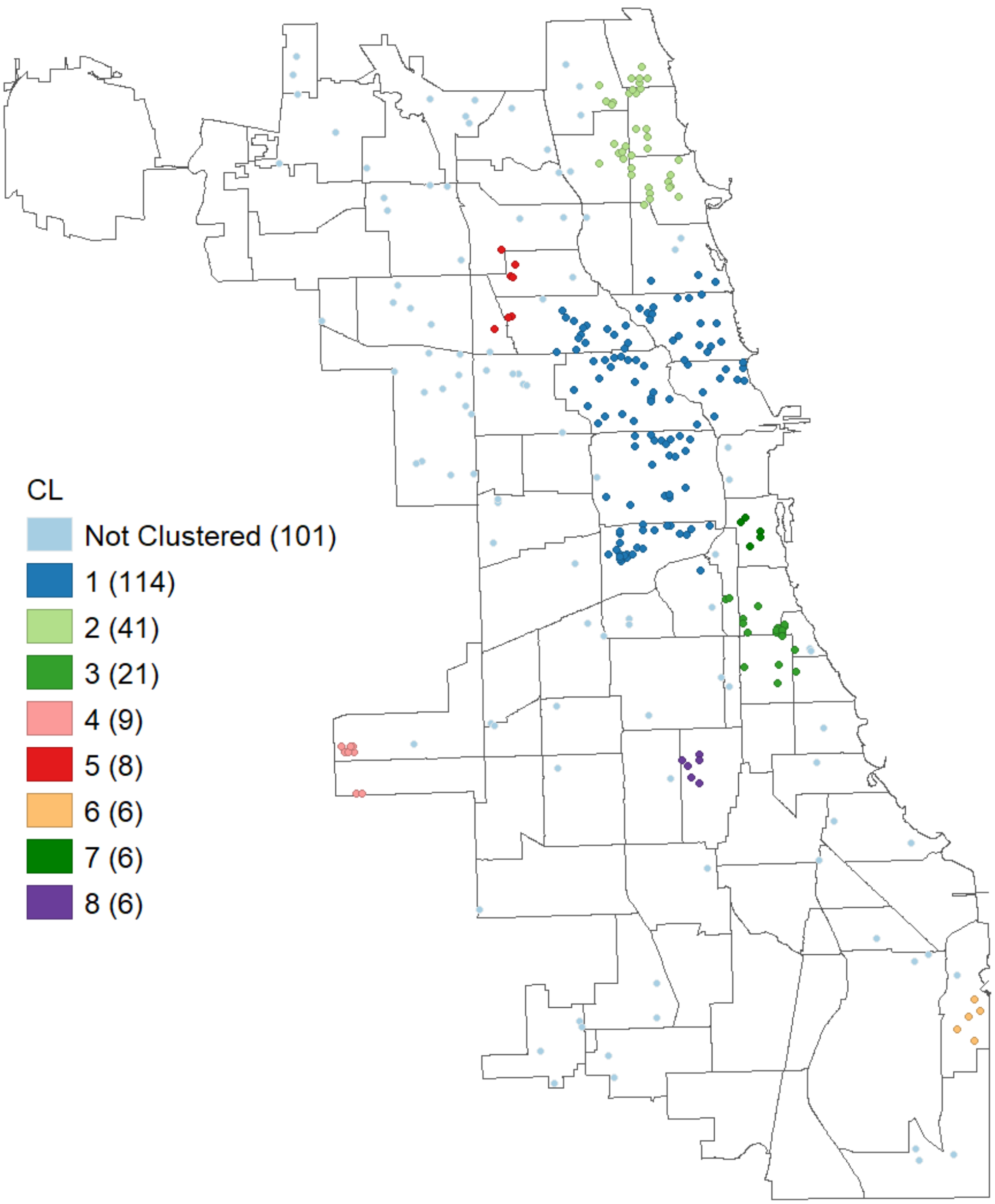

Figure 35 DBScan measurement of density clustering based on a radius of .2 epsilon and minimum cluster size of 5 core connections.*

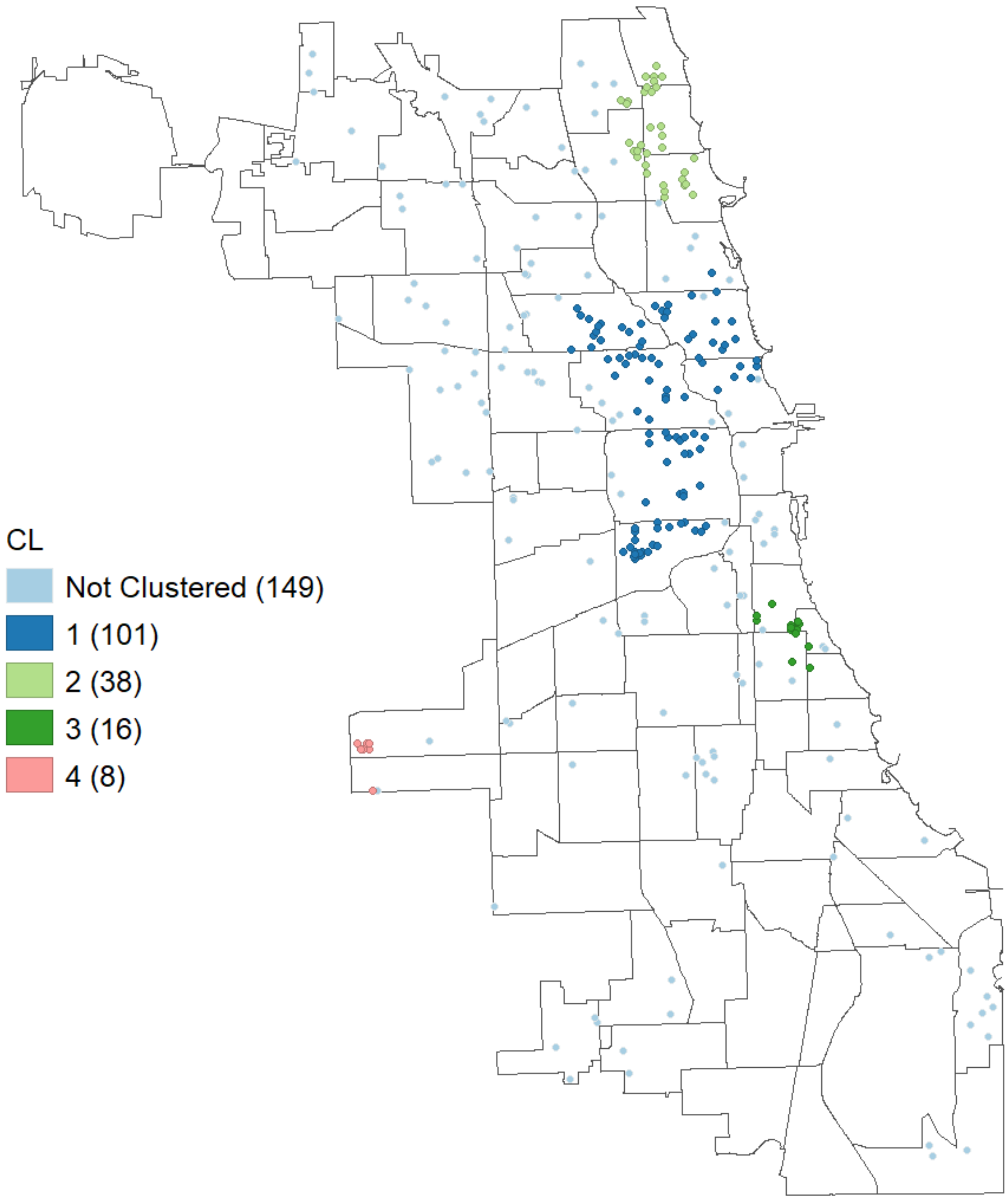

Figure 36 DBScan measurement of density clustering based on a radius of .2 epsilon and minimum cluster size of 7 core connections.*

Although an analysis of spatial clustering of green alley sites could not control for unavailable space in certain community areas, the clustering patterns of individual green alleys reinforced patterns apparent in GAS and KDE maps. At a lower distance threshold of .1 epsilon, indicating smaller scale of analysis, almost all clustering occurred within the urban core. The only instance of clustering outside of the urban core at lower distance thresholds was the clustering of green alley sites in west Garfield Ride and west Clearing. This confirmed the density distribution across Garfield Ridge and Clearing made more apparent in the KDE maps.

At a higher distance threshold of .2 epsilon disparities in clustering patterns across the city became more apparent. The largest cluster of green alley sites (based on the number of alleys in the cluster) occurred in the near north side neighborhoods. The second largest cluster of green alley sites occurs on the far north side. Clustering results indicated a disparity in green alley clustering between the north and south side of Chicago, indicating a higher density of green alleys across the north side. The third largest cluster of green alley sites occurred in near south loop, providing further evidence of a disparity in green alley density between the urban core and urban periphery, as two of the three largest clusters, and the majority of clustered green alley sites occur within the urban core.

