Concentric Perspectives on Urban Densification: A GIS-Based Cluster Analysis in the Great Lakes Region

by

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A dissertation submitted in partial fulfillment
of the requirements for the degree of
M.S. in Environment and Sustainability
(Geospatial Data Science)
in the University of Michigan
2023

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Acknowledgements

I would like to thank my supervisor Dr. Derek Van Berkle for all the help and advice with this Practicum. I would also like to thank my husband, whom without this would have not been possible. I also appreciate all the support I received from the rest of my family.

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Abstract

Understanding urban densities is crucial as it directly influences urban planning and sustainable development. These planning and development processes directly impact equitable resource allocation, transportation efficiency, and environmental quality. Understanding urban densities enables urban planners and policymakers to create more inclusive, equitable, livable, and resilient urban spaces that cater to the evolving needs of diverse populations. This study uses a geospatial approach influenced by Von Thünen's land use theory to examine urban densification in the Great Lakes region of the US. It applies Geographic Information Systems (GIS) to identify concentric zones extending one mile from urban centers in Michigan, Wisconsin, Illinois, Indiana, Ohio, and Pennsylvania. The study analyzes over 750 urban areas, considering population density, green space, urban infrastructure, and building heights. The population density data are sourced from a Dasymetric map provided by the EPA. Green space is mapped using a raster created from park shapefiles. Urban infrastructure is identified from impervious area raster from the NLCD dataset, and building heights are derived from GML files. This methodology reveals patterns in urban development and their implications for policymaking. It suggests prioritizing downtown densification to address urban sprawl and support environmental sustainability. The key findings were four distinct urban development clusters, each with unique characteristics: Cluster 1 included cities like Detroit and Chicago, showing potential for suburban densification around well-established infrastructure; Cluster 2 featured cities such as Champaign (mostly tier 2 cities), with opportunities for densification without compromising environmental quality; Cluster 3 encompassed cities with notable decreases in infrastructure and population densities (cities with population under 30000), indicating areas ripe for urban density increase; and Cluster 4 represents a small group of cities where densification was balanced with green space expansion. These insights inform urban planning, highlighting downtown densification's importance in countering urban sprawl and enhancing environmental sustainability in the American Great Lakes region.

Chapter 1 Introduction

Since the mid-19th century, the landscape of American cities has evolved considerably due to industrialization and technological advances, leading to increased urban sprawl (The Explosive Growth of American Cities | United States History II, n.d.). Key urban areas saw notable growth during this period, largely fueled by the rise of factories and industrial production (Yuko, 2023). This growth brought with it several challenges including higher population densities underscoring the need for well-thought-out urban planning. Today, the trend of urban sprawl continues to affect natural environments predictions suggest that by 2040, urban expansion in the United States will have a considerable impact on both agricultural and residential lands. Strategies like increasing urban density and rejuvenating city centers are suggested as ways to achieve sustainable urban development, addressing the ongoing challenges posed by urban sprawl and supporting the long-term sustainability of urban environments (Shen et al., 2021).

Urban planning and sustainability scientists are increasingly focusing on the development and application of models that simulate urban morphologies that promote the health and well-being of the residents and the environment (Laidley, 2016; Talen, 2011). Geographic Information Systems (GIS) and spatial analysis have emerged as key tools in these efforts, enabling more precise and effective urban modeling and simulation. Research has demonstrated that spatial analysis techniques can be useful in identifying areas suitable for sustainable urban growth by analyzing factors like existing land use, infrastructure capacity, proximity to public transit, and environmental constraints (Shen et al., 2021). Researchers have modeled changing urban densities, thus providing crucial insights into urban development patterns. (Wang et al., 2019). Geospatial modeling has also allowed researchers to find that densification can relieve infrastructural pressure on cities, conserve vital greenspace, and still accommodate growing population (Pelczynski & Tomkowicz, 2019; Van Neste & Royer, 2022). To support densification, other studies have also found an increasing desire to live near Central Business Districts (CBDs) (Ehrenhalt, 2022), signifying a shift towards decentralized urban employment (Angel & Blei, 2016). Still, the dominant mode of urban planning is often oriented towards suburbanization and single family unit development (Moos & Skaburskis, 2008), and this is causing loss of working lands, insufficient tax base to provide adequate infrastructure and services, and increased environmental pressures (Habibi & Asadi, 2011). With projected population increases (Bureau, 2023) there is a growing need to prepare American cities for sustainable growth to accommodate this expanding population. Promoting densification in US cities requires comprehensive understanding of urban morphologies for spatially targeting where densification might be possible. Such knowledge would support policymakers in developing their cities that maintains ecological balance and sustainability.

This Practicum explores the spatial variation of urban density within the Cities of the Great Lakes, United States. The study draws on the theoretical constructs of Johann Heinrich Von Thünen's land use theory and GIS analysis to investigate the relationship between population densities and distance from the central business district to understand a potentially smaller urban footprint across US cities (Fujita et al., 1999). The Great Lake areas, encompassing Michigan, Wisconsin, Illinois, Indiana, Ohio, and Pennsylvania, provide a diverse tapestry for examining urban expansion and its implications. Our analysis of conceptual concentric rings of urban density (Fontes & Palmer, 2018; Roos et al., 2018; Smith et al., 2019) for the cities in the GL allows for the building typologies of population patterns based on cluster analysis (Spielman & Logan, 2013). Based on densification potentials, the resulting clusters form the basis for targeted urban planning recommendations that could bolster urban cores' vitality, enhancing sustainability and livability (Rodrigue et al., 2013).

Chapter 2 Literature Review

The Industrial Revolution, the advent of the automobile and laissez-faire planning policy in the mid-19th century significantly contributed to sprawling urban morphologies with large urban foot-prints. The development of steam engines and electricity allowed factories to be located near urban centers rather than just near rivers and seaports (*The Explosive Growth of American Cities | United States History II*, n.d.). Between 1880 and 1890, nearly 40% of townships in the United States lost population due to this migration. This shift was driven by industrial expansion and population growth, radically changing the nation's urban landscapes (Library of Congress, n.d.). Cities like Boston, Philadelphia, New York City, and Baltimore saw significant growth due to the establishment of mills, factories, and mass production sites, attracting people to urban areas for job opportunities (Yuko, 2023). As city populations surged, challenges such as housing availability, overcrowding, and the spread of infectious diseases had to be addressed to maintain the viability of these growing urban centers (Yuko, 2023). This trend, driven by the desire for urban conveniences blended with rural tranquility, was particularly noticeable in cities like Los Angeles, which emerged as a paradigm of suburban development. The growth of these areas was increasingly tailored to the needs of the automobile, leading to extensive road networks and car-dependent communities (State of California, n.d.). This shift towards suburban living had several consequences. Firstly, it contributed to the loss of farmland, as agricultural lands were converted into residential and commercial developments to accommodate the growing suburban populations (Lopez et al., 1988). The rise of suburbs also led to a phenomenon known as "urban flight," where a significant portion of the population, particularly the middle and upper classes, moved from city centers to suburban areas. This migration resulted in a loss of tax base for the urban areas, as the residents who moved took their economic contributions with them. The decreased tax revenue affected the cities' ability to maintain and improve public services and infrastructure, exacerbating urban decline in some cases (Publisher, 2016). The phenomenon of urban sprawl that began in this era persists in the United States today, characterized by a spiral outward growth pattern, low-density housing, and a blurred distinction between urban and rural areas (Piccard, 2023).

2.1 Urban form in the US and the occurring processes.

Today, the current state of urban development indicates a significant loss of agricultural land due to urban expansion. In the United States, urbanization is projected to compromise 18 million acres by 2040, impacting both non-cultivable and low-density residential land uses. Urban land expansion is expected to reduce croplands by 1.8–2.4% by 2030, predominantly affecting Asia and Africa. This situation emphasizes the critical need for policy measures to manage urban growth while preserving essential agricultural areas (Bren d’Amour et al., 2017; Ewing, 2008; Xie et al., 2023). Another study forecasts a significant increase in urbanization, ranging from 101% to 192%, leading to substantial ecosystem fragmentation. This emphasizes the need for balancing ecosystem health with economic growth and cultural preferences and highlights the importance of policy interventions in guiding sustainable urban development (Terando et al., 2014). While many studies emphasize the need for effective urban planning and governance to balance urban growth, multifaceted urban planning, and public policy reforms to control sprawl (Ewing, 2008; Habibi & Asadi, 2011), some studies also point to densification as a strategy to combat urban sprawl leading to more sustainable urban development (Pelczynski &

Tomkowicz, 2019; Van Neste & Royer, 2022). Urban planners and sustainability scientists have also advocated for urban renewal of downtown and central business districts and increased densification. They suggest that the city's urban structure, characterized by a central business district surrounded by largely vacant neighborhoods, highlights the critical need for coordinated development efforts to revitalize underutilized downtown areas and foster sustainable urban growth (Hendrix et al., 2018; Owens et al., 2020). In conclusion, these studies collectively highlight the pressing challenges of rapid urban growth in the United States. They underscore the critical need for strategic urban planning and policy interventions to mitigate the fragmentation or loss of natural ecosystems.