5.1.4.1 Clustering by Year

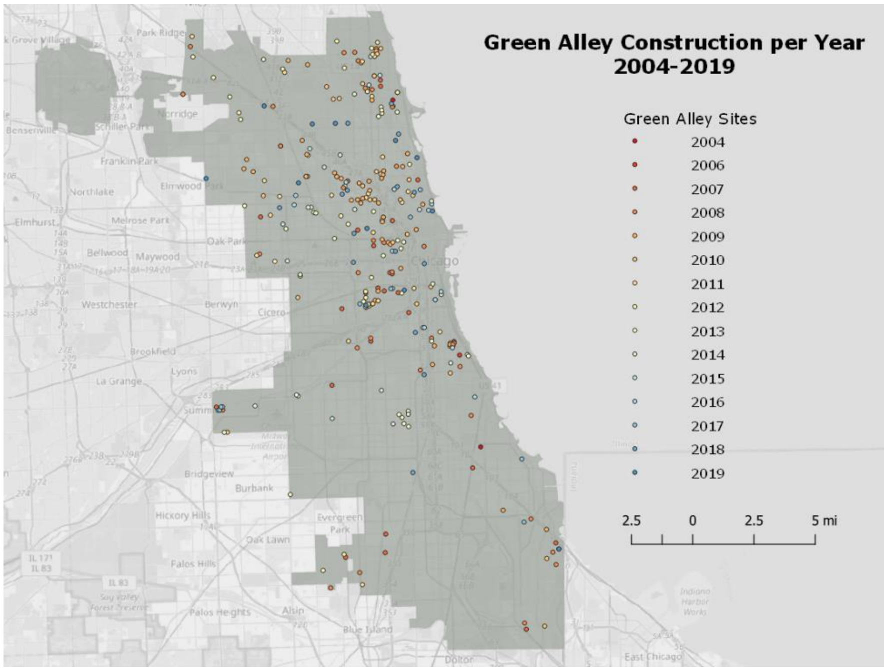

Figure 37 Green alley construction per year from 2004-2019. 2004 was the pilot green alley site.

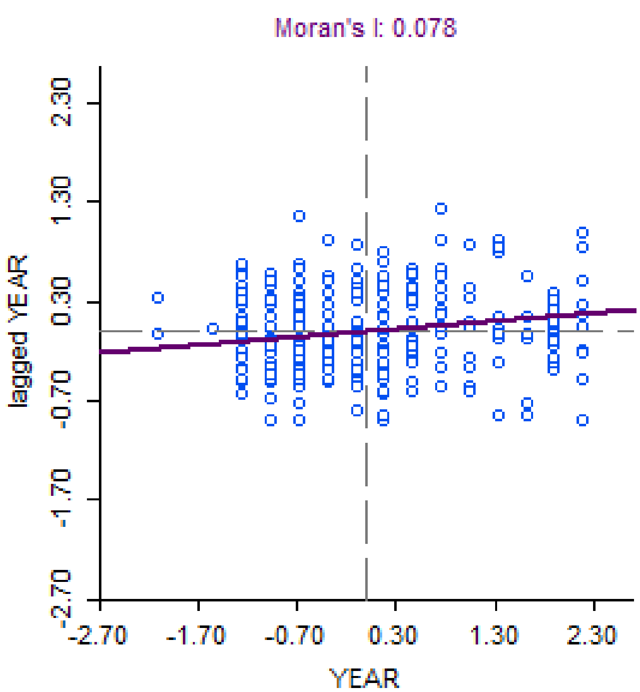

Figure 38 Moran's I scatterplot indicating insignificant spatial clustering and autocorrelation of alley development over time. There is no correlation between spatial distribution of alleys and the year they were made.

Clustering was measured for green alleys by year using a global univariate Moran's I. This was to identify possible trends in the development of green alleys over time. The Moran's I statistic for correlation of green alley locations by year came back at .078, indicating almost no correlation by year. This indicated that green alley development has been dispersed over time, with each year of the green alley program developing across the city in a statistically random manner.

5.2 Multivariate Correlation

5.2.1 GAS and Land Use Variables

Comparing the spatial distribution of GAS values and the spatial distribution of land use variables was done to control for dependent relationships between green alley density and land use throughout the city. This study analyzed five different land use variables: the blue index, which measured of the amount of community space covered by bodies of water; the green index, which measured the total vegetation coverage as a percent of total community area space; the grey index, which measured total developed land as a percent of total community area space; the road index, which measured the density of road coverage in a community area; and the vegetation index, which measured vegetative land coverage in a community area based on the average number of green pixels in satellite imagery.

If green alley distribution depended upon a particular land use variable (ie: paved surface coverage) then one would expect to find spatial correlation between the distribution of green alleys and that variable. This was not the case. The bivariate Moran's I for all land use variables indicated no city-wide spatial correlation and local correlation patterns were not consistent with any broader patterns of green alley clustering to suggest a dependent relationship between green alley distribution and land use.

5.2.2 Annual Precipitation Levels

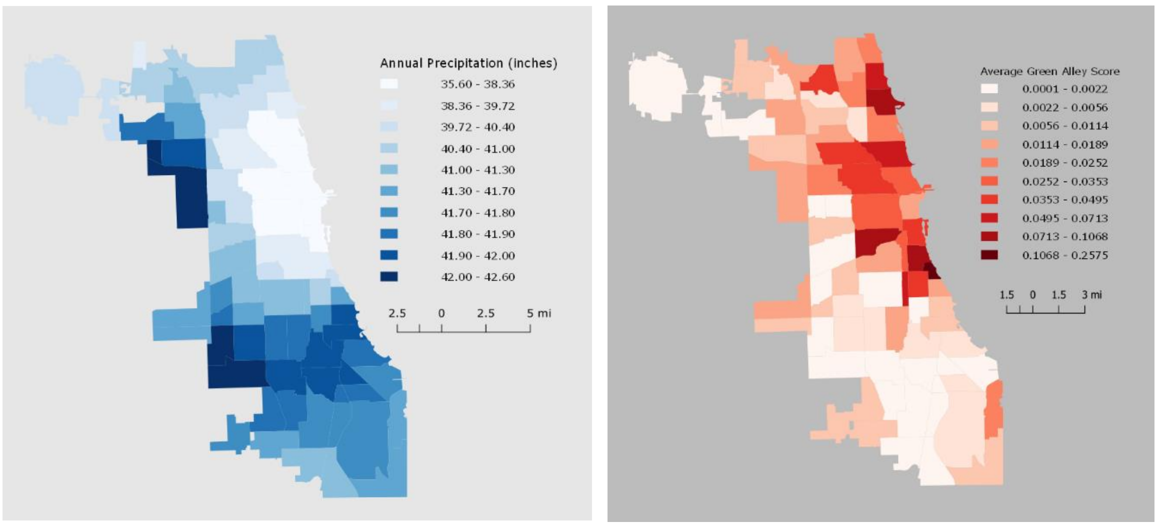

Figure 39 (Left) Annual Precipitation Levels (inches) per community area in 2017. (Right) Average Green Alley Score distribution per community area separated by Jenks Natural Breaks.

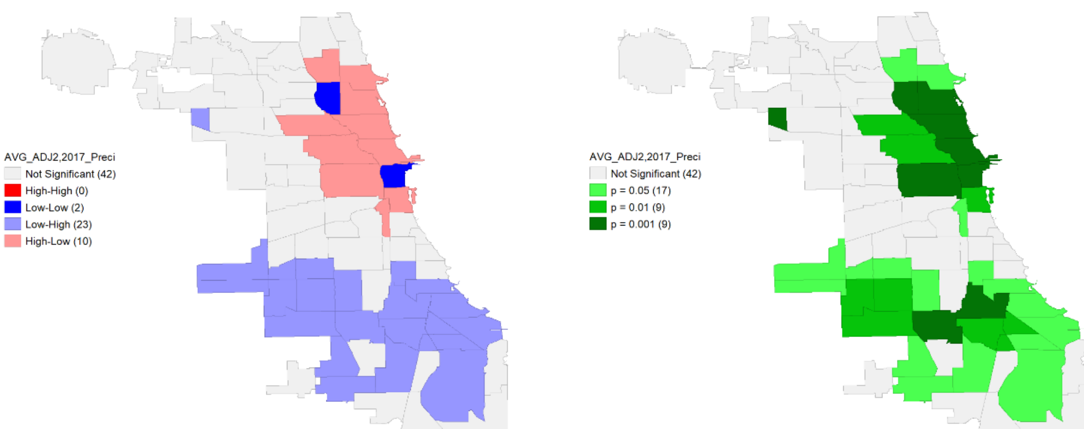

Figure 40 (Left) Statistically significant local correlation clusters between the average GAS (AVG_ADJ2) and precipitation levels per community areas (2017_Preci). The High-Low value indicates higher GAS values but lower precipitation values and the Low-High areas indicate the inverse. (Right) P-values for each cluster allowing for rejection of null hypothesis of random spatial distribution.