Managing urban density becomes crucial for urban planning and environmental sustainability as cities expand. For example, cities experiencing growth are considering different urban expansion scenarios with differing trade-offs that impact the health and well-being of residents and their ecological footprint. Densification has been suggested as a solution that minimizes the loss of farmlands and preserves ecological systems. Moreover, there is also evidence that dense cities can maintain vital urban infrastructure. However, research has also noted the detrimental health and well-being impacts of less access to urban green space and equity considerations (Nesbitt et al., 2019). A study by H.-C. Wang explores the relationship between urban compactness and quality of life (QOL) in 44 U.S. cities. It finds that while increased compactness often improves QOL, excessive compactness can have detrimental effects. This challenges the universal applicability of compact urban development, especially in low-income areas where it may reduce QOL. The study recommends tailoring compact development to local conditions, considering factors such as public transportation, density, and urban form. Additionally, Egger's 2006 study "Determining a Sustainable City Model" delves into the relationship between urbanization and sustainability. It highlights the necessity of considering global network interactions and local city dynamics for sustainable development. This approach balances economic growth, environmental preservation, and social equity. The study underscores the importance of innovation, infrastructure, social capital, and integrated planning in enhancing city resilience and adaptability. Furthermore, the study "Smart Sustainable Cities of the Future" by Bibri & Krogstie, 2017 examines sustainable urban development amidst rapid urbanization. It emphasizes the need for a paradigm shift in urban planning, highlighting the role of Information and Communication Technology (ICT) in urban sustainability. The study investigates how ICT can help address environmental and socio-economic challenges in cities. It explores the interplay between smart and sustainable city concepts, noting the potential yet to be explored between these approaches. In conclusion, these studies emphasize the significance of strategic context-specific solutions in achieving sustainable and equitable urban planning. Effectively harnessing underutilized urban spaces in a city, particularly in downtown regions, while addressing the challenges posed by urban sprawl is key to fostering sustainable urban growth. This approach optimizes city layouts and promotes a more coherent and efficient development framework.

2.2 GIS and model approach to the analysis of cities

The scholarly discourse on model-based urban densification provides a multifaceted understanding of the evolution of urban densification, drawing from diverse methodologies and thematic focuses like socio-economic stability, transportation, preserving the city’s natural scape and so on. A study conducted by L. Wang et al., 2019, investigates urban densification, an essential aspect of urbanization. Utilizing the Land Transformation Model (LTM) and comprehensive datasets, it analyzes urban density changes from 2001 to 2011 in Southeastern Wisconsin (SEWI). Key findings indicate a trend towards lower-density development, with a notable increase in open spaces and lower-density urban areas. The study forecasts continued urban densification, particularly in Milwaukee County, with higher-density areas expected to expand at the expense of lower densities. This research emphasizes the need for detailed urban density categories and various socio-economic predictors in urban planning, advocating for efficient land use and rational densification strategies to promote sustainable urbanization. Similarly, a study by Shen et al., 2021, introduces a methodology to evaluate the suitability of locations for high-density urban development. This approach aims to facilitate spatial decision-making and support justifiable urban planning. Using the Logic Scoring of Preference (LSP) method, the study assesses urban densification suitability from the perspectives of urban developers and planners. It employs GIS-based multicriteria evaluation methods and uses geospatial data from Metro Vancouver, Canada. Another study by Talen, 2011, focuses on developing strategies for suburban retrofit or sprawl repair. Talen's approach involves assessing the potential of various urban locations as catalysts for sustainable development in Phoenix, Arizona. This includes analyzing accessibility, connectivity, density, diversity, and modality of places. These aspects are crucial for sustainable urban form, emphasizing pedestrian-oriented streets, interconnected neighborhoods, and a mix of housing types and land uses. The paper also highlights retrofitting strategies like code reform, targeted public investment, and incentives for private development. These strategies aim to foster sustainable urban development through small, focused interventions within a larger city planning context. Kyttä et al., 2013 explore the complex dynamics of urban densification and its impact on residents. The study recognizes that while urban consolidation is essential for sustainable urban development, it often clashes with the preferences of residents who fear losing valued environmental qualities. The research involves a large-scale softGIS survey with over 3100 participants from the Helsinki metropolitan area, collecting over 10,000 place experiences related to urban structural characteristics such as density and green structure proportion. Such localized sensitivity complements this study's broader geographical scope and data-driven comparative analysis.

The role of simulation and modeling in forecasting urban growth has been underscored, with built-up densification processes identified as crucial for policymakers to limit sprawl. Integrating Cellular Automata within GIS environments reflects the interdisciplinary nature of modern urban studies (Chakraborty et al., 2022). Community-scale GIS-based analyses have similarly aimed to inform sustainable urban renewal strategies, aligning with the objectives of the present study to develop sustainable urban form policies through densification (Chen et al., 2023). Simulation platforms have also been conceived to facilitate the visualization of urban densification, integrating topographic data and population density metrics within a GIS framework, resonating with the methodological approach of this study but diverging in the specific application and focus on comparative data analysis (Saxena et al., 2021). Furthermore, the challenge of delineating urban areas using building density data has been addressed, developing new methodologies for understanding urban forms, which complements the analytical techniques employed in this research (De Bellefon et al., 2019). Lastly, the social sustainability of urban densification has been examined, viewing density as a critical dimension of urban sustainability and a vital tool for achieving environmental, economic, and social objectives, thus contextualizing the densification efforts within a broader sustainability framework (Cavicchia & Cucca, 2022). Collectively, these studies provide valuable insights into the spatial patterns of urban densification. Utilizing GIS technology, modeling, and comparative analysis, this study adds to understanding urban development complexities, aiding urban planning decisions in addressing urban sprawl.

The collection of studies reviewed here presents a comprehensive analysis of urban growth and its various dimensions in the United States, with a specific focus on urban densification, sustainability, and the evolving spatial structure of cities. While each study contributes unique insights into urban planning and development, the current research stands out for its innovative approach. This study employs the concentric ring theory, coupled with Geographic Information System (GIS) technology, to analyze and understand various urban attributes such as green space, population density, building heights, and infrastructure. By applying this theory, the research successfully clusters cities with similar characteristics, providing a nuanced understanding of spatial pattern of the city. This novel approach not only sheds light on the physical expansion of cities but also delves into the potential for urban densification in different typology of the cities.

Chapter 3 Methodology

This study employs spatial analysis of urban morphological patterns across over 750 cities in the Great Lakes region of the US to identify and understand the diverse urban development trends in this area. It categorizes population density, green space availability, building height, and infrastructure distribution key measures of urban morphology to understand which cities could adopt densification strategies and where this should be targeted. The following sections detail the methodologies used in data preparation, processing, and zonal statistical analysis, leveraging the capabilities of GIS and custom Python scripting. Integrating various data sources, including the National Atlas of the United States, EPA Dasymetric maps, and the Open City Model, provides a comprehensive framework to understand the complexities of urban expansion and its implications on urban planning and decision-making.

3.1 Rationale behind choosing the attributes.

The four attributes considered in the analysis are population density, green space, building height and infrastructure facilities (roads and parking)

3.1.1 Urban green spaces

Studies have shown that urban green spaces are pivotal in curbing urban sprawl and fostering sustainable cities by acting as natural boundaries that contain urban expansion. (European Commission. Directorate-General for the Environment, 2010). Studies have also shown that by enhancing the livability and attractiveness of urban cores, green spaces draw residents and businesses inward, alleviating the push towards outward expansion. (Anguluri & Narayanan, 2017). The current study understands the importance of green spaces in urban densification; sustainable urban growth demands a balanced approach where development does not come at the cost of green spaces (Pourtaherian & Jaeger, 2022). Furthermore, the equitable distribution of these green areas is vital to ensure that all city residents, regardless of their location within the urban fabric, have access to the benefits provided by green spaces. This aspect is particularly important in the context of rapid urbanization, where green spaces are often under threat from development pressures or are not equitably accessible to all the residents.

3.1.2 Infrastructure

Parking and road infrastructure, integral to urban densification, are undergoing a paradigm shift in American cities. With public transportation becoming more accessible (Block, 2023). The large parking areas offer potential for new developments. This is especially relevant as urban population growth intensifies housing demands and compels a reevaluation of urban density (Harrison, 2023). Cities are critically reassessing parking mandates, traditionally requiring more spaces than necessary, aiming to optimize urban land use more effectively. This shift towards reducing parking spaces is not only a strategic move to alleviate housing shortages but also a step towards enhancing urban density and sustainability (Woodard, 2023).

3.1.3 Building height information

Building height information is crucial in urban densification as informs analyses of urban sprawl and resilience planning as in helps in understanding whether or not high-rise can be built, and assists in understanding urban form using data on neighborhood morphology and infrastructure network networks (Milojevic-Dupont et al., 2020). Additionally, building height correlates with a building's location within a city, with denser areas like city centers typically having taller buildings. This correlation along with population information can help in assessing the potential locations for densification within a city (Agius et al., 2018).

3.1.4 Population density

Population density is central to urban planning, as it influences how cities grow and adapt (Guha, 2014). As urban populations grow, it becomes crucial to understand existing population densities to effectively manage new population influxes (Benzow, 2023). Identifying already densely populated areas helps in avoiding overburdening them further. Conversely, areas with low population but high infrastructure and building capacity can be targeted for densification. This approach not only optimizes urban space use but also ensures a balanced distribution of population. Therefore, analyzing spatial properties of population density is vital for sustainable urban planning, enabling cities to accommodate growth while maintaining livability and preventing over-concentration in certain areas (Kii, 2021).