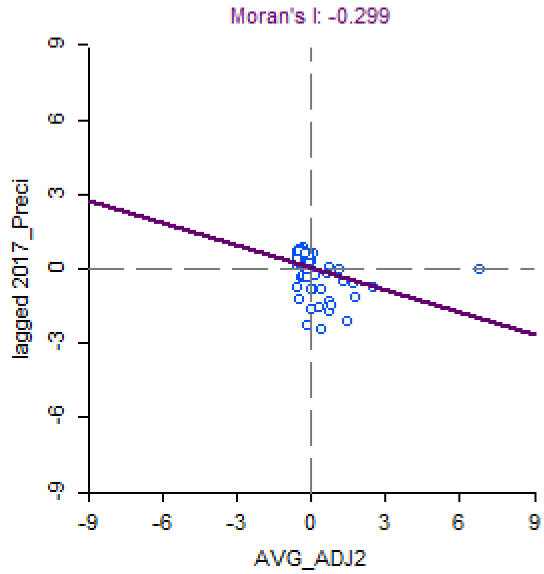

Figure 41 Moran's I scatterplot for the spatial correlation of Average GAS values (x axis) and precipitation levels (y axis) per community areas.

There are variations in annual precipitation across the city of Chicago. Based on the 2017 annual precipitation levels, higher levels of precipitation occur around the Calumet River on the southwest and south side and as well on the northwest side. Lower levels of precipitation occur on the Northeast side and around the Loop. This is consistent with FEMA estimates for areas at risk of flooding in Chicago.

Local variation in precipitation is one factor directly responsible for basement flooding, as basement flooding is the result of blockages and overflows in local sewer systems prior to reaching the CSO system. Therefore, understanding local precipitation clustering patterns can improve the distribution strategy of green alley development. It is interesting to note the negative correlation between the increase in precipitation across the city and the increase in green alley density indicated by local clustering patterns.

Neighborhoods in the Calumet river region of the city had higher precipitation levels but lower green alley density. This was reflected by the clustering of Low-Low scores determined by the local Moran's I. The Moran's I statistic for the relationship between average GAS and annual precipitation levels was -.299, indicating no statistically significant correlation between the variables with respect to the entire city. However, statistically significant clustering did indicate a non-random negative correlation between local green alley density and precipitation levels in the southwest and northeast side. This was both statistically and contextually significant because local precipitation clustering is relevant to urban flood prevention. The lowest precipitation levels occurred in the urban core of Chicago, while clustering for high levels of precipitation in the southwest side of Chicago correlated consistently with the same low green alley density clusters evidenced by GAS and KDE maps. This was interesting because green alleys mitigate precipitation runoff to prevent sewer back-ups which cause basement flooding. In areas where there are higher levels of direct precipitation green alleys could offer greater maximum runoff reduction than in areas with lower levels of precipitation.

5.2.3 Per Capita Income Levels

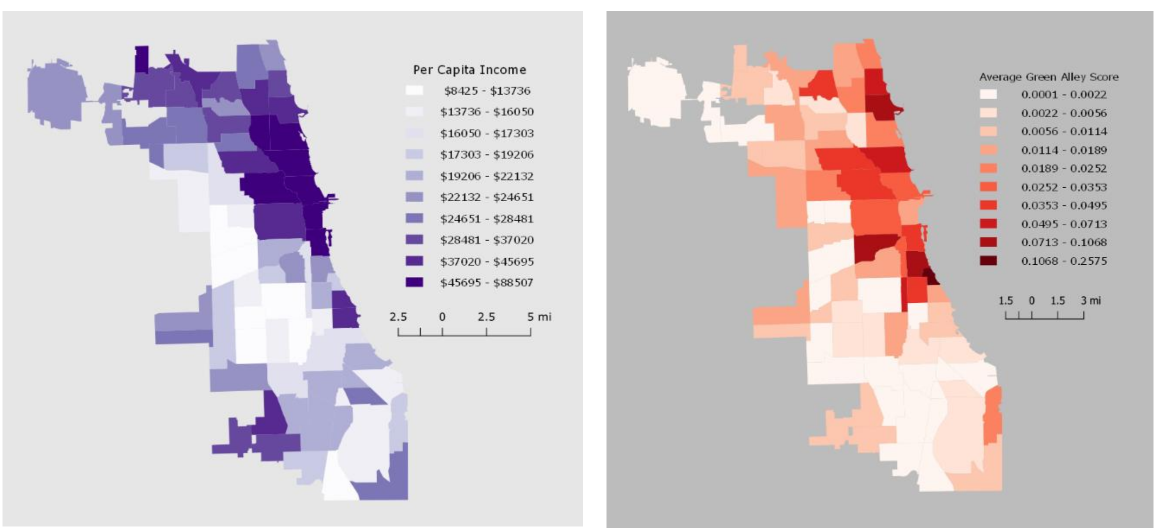

Figure 42 (Left) Per Capita Income per community area across Chicago. (Right) Average GAS value distributed across community area.

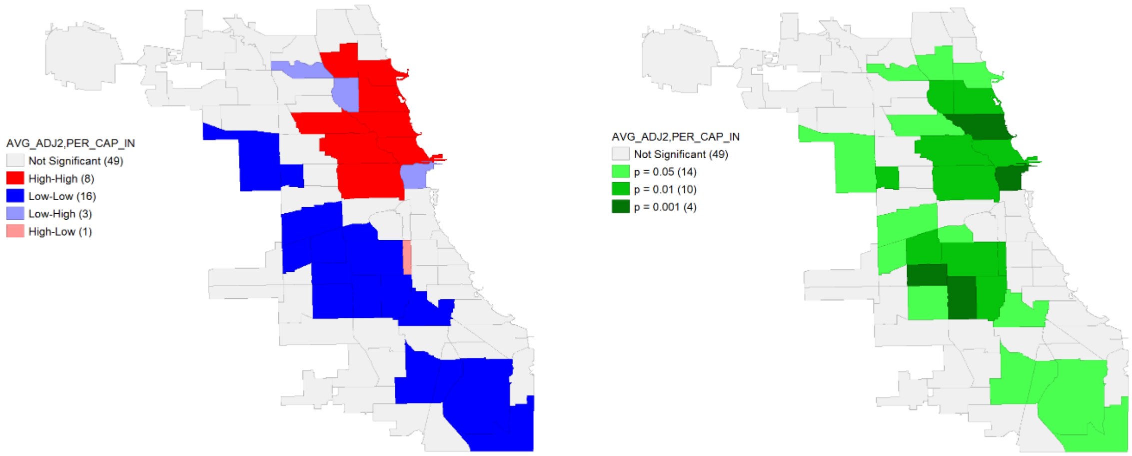

Figure 43 (Left) Local bivariate Moran's I clustering of green alley scores (AVG_ADJ2) correlated with per capita income levels across community areas (PER_CAP_IN). (Right) P values indicating degree of statistical significance for clustering.

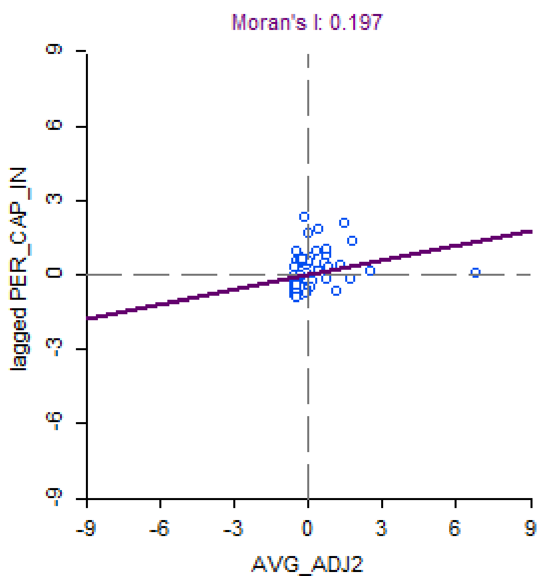

Figure 44 Moran's I scatterplot for the spatial correlation of Average GAS values (x axis) and per capita income levels (y axis) per community areas.

With a bivariate Moran's I statistic of .197 there is no statistically significant correlation between the distribution of per capita income across Chicago and the distribution of green alley density. The spatial distribution of per capita income across Chicago emphasizes a disparity between the north, west, and south side of the city. With the northside, near northside, and far north east side of the city having higher per capita income values than the south and west side of the city. The distribution of per capita income levels across the city is not the same as the distribution of green alley density, which tends to cluster at greater levels in the urban core than on the north side; however, the clustering depicted in the green alley site cluster maps showed that the two largest clusters of green alleys occurred on the near north side and far north side. Clustering which is consistent with the local Moran's I patterns indicating a correlation between high per capita income on the near north side and high green alley density. The local Moran's I clustering patterns as well indicate a statistically significant correlation between low green alley density and low per capita income throughout the far south and west side.

5.3 Further Studies Needed

Using the scale of the community area had drawbacks when performing a detailed spatial analysis. There was significant variability in the size of community areas, and by analyzing at the community area scale, densities near borders and density patterns within community areas were not captured. Future studies would greatly improve spatial density analysis by analyzing green alley density at the census tract level.