3.2 Data preparation and processing.

Urban area point shapefiles were sourced from the National Atlas of the United States for the Great Lakes states of Michigan, Pennsylvania, Ohio, Indiana, Illinois, and Wisconsin to represent the geographic centers of cities. These points represent the central commercial area in the city. Another dataset, the polygon shapefile of urban areas of the Great Lakes States, was downloaded from TIGER/Line Shapefile, 2019, 2010 Nation, U.S., 2010 Census Urban Area National, n.d. (Note: This study did not incorporate Urban Areas data from the 2020 United States Census. The 2020 urban area dataset was released in the third quarter of 2023, after the data preparation and processing phase of this research, which was carried out during the summer of the same year (US Census Bureau, 2023).

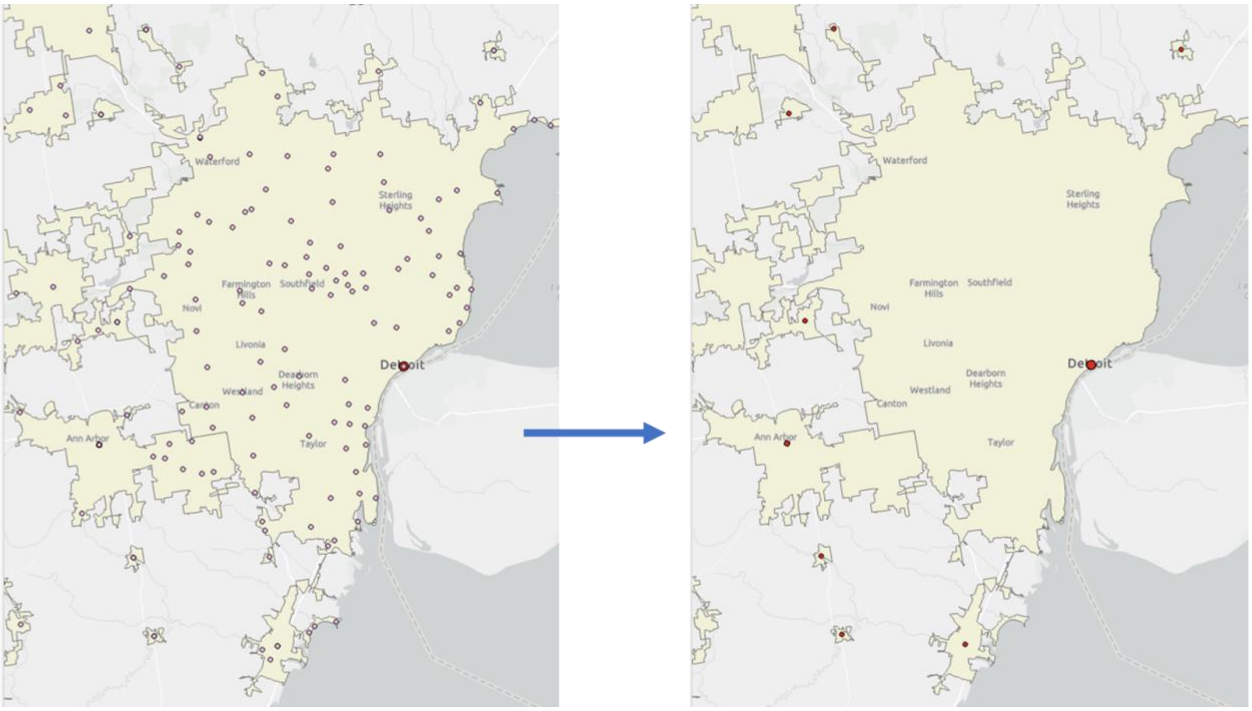

Figure 1: Delineating primary cities for further analysis.

In larger metropolitan areas comprising multiple towns and cities, the urban area point shapefile typically included points for each smaller city. However, for analytical purposes, only the point shapefile for the primary city is retained, with all other towns and cities being discarded; a fuzzy matching technique was used for this operation to match names between the urban area polygon file and the urban area point file. For example, the Detroit Metropolitan Area encompasses suburbs like Sterling Heights, Troy, Rochester, Farmington, and Royal Oak, among others. The urban area point shapefile contains points for each city. However, the study focused solely on retaining the City of Detroit's point shapefile, excluding points from other parts of the Urban Area. Figure 1 demonstrates this in detail.

After extracting primary city point files, Python code was written to create the multi-ring-buffers. The operation was executed to create concentric rings around these city center points, each extending one mile from the central business district, resembling the shape of a 'donut.'

These rings were then clipped to the boundaries of their respective urban area polygon shapefiles accounting for the varying sizes of cities; larger cities manifested as a series of multiple donuts, while smaller towns presented fewer rings. Figure 2 shows the donuts clipped to the urban area shapefile.

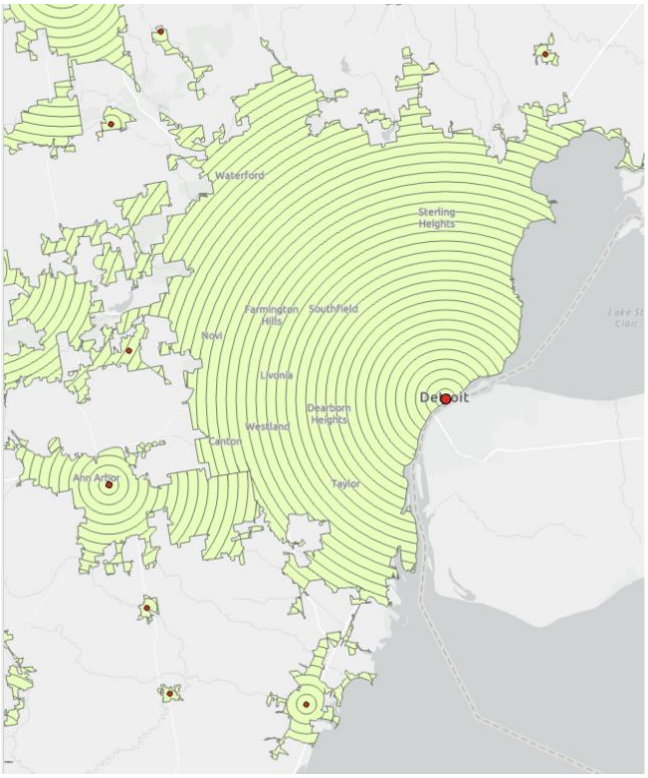

Figure 2: Concentric 1-mile-wide multi-ring donuts created around urban area point file, clipped to Urban area polygon shapefile.

For this analysis, the raster used were the novel EPA Dasymetric map for the year 2020, park raster, infrastructure raster, and building heights raster. The novel EPA Dasymetric map, covering the contiguous United States, was procured at a 30-meter resolution and projected to the Albers Equal Area Conic projection (US EPA, 2015). Dasymetric mapping is a geospatial technique that uses information such as land cover types to distribute data assigned to selected boundaries like census blocks accurately (US EPA, 2015). The EPA's approach to creating the Dasymetric map, known as Intelligent Dasymetric Mapping (IDM), is designed to produce refined population density estimates by identifying and excluding uninhabited areas. This approach involves using various geospatial datasets to enhance the specification of uninhabited areas in the U.S. Environmental Protection Agency's (EPA) EnviroAtlas Dasymetric Population Map for the conterminous United States (CONUS) (Baynes et al., 2022).

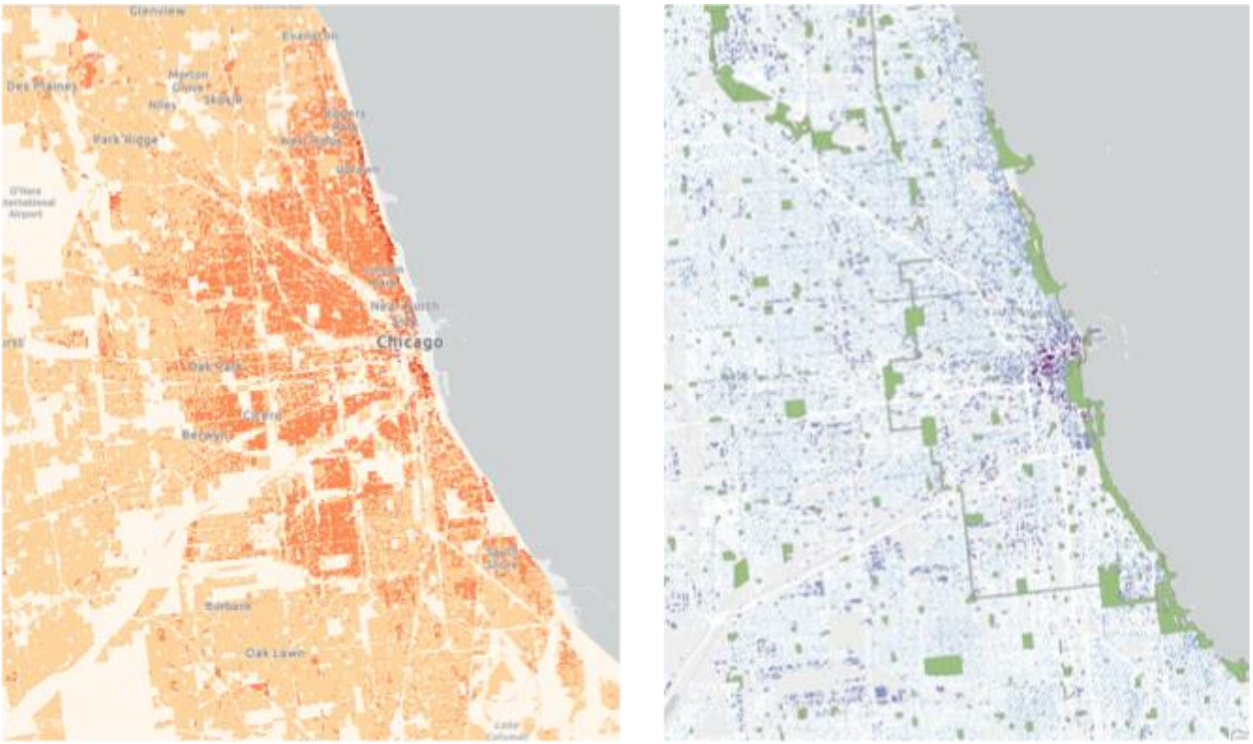

Figure 3: (left) EPA’s Dasymetric map sample clipped to the Chicago region and (right) Building height sample raster for the Chicago area interspersed with green spaces. In this (left) raster representation, the colors are graduated, with darker-colored pixels indicating areas of higher population density and lighter colors representing lower population densities.