As well, measurements done by future studies should more accurately report available areas through separating alley polygons. All values used for determining the green alley score were approximations. This thesis aims to begin the process of analyzing the spatial distribution of green alleys across Chicago by comparing the values. The approximations for the GAS when coupled with the in-depth analysis of clustering and autocorrelation help identify directions of possible research into the spatial distribution of green stormwater infrastructure. As estimates, however, these scores do not report the actual green alley coverage percentage and may include error caused by variations in block size for equivalent alley area. Future studies should validate this study by creating scores which can reflect information about the total green alley coverage and accurately compare between neighborhoods with closer GAS values. One way to do this would be for future studies to isolate shapefile polygons of only alley space and determine a new GAS based on the percentage of green alley area out of total alley area in a community area. Another method would be to determine a total block count for green alley blocks and measure the ratio between that block count and the total block count for blocks in a community area which could host green alleys. Developing more accurate scores which reflect permeable surface area can also contribute to studies of green alley performance, as increased surface area should also decrease total rainwater runoff.

More variables should be analyzed to further contextualize the distribution of green alley sites throughout Chicago. Assessing the average age of buildings based on the Chicago Data Portal's building footprints file could reveal correlations between the older buildings and green alley sites. As older buildings are more at risk of flooding events, this could improve the strategic development of green alley sites. As well, the relationship between green alley density and population density should be explored, to further control for potentially confounding variables which could explain green alley development.

Finally, more research needs to be done on the spatial distribution of urban flooding throughout Chicago. Understanding the flood patterns of Chicago neighborhoods would help to better strategize the placement of green alley sites across the city. Information on the distribution of urban flood risk is currently publicly available as raster data but should be transformed into vector data for comparative spatial analysis.

6. Conclusion

A spatial analysis of Chicago's green alley infrastructure is strategically useful to city planners as it can provide insights which could inform future planning decisions and green alley development. There has been little holistic research into the effectiveness and development of Chicago's green stormwater infrastructure, primarily because Chicago's GSI development process is decentralized and gradual. No research has yet been published on the spatial distribution of green stormwater infrastructure across Chicago. As green stormwater infrastructure is part of a larger project attempting to establish sustainable urban infrastructure in American cities, it is important that studies are conducted to assess the effectiveness and progress of green stormwater infrastructure.

This paper introduces to literature on green stormwater infrastructure an initial spatial analysis of patterns in green alley distribution across Chicago. Multiple methods were used to assess various distribution and spatial density patterns across the city. Further studies are needed to determine a causative explanation for the distribution patterns identified in this study. Although no conclusions regarding the reason for disparities in green alley distribution can be made from this study. Comparison of green alley distribution with the distribution of other variables provides a starting point for later studies attempting to explain the distribution of green alleys by controlling for variables which could potentially influence density and distribution.

Green alley infrastructure throughout Chicago clusters around the urban core of the city. The urban core has a higher green alley density than the periphery, except for community areas on the far northeast side which are comparable in density to the core. This was evidenced by density clustering patterns, KDE values, GAS values, and univariate local Moran's I clustering patterns. There are a few areas with high green alley density across the far east side and west side, but GAS values, GAS percentile values, and univariate local Moran's I clustering patterns indicate a statistically significant deficit of green alleys across the far south side. Specifically, GAS maps and univariate local Moran's I clustering patterns depict a significant deficit of green alley density west of the Calumet river and lake Calumet, despite these community areas being predominantly residential. As well, GAS maps and KDE maps indicate a disparity in density going east to west across the north side of Chicago. This disparity is reflected going west from the center of the city as well, with urban periphery community areas on the west side having comparably fewer green alleys.

Although there is no statistically significant global correlation between the distribution of green alleys and the contextual variables analyzed in this paper, the green alley deficit present in the urban periphery and urban core demonstrates local correlation with per capita income, suggesting distribution patterns worth researching further. As well, there was statistically significant inverse local correlation between green alley sites in the Calumet river and lake Calumet region and the higher levels of precipitation in these regions.

The green alley deficit present in the Calumet river and lake Calumet region is significant because it has a statistically significant spatial correlation with higher precipitation levels in Chicago. This relationship is interesting to note as local precipitation levels are directly responsible for instances of basement flooding and green alleys mitigate basement flood through redirecting precipitation flows away from sewer systems.

The disparity in green alley development across the urban periphery versus the core could raise environmental justice concerns as communities of color across the urban periphery experience higher rates of urban flood damage. As well, this disparity could raise concerns on the overall effectiveness of the green alley program in mitigating the effects of urban flooding, as urban flooding depends on local infrastructure quality, and if green alleys are not situated in proximity to higher urban flood risk areas, they most likely have minimal effect on mitigating urban flooding in areas with the highest urban flood risk. These results could outline future directions for green alley development that focus on neighborhoods such as Pullman, South Deering, Chatham, and Roseland, where urban flood damage is comparatively higher.

Further studies should investigate the relationship between precipitation levels which had one of the highest Moran's I statistics out of all variables measured against green alley density. Further studies are needed to explain the disparities of green alley density between the urban core and urban periphery. However, the information presented within this thesis concerning the distribution of green alley sites across Chicago provides relevant insights as to where green alley development has occurred and which community areas throughout Chicago are lacking green alleys. This provides a useful starting point for future evaluation on the effectiveness of green alley infrastructure and possible spatial explanations for possible disparities in effectiveness across the city.

Acknowledgements

First and foremost, I would like to express my sincerest appreciation to my advisor, Dr. Sabina Shaikh, without whom this project would not have been possible. It was at her recommendation that I chose to pursue the topic of sustainable stormwater infrastructure and urban flooding for my thesis. Her willingness to help with all aspects of the project and her unfailing support and generous availability have been invaluable assets in my ability to complete this project.

I would also like to thank my preceptor, Matthew Knisley, for providing guidance and donating generous time and support to answering my questions in terms of thesis formatting as well as content structure. I would not have been able to even process how to start this paper without the BA Colloquium class he taught fall quarter.

Further, I would like to thank Dr. Marynia Kolak, for her statistical and GIS insight, which advised the development of the Green Alley Score as a means of controlling for confounding land use variables. Dr. Kolak's instruction during the intro to GIS sequence I took junior year was essential for me to develop the skills I needed to analyze data during this thesis.

I would also like to thank the team at Chicago Studies, Julie Erdmann, and my professors who granted me time and extensions amidst constant busy schedules to complete my thesis work. Without these extensions I would not have been able to complete this thesis.

Finally, I would like to thank my family who have always provided their support to me throughout the years and have encouraged me to strive to do my best.

Appendix

Land Use Codes

A list of all land use codes with notes on whether they were included or excluded from devising the GAS values and a reason for why certain areas were excluded.

1111 – Single Family Residential Detached – Included in GAS

1112 – Single Family Residential Attached – Included in GAS

1130 – Multifamily Residential – Included in GAS

1140 – Mobile Home Parks and Trailer Courts – Included in GAS

1151 – Common Open Space in Residential Development – Included in GAS

1211 – Shopping Malls – Included in GAS

1212 – Regional and Community Retail Centers – Included in GAS

1214 – Single Large Site Retail – Included in GAS

1215 – Urban Mix – Included in GAS

1216 – Urban Mix with Residential Component – Included in GAS

1220 – Office – Included in GAS

1240 – Cultural/Entertainment – Excluded from GAS 3

1250 – Hotel/Motel – Included in GAS

1310 – Medical Facilities – Included in GAS

1321 – K-12 Facilities – Included in GAS

1322 – Post-Secondary Education Facilities – Included in GAS

1330 – Government Administration and Services – Included in GAS

1340 – Prison and Correctional Facilities – Included in GAS

1350 – Religious Facilities – Included in GAS

1360 – Cemeteries – Excluded from GAS as cemeteries lacked alley space.

1370 – Other Institutional – Included in GAS

1380 – National Laboratory – No national laboratory land use in Chicago.

1410 – Mineral Extraction – Excluded from GAS due to potential toxic materials presence.

1420 – General Industrial (<100,000 sq ft) – Included in GAS

1431 – Industrial G/E 100,000 sq ft: Manufacturing/ Processing – Excluded from GAS 2-3

1432 – Industrial G/E 100,000 sq ft: Warehousing/ Distribution – Excluded from GAS 2-3

1433 – Industrial G/E 100,000 sq ft: Flex or Indeterminate – Excluded from GAS 2-3

1450 – Storage – Included in GAS

1511 – Railway – Excluded from GAS due to high impact vehicles, sub-ground infrastructure, and potential for contaminant seepage.

1512 – Roadway – Excluded from GAS due to high impact vehicles.

1520 – Other linear transportation – Excluded from GAS due to high impact vehicles.

1530 – Aircraft Transportation – Excluded from GAS due to high impact vehicles.

1540 – Independent Automobile Parking – Included in GAS

1550 – Communication – Included in GAS

1561 – Utility Right of Way – Excluded from GAS due to sub-ground infrastructure.

1562 – Wastewater Treatment Facility – Excluded from GAS due to potential toxic materials seepage and sub-ground utilities infrastructure.

1563 – Landfill – Excluded from GAS due to lack of green alleys and potential toxic materials.

1564 – Other Utility/ Waste – Excluded from GAS due to potential toxic materials and sub-ground infrastructure.

1565 – Stormwater Management – Excluded from GAS due to primarily including rainwater detention basins, which were not the same as green alleys.

1570 – Intermodal Facility – Excluded from GAS due to high impact vehicles.

2000 – Agriculture – No presence in Chicago.

3100 – Open Space Primarily Recreation – Excluded from GAS due to green space lacking paved alley developments.

3200 – Golf Course – Excluded from GAS due to lack of paved alley developments.

3300 – Open Space, Primarily Conservation – Excluded from GAS due to lack of paved developments.

3400 – Non-public open space – Excluded from GAS due to lack of paved developments.

3500 – Trail or Greenway – Excluded from GAS due to lack of paved alley space.

4110 – Vacant Residential Land – Included in GAS due to potential for green alley development.

4120 – Vacant Commercial Land – Included in GAS due to potential for green alley development.

4130 – Vacant Industrial Land – Excluded from GAS 2-3

4140 – Other Vacant – Included in GAS due to potential for green alley development.

4210 – Under Construction, Residential – Included in GAS due to potential for green alley development.

4220 – Under Construction, Commercial – Included in GAS due to potential for green alley development.

4230 – Under Construction, Industrial – Excluded from GAS 2-3

4240 – Under Construction, unknown – Included in GAS due to potential for green alley development.

5000 – Water – Excluded from GAS due to lack of paved alley space.

6000 – Non-Parcel Areas – Excluded from GAS 1-3 due to high impact vehicles and bodies of water.

9999 – Not classifiable – Excluded from GAS due to not being very prevalent as well as uncertainties in classification.

No Correlation Variables

4.2.1 GAS and Land Use Variables

4.2.1.1 Blue Index

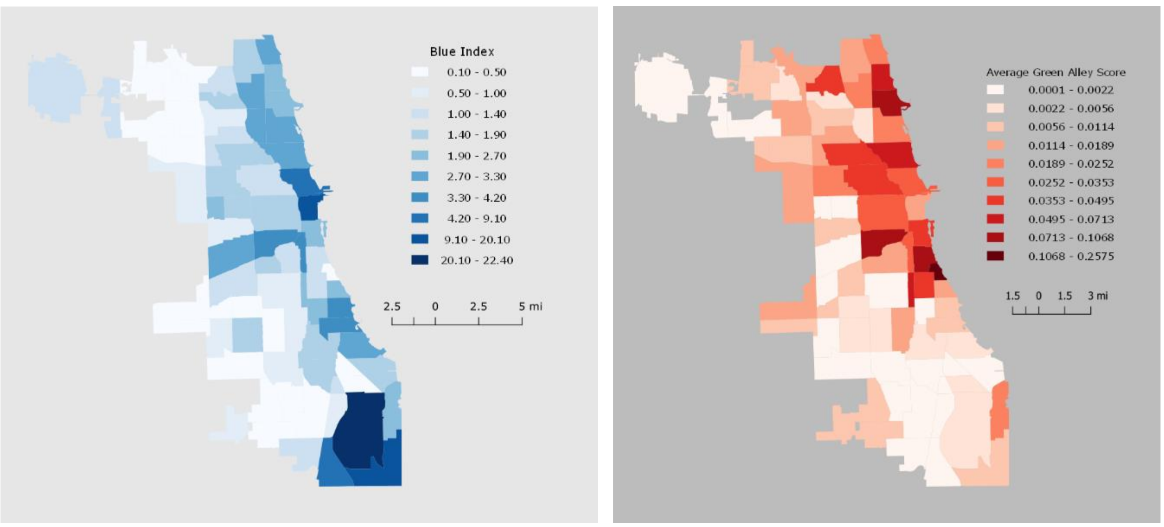

Figure 45 (Left) Distribution of blue index values across community areas. The Blue index is a measurement of the amount of a community area covered by water. (Right) The distribution of Average GAS values across community areas.

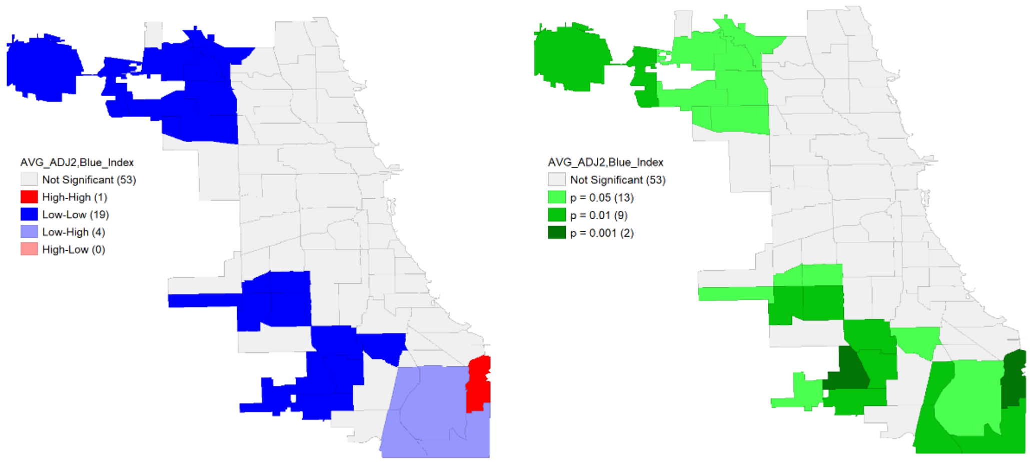

Figure 46 (Left) Map depicting where statistically significant local clustering of blue index values (Blue_Index) was consistent with clustering of GAS values (AVG_ADJ2). (Right) Map depicting the p values of statistically significant clusters, indicating the degree of significance.

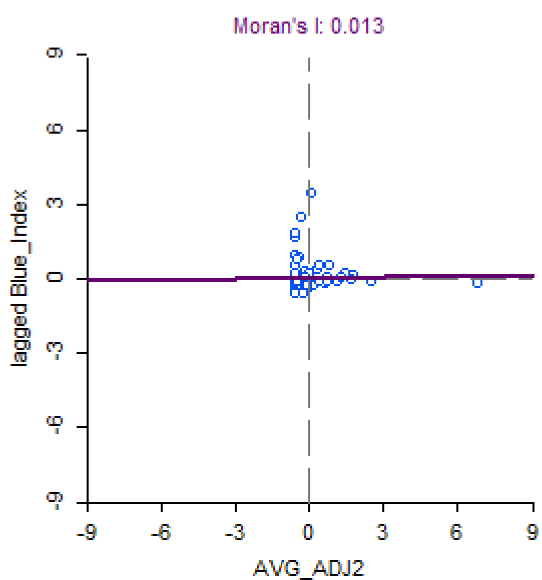

Figure 47 Moran's I scatterplot for the spatial correlation of Average GAS values (x axis) and blue index levels (y axis) per community areas.

The blue index is a measurement of the amount of community space covered in water. With a global Moran's I value of .013 there is no correlation between the spatial distribution of green alleys and the distribution of "blue" land coverage. Clustering patterns varied significantly with clustering between community areas with high blue indices and low green alley scores occurring on the far south side and clustering between low blue indices and low green alley scores occurring on the west and northwest side. These clusters did not match with broader patterns of green alley distribution and density, suggesting statistically significant clustering but no broader trends in terms of the spatial distribution of green alleys in relation to water coverage. Clusters of low green alley density community areas, shown on the univariate local Moran's I maps, were broken up across multiple clusters of blue index, suggesting that local clustering of green alley density was independent of the clustering of water coverage. If high water coverage was related to lower green alley density one would expect to see consistently lower green alley density in areas with higher water coverage, however areas with high water coverage have varied green alley density, with high density community areas such as East Side having high blue indices as well as low density community areas such as Chatham.

4.2.1.2 Green Index

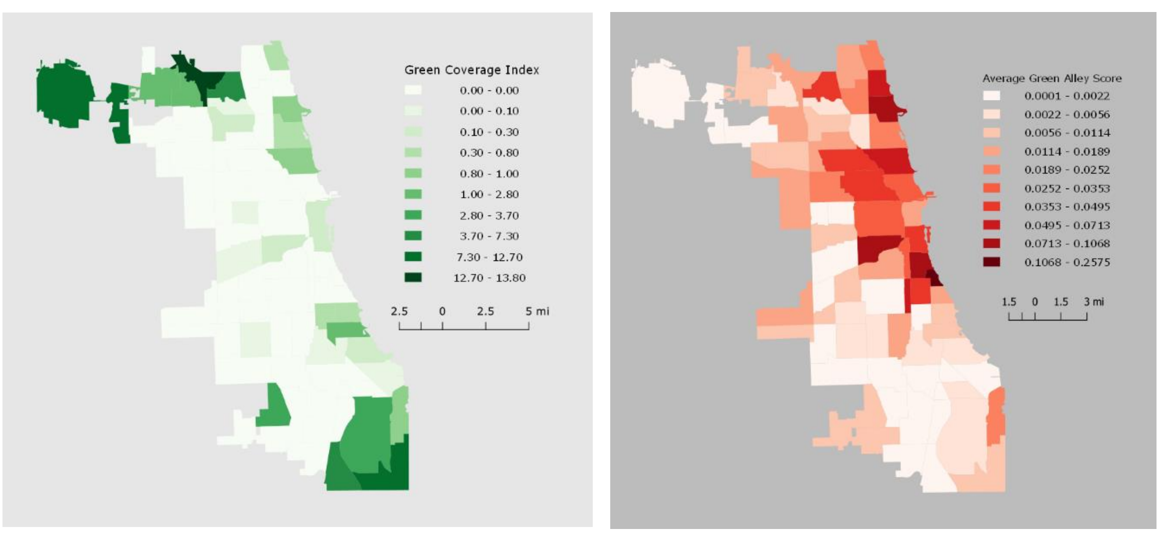

Figure 48 (Left) Distribution of green index values across community areas. The Green index is a measurement of the amount of a community area covered by vegetative land. (Right) The distribution of Average GAS values across community areas.