The park area data was sourced from the "*USA Parks - Overview,* 2010 shapefile. shapefile. Originally covering the contiguous United States, this dataset was specifically modified for the Great Lakes region of the US. It was then converted into a 30-meter raster using the "Polygon to Raster" tool in ArcGIS 3.1, aligning with the Albers Equal Area Conic projection to maintain consistency with other datasets. Building height data was obtained from the *Open City Model,* 2018/2023, initially in GML format for each Great Lakes state. Custom Python scripts were utilized to transform these datasets into 30-meter raster. These raster were merged using ArcGIS 3.1’s mosaic tool, forming a comprehensive regional building height map. Figure 3 (left) illustrates a sample of the EPA’s Dasymetric map clipped to the Chicago region and (right) illustrates a sample raster of building height and green space, specifically focused on the Chicago region. The building heights are depicted using a graduated scale, with darker colors indicating taller buildings. Meanwhile, green pixels interspersed among the building height data represent urban green spaces.

3.3 Zonal Statistics and Attribute Analysis

Each 1-mile concentric ring served as the zone for the application of the zonal statistics tool in ArcGIS 3.1, facilitating the analysis of four distinct raster datasets: EPA dasymetric maps, building heights raster, park area raster, and infrastructure raster (indicating roads and parking areas). The infrastructure raster, representing elements like roads and parking areas, was derived from the impervious surfaces map by the Multi-Resolution Land Characteristics Consortium (MRLCC) (Dewitz, 2021) and the building height raster developed for this study. The MRLCC impervious surface raster, denoting the percentage of impervious cover per pixel, was reclassified to retrieve absolute impervious area per pixel. The absolute impervious area was used in performing the zonal statistics. This building area info (calculated using a building height raster) was then subtracted from the impervious area information retrieved from zonal statistics to get information on the infrastructure area.

Similarly, zonal statistics were performed on the Dasymetric, green space, and building height raster. Upon the completion of the tool, the results of the zonal statistics table were exported to Excel. All the variables were joined to form a singular Excel dataset with the donut name as a primary key, and each donut was attributed with data representing population density, green space, building heights data (minimum, maximum, and average), and infrastructure area per square mile. Figure 4 demonstrates sample zones and raster used in zonal statistics.

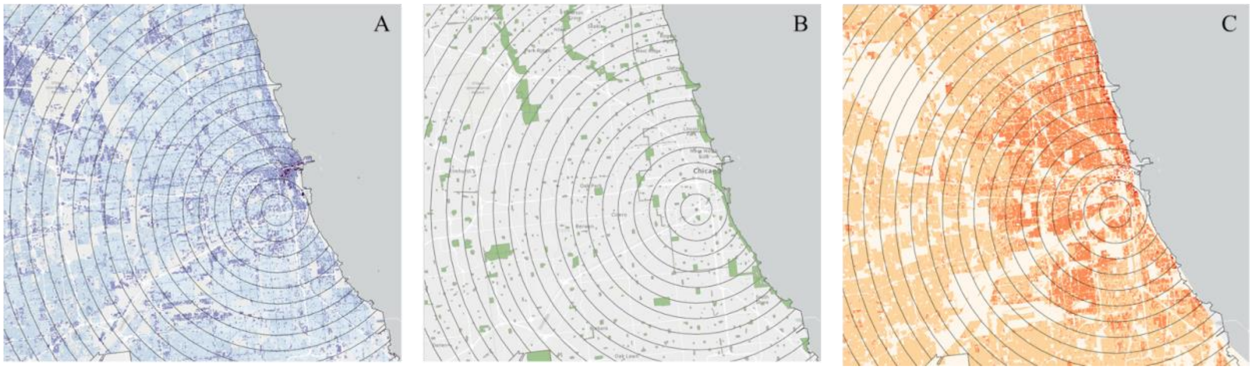

Figure 4: Zones and raster for zonal statistics (A: Building heights, B: Green Space, C: Dasymetric)

3.4 Linear regression for trend slopes

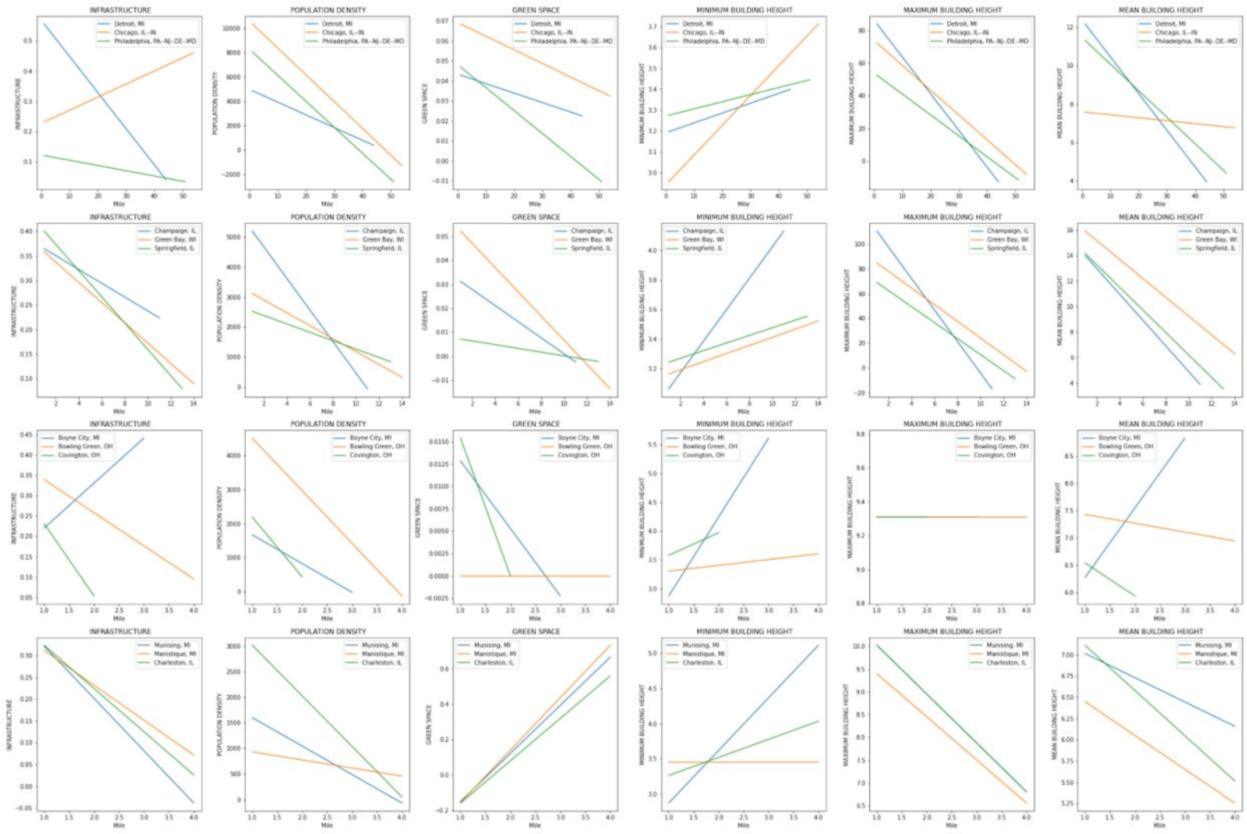

Figure 5: Graph for trends of infrastructure density, population density, minimum building height, maximum building height, and mean building height for sample cities in each cluster.

The initial stage involved conducting linear regression analysis of the urban metrics (infrastructure density, population density, green space density, and minimum, maximum, and average building heights) for each city. We calculated slope for each metric as a product of distance from the city center. The slope, or coefficient, from this regression, reflects the rate of change, where a positive slope signifies an increase from the city center and negative a decrease. For example, areas further from the center may have a rising number of parks. Figure 5 shows the trend slope retrieved for various metrics in question.

3.5 Standardizing the trend slopes

We standardized all measures using the “StandardScaler” method in Python. “StandardScaler” standardizes a feature by subtracting the mean and then scaling it to unit variance (Upadhyay, 2020). This step recalibrated the data such that the mean of each trend slope was zero, and the standard deviation was one. Standardization aimed to negate the influence of disparate scales across different metrics, ensuring uniformity in the data's variance and mean. This uniformity was vital for the subsequent clustering process. It ensured each urban metric contributed to an equal footing without any metric disproportionately influencing the clustering due to its numerical range or variability.

3.6 Cluster Analysis

We used cluster analysis find common patterns and relationships within urban morphology of Great Lake cities. The outcome was grouping cities into clusters that reflected commonalities in how their urban landscapes evolved with the spatial gradient away from the urban core.