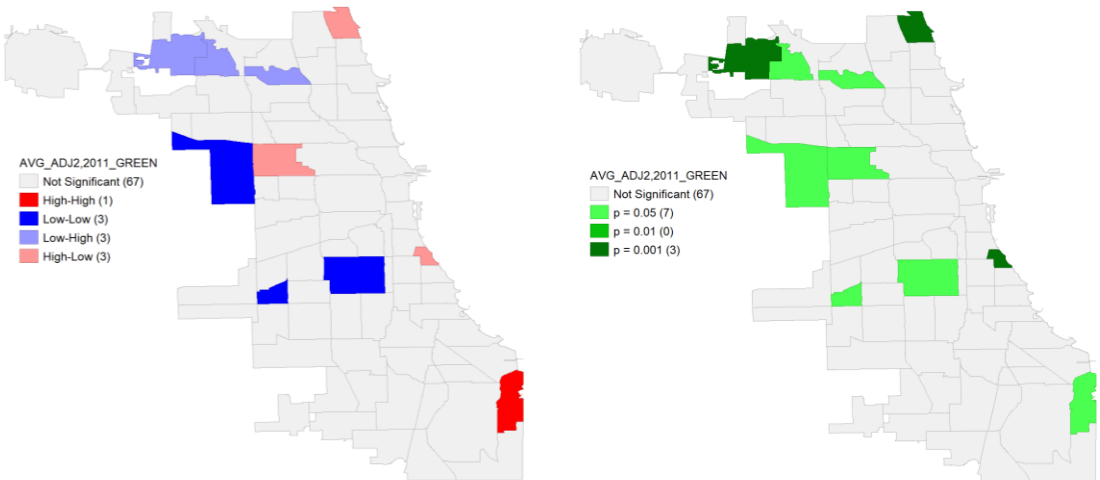

Figure 49 (Left) Map depicting where statistically significant local clustering of green index values (2011_GREEN) was consistent with clustering of GAS values (AVG_ADJ2). (Right) Map depicting the p values of statistically significant clusters, indicating the degree of significance.

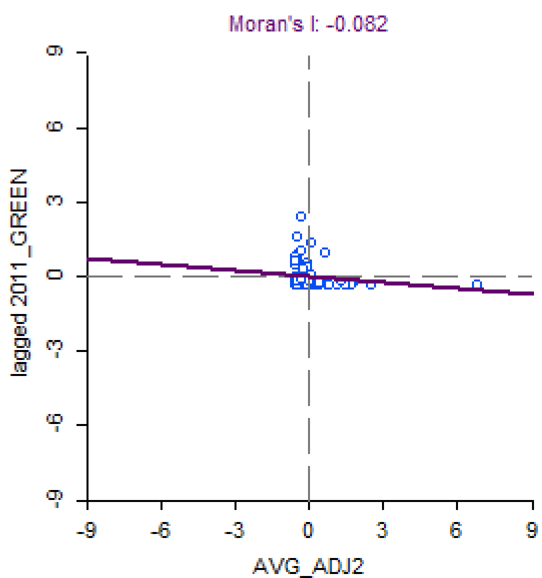

Figure 50 Moran's I scatterplot for the spatial correlation of Average GAS values (x axis) and green index levels (y axis) per community areas.

The green index is a measurement of total vegetation land coverage as a percent of total community area space. If green alley sites were inversely dependent on the amount of vegetation in an area, one would expect to find lower GAS values correlating with higher green index scores. This was not the case. With a global bivariate Moran's I statistic of -.082 there is no correlation between the spatial distribution of green coverage and the spatial distribution of green alley density. Local Moran's I clusters indicate statistically significant correlation between several community areas dispersed across the city. However, these clusters vary significantly and do not confirm a broader relationship between the green index and green alley density across the city.

4.2.1.3 Grey Index

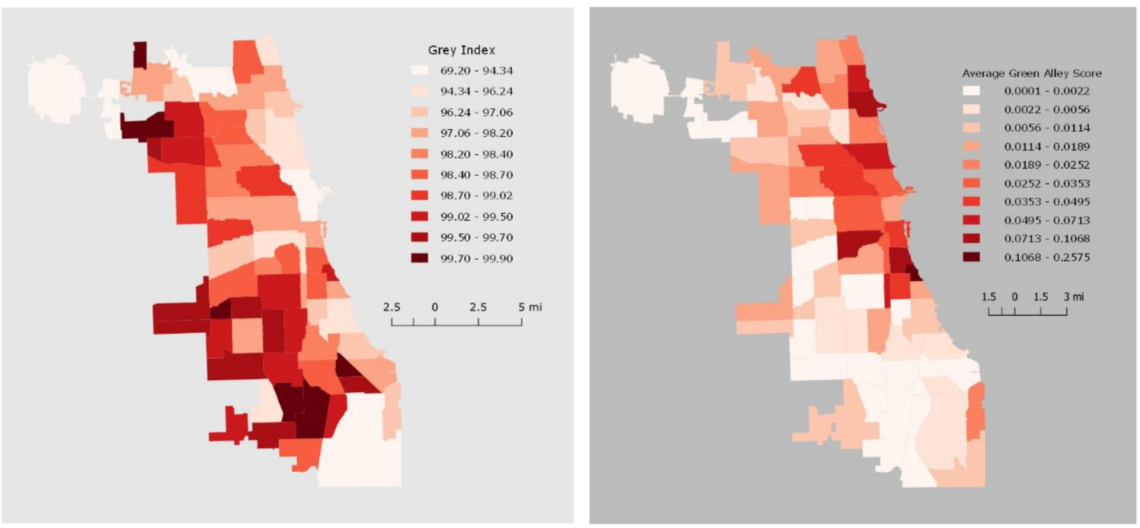

Figure 51 (Left) Distribution of grey index values across community areas. The grey index is a measurement of the percent of a community area covered by developed land. (Right) The distribution of Average GAS values across community areas.

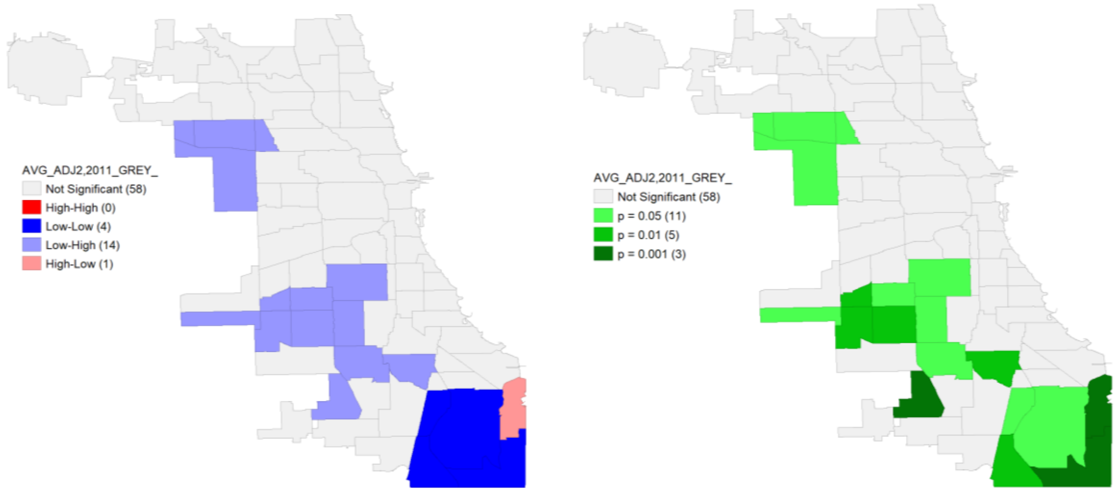

Figure 52 (Left) Map depicting where statistically significant local clustering of grey index values (2011_GREY_) was consistent with clustering of GAS values (AVG_ADJ2). (Right) Map depicting the p values of statistically significant clusters, indicating the degree of significance.