3.6.1 K-means Clustering

We used K-means clustering based on the normalized infrastructure density, population density, green space density, and minimum, maximum, and average building heights. K-means create clusters where the "within-cluster variance" is minimized, meaning cities within the same cluster share similar morphology. K-means clustering is a commonly used clustering technique in urban GIS due to its simplicity, scalability, and speed. (Han, 2022; Mahtta et al., 2019).

The number of clusters were set at 4 based on the elbow method of testing (Syakur et al., 2018). Figure 6 shows the graph for the elbow method. The elbow method demonstrates that before 4 clusters, the rate of decrease in inertia is steep, indicating that each new cluster is providing a substantial amount of additional explanatory power. After 4 clusters, the rate of decrease flattens out, showing diminishing returns on explanatory power per additional cluster.

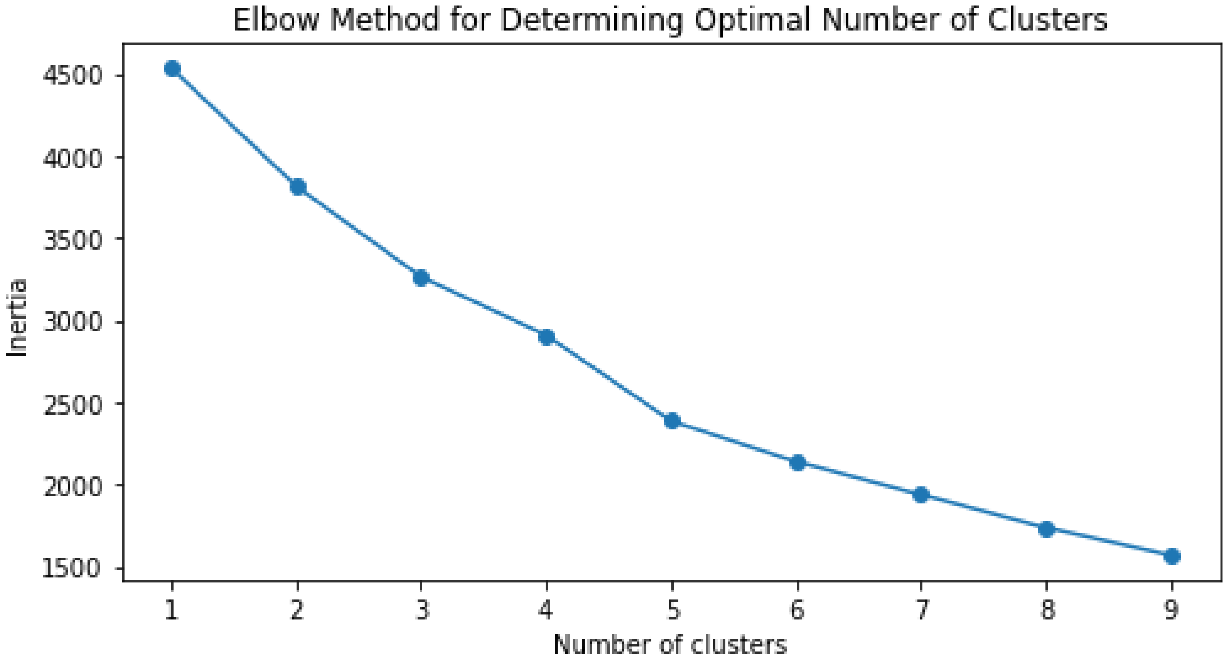

Figure 6: Elbow method for determining the optimal number of clusters.

3.6.2 PCA for Dimensionality Reduction

In addition, we conducted a Principal Component Analysis (PCA) of the data to further help in visualizing and interpreting the clustering results. PCA reduces the multi-dimensional data to components. The first two components in our data account for 95.32% of the total variance. Figure 7 demonstrates the graph generated for PCA.

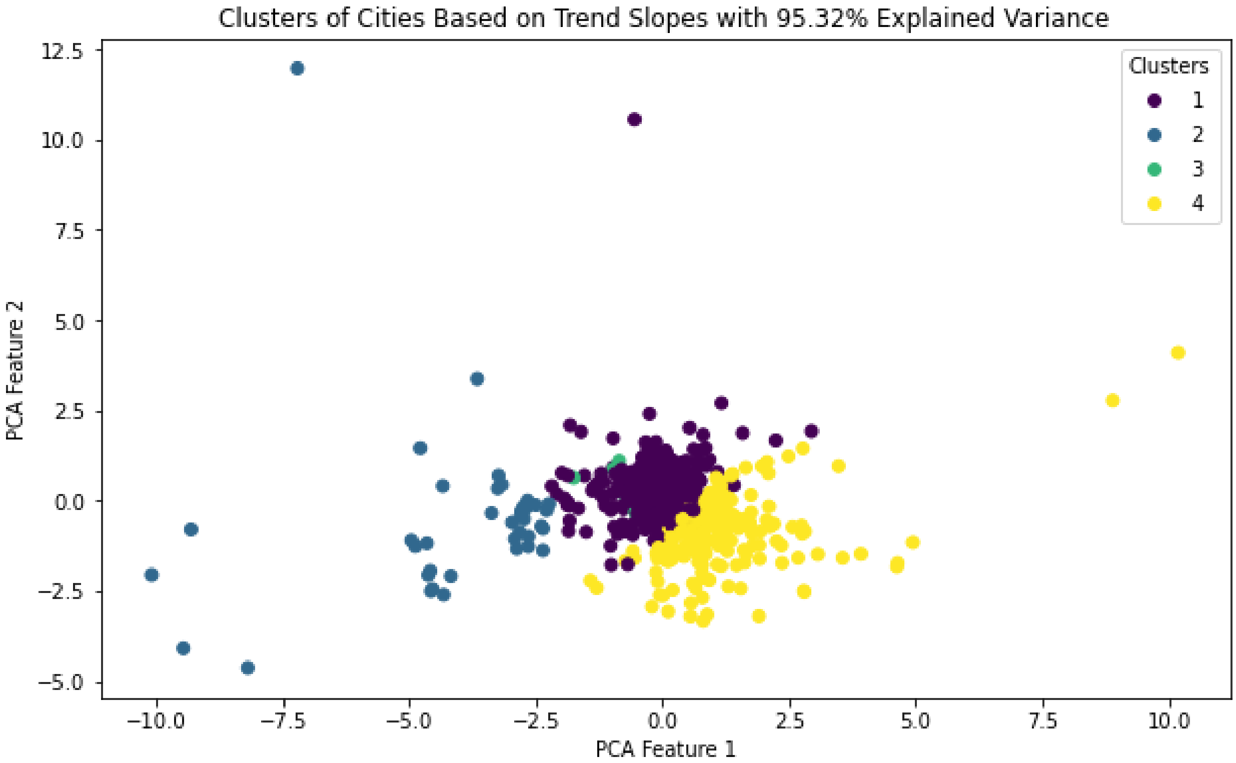

Figure 7: Results of PCA for the cluster of cities (95.32% variance explained)

3.7 Visualization

Finally, we visualized the k-means clusters of the first two components derived from the PCA. Each city was plotted as a point whose coordinates corresponded to its values for the first and second principal components as represented in figure 7.

Chapter 4

Table 1: Average slope of population density, green space, building height, and infrastructure densities.

Cluster	Infrastructure density,	Population density	Green space	Minimum Building height	Maximum Building height	Mean Building Height	City Count
1	-0.0243	-185	-0.002	0.10	-0.54	-0.22	516
2	-0.0034	-444	-0.004	-1.37	-4.64	-2.5	39
3	-0.07	-1244.3	-0.009	0.56	-0.30	0.57	193
4	-0.082	-478	0.22	0.29	-0.93	-0.62	8

The clustering analysis revealed differentiated urban form and development patterns across four distinct groups, with a total of 756 cities analyzed. The urban morphology of Cluster 1 (Established Urban Centers), comprising 516 cities and major cities like Detroit, Chicago, and Philadelphia, was distinctive as infrastructure and population densities decreased with increasing distance from city centers. This suggested that these cities maintained significant infrastructure in suburban areas. The population density in these areas was moderately high, indicating developed urban cores emphasizing green spaces within the urban fabric. Cluster 2 (Suburban Green Belt Cities), with 39 cities, including Champagne and Green Bay, was characterized by a lower infrastructure density and a marked decrease in population density away from city centers. Cluster 3 (Mixed Growth Metropolis) encompassed 193 cities. This cluster displayed a pronounced decrease in infrastructure and population densities, signifying potential areas for densification to utilize existing infrastructure better. Further infrastructure can be built in the area suggesting upon suitability analysis to accommodate new population. The trend towards increasing minimum building heights on the urban periphery suggested a shift towards vertical growth. Cluster 4 (Green Expansion Cluster), the smallest cluster with eight cities, exhibited a significant decrease in infrastructure density but an increase in green space, presenting a unique model of urban expansion where densification is balanced with the expansion of green spaces.

Table 1 summarizes the average slope of population density, green space, building height info, and infrastructure density.

4.1 Cluster 1: Established Urban Centers

4.1.1 Cluster characteristics

Cluster 1 represents cities with urban environments where infrastructure and population density are concentrated around the CBD. The infrastructure density in these cities showed a nominal decrease with distance from the city center. This gradual decline suggested that while the most substantial infrastructural elements were centralized, infrastructure was still notable in the outskirts. This existing infrastructure suggests possibilities for an increase in densification in these areas without overextending city services, thereby preventing sprawling into the suburbs. Despite this, the population density decreases moderately, hinting at denser urban areas that progressively spread into less “densely populated” suburbs. The slight negative trend in green space density reflected a <u>strategic distribution</u> of parks and recreational areas.