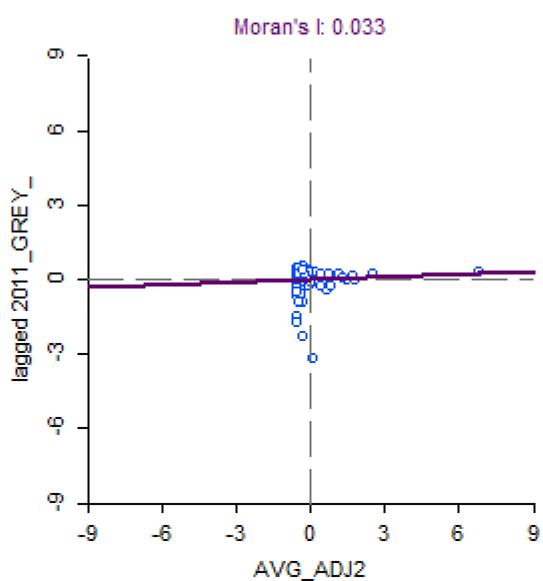

Figure 53 Moran's I scatterplot for the spatial correlation of Average GAS values (x axis) and grey index levels (y axis) per community areas.

The grey index is a measurement of total developed land as a percent of total community area space. A statistically significant relationship between green alley density and the grey index would indicate that the percent of developed land in a community area could possibly explain the presence of greater green alley density. With a global bivariate Moran's I statistic of .033 there is no correlation between the spatial distribution of grey coverage and the spatial distribution of green alley density. Local Moran's I clusters indicate no broader patterns of local correlation between green alley density and developed land coverage in an area. Community areas with low grey land indices both have low and high green alley density. Similarly community areas with high grey land indices occur generally throughout the west side of the city and thus statistically cluster with low green alley density clusters on the west side, but there is no broader pattern of relationship between high grey indices and low green alley scores, as several community areas with high grey indices also have high green alley scores, such as West Town and Logan Square.

4.2.1.4 Road Index

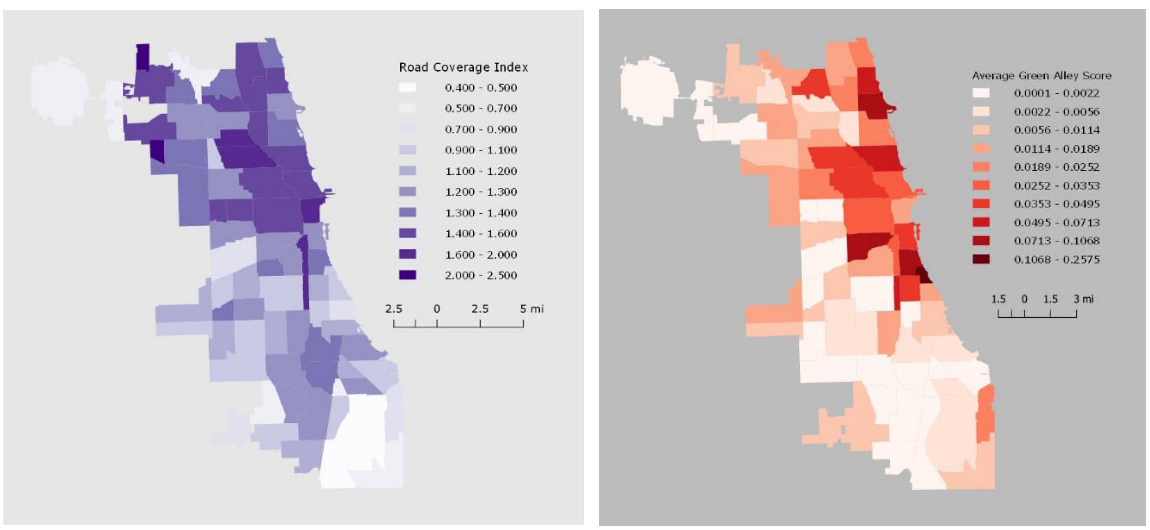

Figure 54 (Left) Distribution of road index values across community areas. The road index is a measurement of the road density in a community area. (Right) The distribution of Average GAS values across community areas.

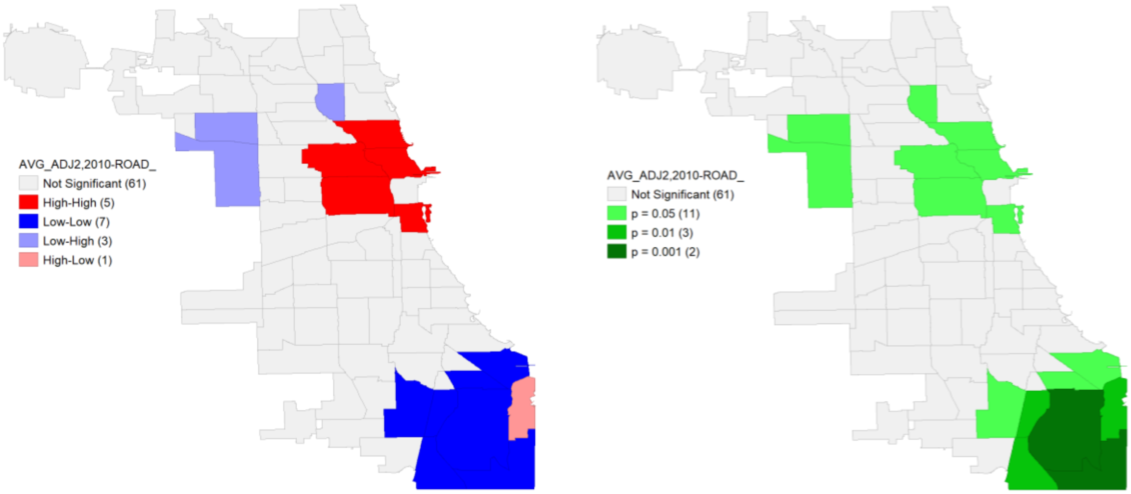

Figure 55 (Left) Map depicting where statistically significant local clustering of road index values (2010-ROAD_) was consistent with clustering of GAS values (AVG_ADJ2). (Right) Map depicting the p values of statistically significant clusters, indicating the degree of significance.

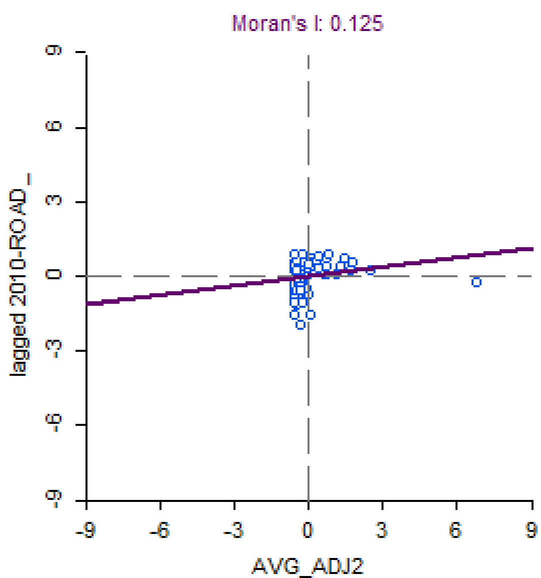

Figure 56 Moran's I scatterplot for the spatial correlation of Average GAS values (x axis) and road index levels (y axis) per community areas.

The road index is a measurement of the density of road coverage in a community area. With a global bivariate Moran's I statistic of .125 there is no correlation between the spatial distribution of road coverage and the spatial distribution of green alley density. Local Moran's I clusters indicate statistically significant correlation between near north side neighborhoods and high road coverage, but broader patterns of clustering indicating a relationship between road coverage and green alley density were not apparent.

4.2.1.5 Vegetation Index

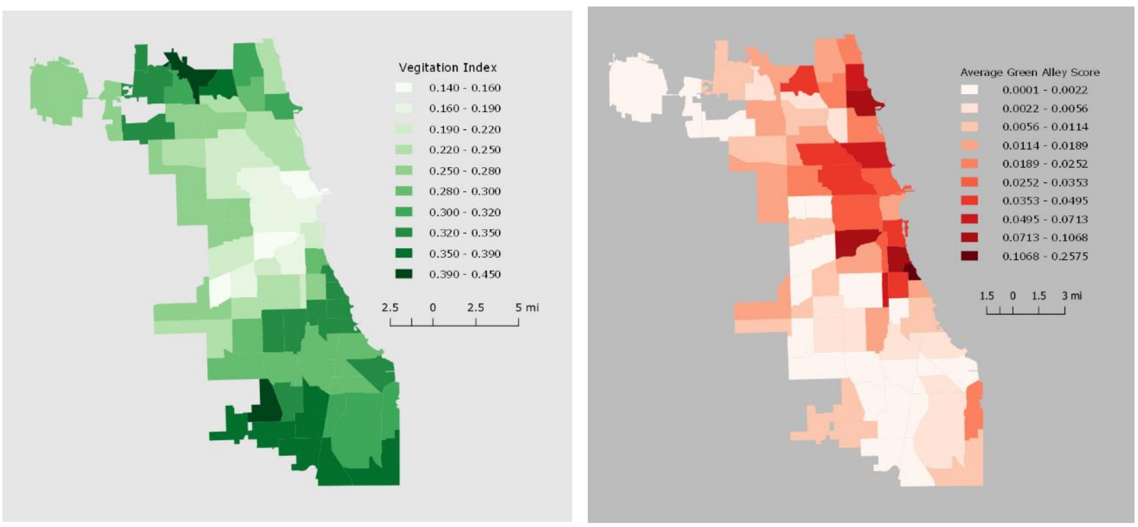

Figure 57 (Left) Distribution of vegetation index values across community areas. The vegetation index is a measurement of the amount of a community area covered by vegetation. (Right) The distribution of Average GAS values across community areas.