In Cluster 1, population density and building height measures suggest an intermediate zone connecting the CBD and suburban areas. The urban core in this cluster is marked by high population density, implying a developed city center with significant commercial, business, and cultural activities. Concurrently, building heights in this cluster exhibited a moderate reduction in maximum and average heights away from the city center, suggesting that taller and generally larger buildings were concentrated in the central area—this trend in building heights aligned with the observed population distribution. The slight increase in minimum building heights indicated newer developments or diversification in building styles outside the central areas. This could increase urban density in a manner that is congruent with the existing cityscape, preserving the distinct blend of dense urban areas and more expansive suburban settings in Cluster 1. These characteristics of Cluster 1's cities suggested room for growth in terms of increasing the density of existing infrastructure and developing underutilized spaces, especially in legacy cities where downtowns are underutilized (Owens et al., 2020). This growth could be achieved by focusing on areas with lower building heights, increasing the density in a way that complements the existing urban structure and maintains the balance between built and natural environments. Figure 8 demonstrates the trends of infrastructure density, population density, minimum building height, maximum building height, and mean building height for sample cities in cluster 1.

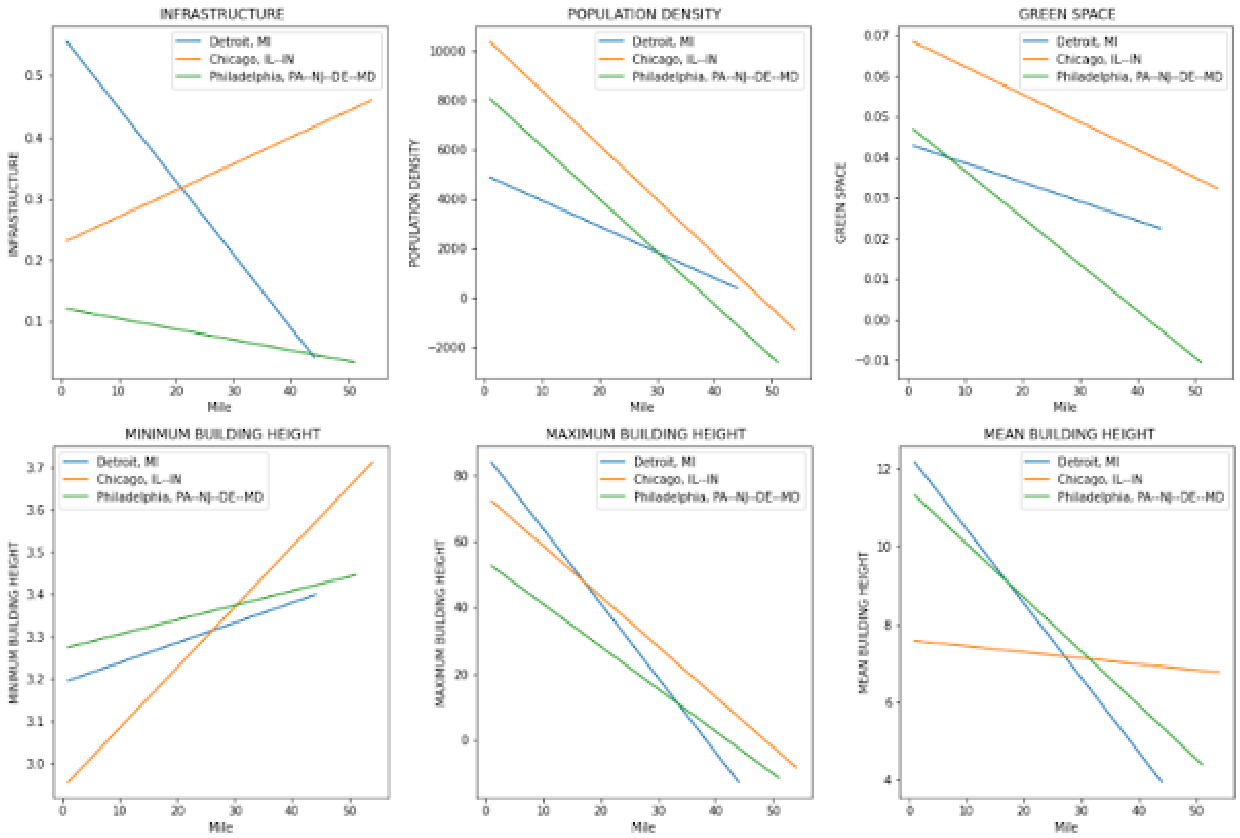

Figure 8: Graph for trends of infrastructure density, population density, minimum building height, maximum building height, and mean building height for sample cities in cluster 1

4.1.2 Cluster-specific example

Metro Detroit, including the city of Detroit and its surrounding suburbs, is a prime example of the Cluster 1 urban planning profile. In the urban core of Detroit, there is a high infrastructure density, which notably decreases but not sharply as one moves away from the city center. (Hendrix et al., 2018). There is also a notable concentration of taller buildings in the downtown area, which gradually reduces as one moves toward the suburbs. This demonstrates a gradual transition, a characteristic observed in the city's downtown and midtown areas, with a significant concentration of commercial, business, and cultural activities (Hendrix et al., 2018; Owens et al., 2020). The suburban areas around Detroit, such as Southfield, Dearborn, and Sterling Heights, mirror this trend by showing a gradual decline in infrastructure and population density. While the overall population might increase in suburban areas, their population density (number of people living per square mile) is significantly lower. This indicates a low-density sprawl in suburbs such as Southfield, Dearborn, and Sterling Heights. In contrast, Detroit's urban core is much denser, reflecting a concentrated urban environment. This density gradient, with a dense city center tapering into less dense suburban areas, highlights the different dynamics of urban and suburban living within the Metro Detroit area (Hendrix et al., 2018). Another critical aspect of Metro Detroit's urban planning is the strategic distribution of green spaces. The density of green spaces reduces slightly as one moves away from the city. Despite notable parks and recreational areas like Belle Isle Park and the Detroit Riverwalk, the distribution of green spaces is uneven across all cities in the Metro Detroit region. A study by Guan et al., 2023 noted that access to urban green spaces is highly unequal in 70% of the urban areas in the region. The study also emphasizes the importance of the shape and size of urban green spaces in promoting equality, suggesting that implementing several small green spaces within walking distance of residents could provide more accessible urban green spaces and promote equity (Guan et al., 2023).

Detroit’s emergence as a significant city began with good planning, including the design of its radial downtown street plan by Pierre L’Enfant and the redesign of Belle Isle Park by Frederick Law Olmsted. Post-World War II, however, urban planning became increasingly professionalized, and planners lost control over the design of city infrastructure, focusing instead on influencing private development through tools like zoning and eminent domain (Hendrix et al., 2018). Metro Detroit, particularly in its legacy city areas, has the potential for growth through increasing the density of its existing infrastructure and developing underutilized spaces. There is an opportunity to introduce a variety of building forms in peripheral areas to enhance urban density in a way that blends seamlessly with the existing cityscape. Complementing this approach, Hendrix et al., 2018 finds that modern urban planning trends in Detroit have shifted towards "form-based" zoning. This method emphasizes the structures' external form and relationship to the street, aligning well with the city's observed building height and density trends.

4.2 Cluster 2: Suburban green belt cities

4.2.1 Cluster Characteristics

Cluster 2 cities exhibited a lower infrastructure density overall and this decreases away from the city center. This is associated with a less developed network of roads, public transportation, and utilities—any changes and developments happening in recent times. For instance, transportation infrastructure development has recently been a significant focus in Springfield, Illinois to alleviate congestion, ease connections on the Chicago to St. Louis line, and encourage more people to visit and live downtown Springfield (Crawford, 2021). Another example is Green Bay, WI’s recent focus on road infrastructure and adopting green infrastructure approaches. The City of Green Bay Department of Public Works set a goal in 2020 to resurface or reconstruct approximately 31,000 to 34,000 lineal feet of roadway each year, primarily targeting residential streets, with additional work on major streets supported by federal or state grants (*21st Century Infrastructure | Green Bay, WI*, n.d.).

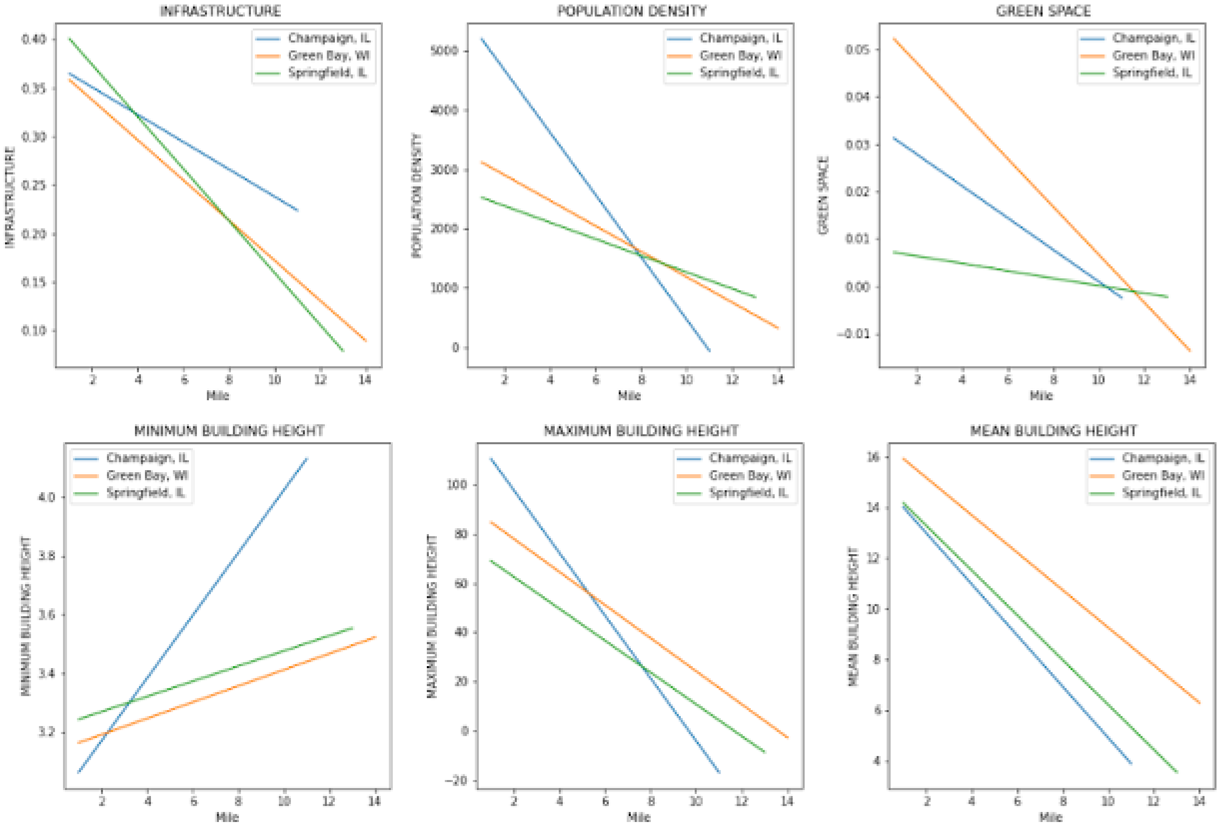

Figure 9: Graph for trends of infrastructure density, population density, minimum building height, maximum building height, and mean building height for sample cities in Cluster 2

Cluster 2 cities have significantly lower population density compared to those in Cluster 1, and building heights decline as the distance from the urban core increases significantly. These patterns indicated a landscape primarily of low-rise buildings, likely shaped by urban planning strategies or specific regulatory measures with fewer high-rise buildings. This trend contrasted sharply with Cluster 1 cities, which typically featured a higher concentration of high-rise buildings. Such a planning preference suggested a bias for low-rise urban profiles while maintaining the flexibility for selective vertical expansion in designated areas. These elements collectively influenced the urban landscape, leading to a blend of low-rise and selectively higher-rise buildings that catered to the evolving needs of the urban population. The slight negative trend in green space density reflected a strategic distribution of parks and recreational areas similar to cluster 1. This indicates an effort to concentrate green spaces within or near the urban core, to create central community activity and recreation hubs. Figure 9 demonstrates the trends of infrastructure density, population density, minimum building height, maximum building height, and mean building height for sample cities in Cluster 2.

4.2.2 Cluster specific example

Champaign, Illinois, fitting into Cluster 2, exemplifies several critical characteristics of this category. While capable of meeting basic needs, the city's infrastructure needs more complexity and density in more urbanized areas. This is evidenced by a more straightforward road network and an adequate public transportation system, which is less developed than in larger cities. Champaign's recent 'Champaign Moving Forward' (planning and development department, n.d.) program reflects an acknowledgment of this and a proactive approach to enhance urban mobility, indicating an evolution towards a more integrated transportation network. The city's urban landscape is predominantly characterized by low-rise buildings, a trend common in Cluster 2 cities. This architectural choice suggests a preference for horizontal expansion over vertical growth, likely influenced by various factors. A similar urban development pattern was observed in Champaign, IL. Particularly in the Campustown neighborhood, there was an increase in student housing development recently, marked by the construction of 25 new developments and over 2500 housing units between 2008 and 2019. Notably, this growth included buildings exceeding ten stories, signaling a move towards higher-density construction in specific zones. This shift in Champaign was shaped by several factors, including infrastructure investment, university enrollment policies, and zoning regulations, as analyzed by (Pendall et al., 2022).

Champaign's approach to urban planning focuses on incremental development, which promotes small-scale development in existing neighborhoods. This strategy is geared towards providing new housing and business opportunities while preserving the spread-out nature of the city. Such an approach is consistent with the characteristics of Cluster 2 cities, where urban development is more horizontally spread rather than vertically concentrated in selected neighborhoods. (*Incremental Development*, n.d.).

Champaign mirrors the strategic distribution regarding green space observed in Cluster 2 cities. The presence of the University of Illinois at Urbana-Champaign as a central green hub is a prime example of how the city concentrates its recreational areas to create community activity centers. Overall, Cluster 2, Champaign, IL, represents a transition city, balancing its existing low-density, low-rise character and gradually shifting towards higher-density and more complex urban development in select areas. This evolution is guided by local needs, planning policies, and infrastructural investments, reflecting a dynamic urban growth and development approach.

4.3 Cluster 3: Mixed Growth Metropolis

4.3.1 Cluster Characteristics

Cluster 3 shows a noticeable downward trend in infrastructure and population densities alongside a slight decrease in green space density. Many of the cities in this cluster can be characterized as “small towns”, with a population under 30000. The trend in infrastructure density for Cluster 3 cities indicated a significant decrease in infrastructure provision as one transitioned from the city centers. This reflected a central concentration of services and amenities that taper off in the suburbs and rural outskirts. The sharp decline in population density indicated cities where there was a stark contrast between the urban centers and the more sparsely populated peripheries.

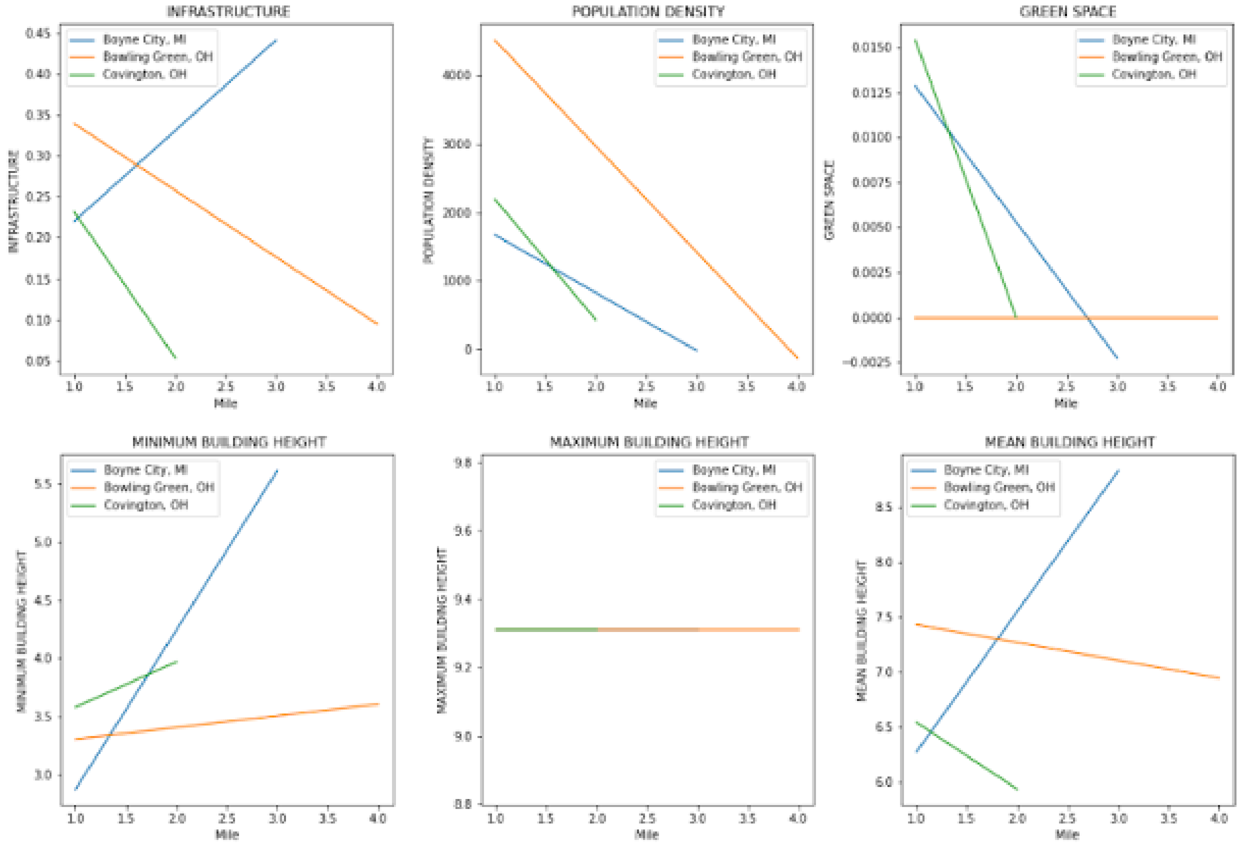

Figure 10: Graph for trends of infrastructure density, population density, minimum building height, maximum building height, and mean building height for sample cities in Cluster 3

This could result from urban sprawl or deliberate city planning that encourages residential developments over a broader area to avoid overcrowding and promote a more balanced urban-rural interface. The slight negative trend in green space density suggested that as these cities expand, the development of parklands and recreational areas was needed to keep up with urban sprawl. This may point to an area of potential improvement for urban planners to ensure that the benefits of green spaces are equitably distributed across the urban gradient. The positive slope for minimum building heights and the slight negative slope for maximum building heights indicated a cityscape experiencing a mix of building developments. In contrast, the slight decrease in maximum building heights suggested that high-rise buildings were primarily still a feature of the central urban areas. Figure 10 demonstrates the trends of infrastructure density, population density, minimum building height, maximum building height, and mean building height for sample cities in Cluster 3.