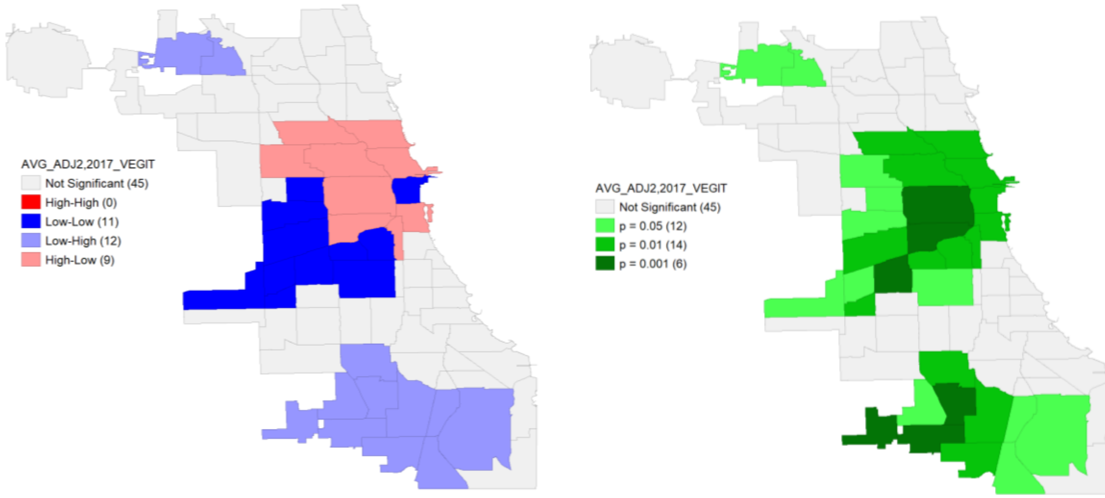

Figure 58 (Left) Map depicting where statistically significant local clustering of vegetation index values (2017_VEGIT) was consistent with clustering of GAS values (AVG_ADJ2). (Right) Map depicting the p values of statistically significant clusters, indicating the degree of significance.

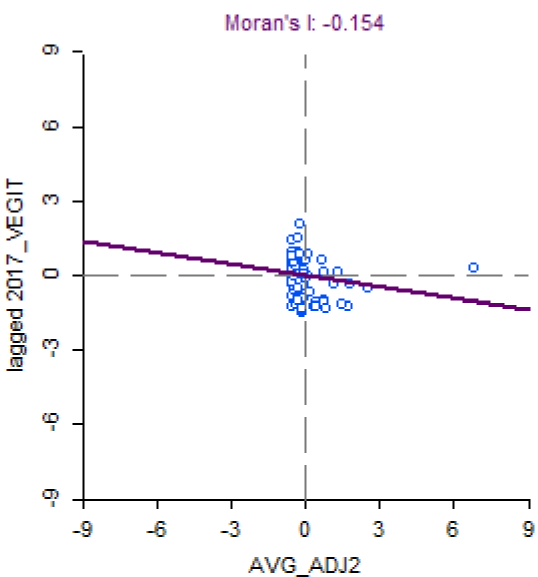

Figure 59 Moran's I scatterplot for the spatial correlation of Average GAS values (x axis) and vegetation index levels (y axis) per community areas.

The vegetation index is a measurement of total vegetative land coverage in a community area, distinct from the green index because it measures vegetative coverage based on an average number of green pixels in satellite imagery. This allows the vegetation index to assess green coverage on private property as well as in areas not specifically zoned as green space by the National Land Cover Database. With a global bivariate Moran's I statistic of -.154 there is no correlation between the spatial distribution of vegetative coverage and the spatial distribution of green alley density. Broader patterns based on statistically significant local clustering were not apparent although vegetative coverage was present at greater levels in the urban periphery.

GAS and Environmental Variables

4.2.2.2 Coarse Particle Pollution

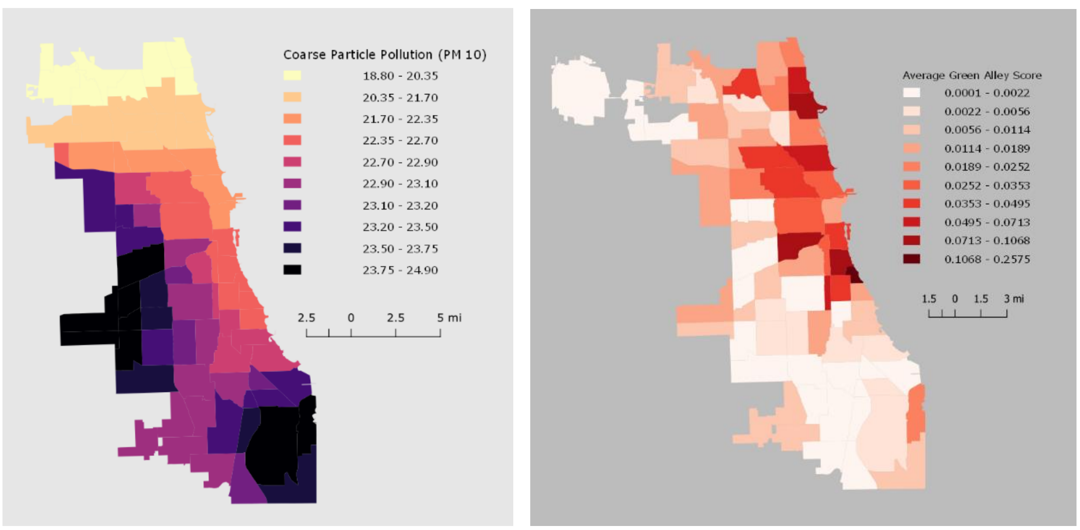

Figure 60 (Left) Coarse particle pollution levels (PM 10) per community area across Chicago. (Right) Average GAS value distributed across community area.

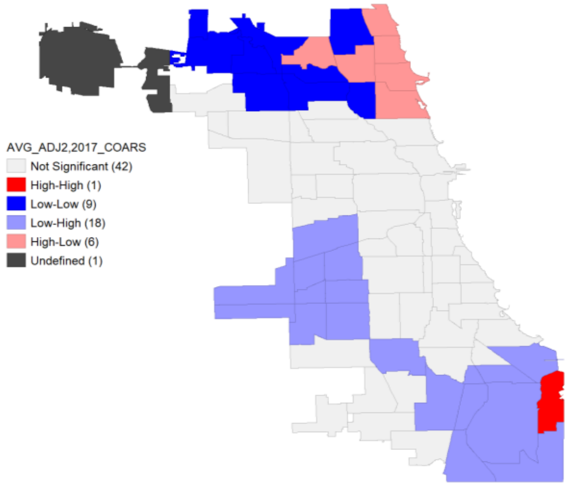

Figure 61 (Left) Local bivariate Moran's I clustering of green alley scores (AVG_ADJ2) correlated with coarse particle pollution levels across community areas (2017_COARS). (right) P values indicating degree of statistical significance for clustering

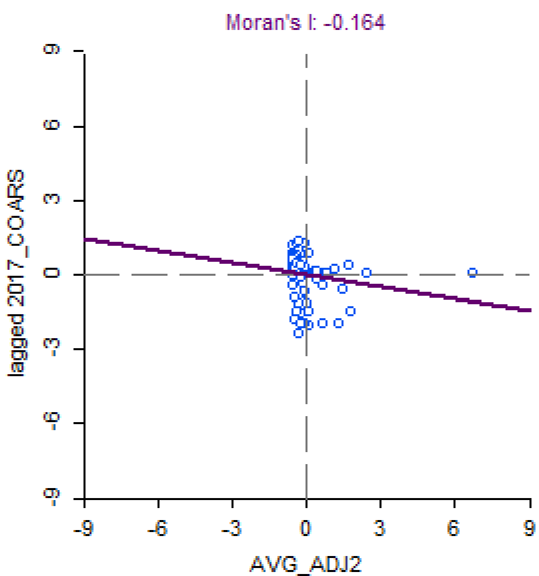

Figure 62 Moran's I scatterplot for the spatial correlation of Average GAS values (x axis) and coarse particle polllution levels (y axis) per community areas.

With a bivariate Moran's I statistic of -.164 there is no statistically significant correlation between the levels of coarse particle pollution across the city and the distribution in green alley density. The distribution of coarse particle pollution (measured as particulate matter less than 10 micrometers in diameter) emphasizes a north-south divide across Chicago, as the highest coarse particle pollutions occur on the far south and west side and the lowest levels occur on the north side. Local bivariate clustering emphasized the north-south patterns apparent in green alley clustering by clustering low green alley scores on the south side with high coarse particle pollution levels. Clustering on the northside with lower coarse particle pollution levels encompassed a range of green alley density clusters and helped to emphasize the east west divide in green alley density along the north side; however, the variation in green alley density across this cluster indicated a lack of relationship between green alley density and coarse particle pollution, as the clustering of coarse particle pollution was not consistent with broader disparities in density between the urban core and urban periphery.

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