4.3.2 Cluster-specific example

The urban planning and development in Wayland, MI, and Bowling Green, OH, align with the characteristics of Cluster 3 cities. This aligns with Cluster 2's trend of decreasing infrastructure and population densities moving away from city centers. Wayland's Master Plan and Bowling Green's Comprehensive Plan support central urban development, which resonates with the central concentration of services in Cluster 3 cities (Community Plans – City of Wayland, n.d.; Comprehensive Plan Information | Bowling Green, OH, n.d.). The focus on parks, recreation, and nonmotorized transportation in Wayland and the emphasis on pedestrian infrastructure in Bowling Green mirror Cluster 3's need for green space development amidst urban sprawls. This suggests efforts to maintain a balanced urban-rural interface and equitable distribution of green spaces, as indicated in Cluster 2's characteristics (Community Plans – City of Wayland, n.d.; Pollauf, 2022).

4.4 Cluster 4: Green Expansion

4.4.1 Cluster characteristics

Cluster 4 is characterized by its unique urban and demographic trends. This cluster, which included eight cities, showed a distinct pattern of urban development and demographic changes. Cluster 3 cities have a more pronounced decrease in infrastructure provision than Cluster 4. This implied that as one moved away from the city centers, there was a significant reduction in the concentration of services and amenities. This could be due to a focused effort to decentralize city services or reflect a trend towards more rural or suburban living. The positive trend in green space density was a unique feature of Cluster 4. Unlike other clusters, these cities increased their green space as they expanded. This suggested a strong emphasis on environmental sustainability and the integration of nature within urban spaces, potentially enhancing the quality of life for residents.

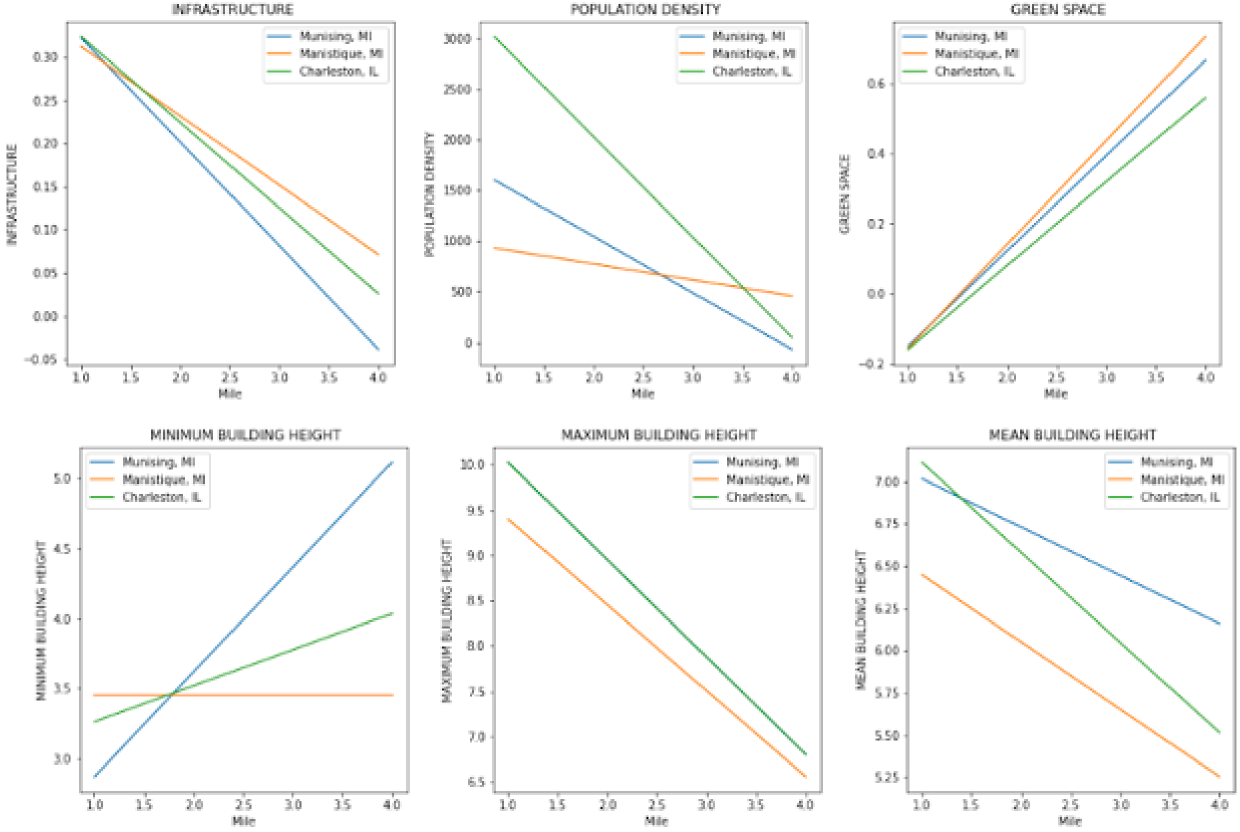

Figure 11: Graph for trends of infrastructure density, population density, minimum building height, maximum building height, and mean building height for sample cities in Cluster 4

The trend in population density for Cluster 4 was not as steep as that of Cluster 3 but was more pronounced compared to Cluster 1, resembling the trend observed in Cluster 2. This indicated a more moderate but notable decrease in population density from urban centers to the outskirts. This trend pointed to more evenly spread population densities across the urban and suburban areas, avoiding the extremes of dense urban centers and sparse rural areas. In Cluster 4, the trends in building heights presented an exciting picture of urban development. The positive trend in minimum building heights indicated that new construction, likely in suburban or fringe urban areas, favored taller structures than traditional housing. Conversely, the trend for maximum building heights pointed to a significant decrease in very tall buildings, signaling a move from high-rises towards more medium-rise constructions. This trend was further reinforced by the negative trend in the mean building height, suggesting a more varied and possibly lower-rise cityscape than the traditional high-rise-dominated urban centers seen in other clusters. Figure 11 demonstrates the trends of infrastructure density, population density, minimum building height, maximum building height, and mean building height for sample cities in Cluster 4.

4.4.2 Cluster specific example

Munising and Manistique, located in Michigan's Upper Peninsula, are excellent examples of the "Green Expansion and Diverse Heights" characteristics found in Cluster 4. These cities are closely associated with significant natural environmental preserves, such as the Pictured Rocks National Lakeshore near Munising and the Hiawatha National Forest near Manistique. These expansive and well-preserved green spaces align perfectly with the trend observed in Cluster 4, where there is a clear emphasis on increasing green space as part of urban expansion.

Conclusion

Chapter 5 Conclusion

While the literature provides a diverse perspective on urban densification and sustainable cities employing various GIS-based analytical techniques, the present study distinguishes itself in several keyways. First, it undertakes a comparative analysis of urban densification by utilizing a novel large-scale Dasymetric dataset from the EPA. Secondly, this research extends the traditional ring-based analysis by incorporating cluster analysis to group urban areas across the Great Lakes region of the US based on their densification characteristics through features like infrastructure, greenspaces, building height, and population. This clustering identifies commonalities across urban spaces and facilitates the tailoring of policies to each urban cluster's specific needs and trends. Translating complex geospatial data into actionable policy recommendations bridges the gap between empirical GIS analysis and practical urban planning strategies. The methodology used in assessing densification using the “one-mile-donut” is novel.

The study identifies four distinct clusters of urban development across the Great Lakes region of the US, each with its unique characteristics and developmental trends. Cluster 1 encompasses established urban centers such as Detroit, Chicago, and Philadelphia, characterized by a dense urban core with gradually declining infrastructure and population density towards the suburbs, alongside a strategic distribution of green spaces. Cluster 2 includes cities like Champaign and Green Bay, marked by lower infrastructure density and more spread-out low-rise buildings, indicative of suburban or tier-2 city profiles with emerging high-density zones. Cluster 3 comprises smaller towns such as Wayland and Bowling Green, with a significant decrease in infrastructure and population densities away from city centers, reflecting a diverse and multifaceted growth pattern. Finally, Cluster 4, with cities like Munising and Manistique, shows a unique trend of increased green space as part of urban expansion, coupled with a pronounced decrease in infrastructure provision and a shift from high-rises to more medium-rise constructions. Each cluster represents a distinct urban planning and development approach influenced by economic, cultural, and environmental factors.

Finally, the geographic scope of this study, encompassing a comprehensive sweep of the Great Lakes region of the US, provides a regional lens on urban densification. This broad yet detailed focus contributes a significant comparative dimension to the existing body of knowledge, offering region-specific insights that are potentially generalizable to other contexts. In sum, this study advances the field of urban planning and GIS by integrating comparative, analytical, and policy-generating processes into a cohesive research framework, thereby offering a distinctive contribution to the literature on urban densification.

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