# Roads, Urbanization, and Heat:
## Implications and Methods to Improve
## Public Health and Equity in Massachusetts

A thesis submitted by

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in partial fulfillment of the requirements for the degree of

Master of Science

in

Environmental Policy and Planning

Tufts University

February 2025

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# Abstract

This thesis used time-series data from 2001-2019 for the state of Massachusetts to explore the influence of major roads on the urbanization of surrounding land cover, of roadways and urbanization on urban heat islands (UHIs), and how policy and planning efforts may increase social equity outcomes and decrease public health risks considering the interplay among these three systems. Two analyses were conducted. The first was quantitative and used ESRI's ArcGIS Pro software with three primary geoprocessing techniques: Local Moran's I, ordinary least squares regression, and multiscale geographically weighted regression. The second was a novel qualitative comparative analysis considering the benefits and tradeoffs of three categorical responses for UHI mitigation, including increasing vegetation, modifying surfaces, and altering urban form. Recommendations include increasing vegetation for daytime mitigation, implementing cool pavements for nighttime mitigation, and that simultaneous air and mean radiant temperature reductions should be prioritized while carefully considering the location of interventions.

# Acknowledgments

There are many people that deserve recognition and have my deepest gratitude related to the completion of this thesis. I do not know that I could possibly include them all here, but not a single piece of support or advice has been forgotten or taken for granted. Thank you, everyone.

Specifically, I cannot have done this without the constant support of my committee, including my advisor, Kathryn Davies, and my reader, Sumeeta Srinivasan. The encouragement you both offered was literally unwavering, and the feedback and insights you shared made it possible to form a coherent academic pursuit out of a cloud of possibilities and interests.

Additionally, I would like to thank Mary Davis and Laurie Goldman, both of whom helped me succeed and grow, personally and professionally, throughout my studies at Tufts University. I would not be the person or scholar I am without both of you, nor without everyone in the UEP department and community.

Finally, thank you to my family. You have all stood by me this whole time and steadied me every time I stumbled. You have given me every resource I could ask for to do well and do good. I strive to live up to that every day. I love you all. Thank you.

# Table of Contents

**Abstract** ........ ii

**Acknowledgments** ........ iii

**Table of Contents** ........ iv

**List of Tables** ........ v

**List of Figures** ........ vi

**Chapter 1. Introduction** ........ 1
  Introducing Urbanization ........ 2
  Research Questions and Key Terms ........ 5
  Major Findings ........ 8
  Thesis Structure ........ 10

**Chapter 2. Literature Review** ........ 10
  Availability of Literature ........ 11
  A History of Roads ........ 11
  Defining Urbanization ........ 14
  Impact of Roads on Urbanization ........ 23
  Surface Urban Heat Island Effect ........ 28
  Contextual Dependencies ........ 32
  Equity Implications ........ 33
  Public Health Implications ........ 37
  Frameworks for Determining “Success” ........ 42
  Conclusions and Next Steps ........ 45

**Chapter 3. Methods** ........ 46
  Conducting the Literature Review ........ 46
  Methods Others Have Used ........ 47
  Data ........ 48
  Spatial Data Analysis ........ 49
  Qualitative Analysis ........ 51

**Chapter 4. Results** ........ 55
  Local Moran’s I and Summary Statistics ........ 58
  Ordinary Least Squares Regression ........ 61
  Multiscale Geographically Weighted Regression ........ 63
  Limitations of this Spatial Analysis ........ 67

**Chapter 5. Discussion** ........ 69
  Consideration of the Results ........ 69
  Significance of Results ........ 72
  Qualitative Comparative Analysis ........ 75
  Reconciling the Two Models ........ 99

**Chapter 6. Conclusions and Recommendations ................................................ 103**
Methods and Results ........................................................................................ 103
Key Takeaways ............................................................................................... 106

**References ........................................................................................................ 109**

## List of Tables

Table 3.1: Datasets and their sources for this study. ..................................................... 49
Table 3.2: A visual representation of the comparative analysis framework in this thesis.... 54
Table 4.1: Summary Statistics of the clustering distribution of the newly urban data. ....... 60
Table 4.2: Summary Statistics of the clustering distribution of the increasingly urban data. ........................................................................................................................ 61
Table 4.3: A summary of the OLS regression output for the newly urban dataset. ............ 62
Table 4.4: A summary of the OLS regression output for the increasingly urban dataset. .... 62
Table 4.5: A summary of the MGWR output for the increasingly urban dataset. ................ 63
Table 5.1: Visualization of increasing vegetation's effect on air and mean radiant temperatures. ............................................................................................................ 82
Table 5.2: Visualization of increasing vegetation's effect on green versus impervious surfaces.................................................................................................................. 82
Table 5.3: Visualization of increasing vegetation's location efficacy. ............................... 84
Table 5.4: Visualization of increasing vegetation's positive impact on equity. ................... 85
Table 5.5: Visualization of modifying surface materials and color's effect on air and mean radiant temperatures. ................................................................................................ 87
Table 5.6: Visualization of modifying surface materials and color's  effect on green versus impervious surfaces. .................................................................................................. 88
Table 5.7: Visualization of modifying surface materials and color's location efficacy. ....... 89
Table 5.8: Visualization of modifying surface materials and color's  positive impact on equity. ..................................................................................................................... 90
Table 5.9: Visualization of altering urban form's effect on air and mean radiant temperatures. ............................................................................................................ 92
Table 5.10: Visualization of altering urban form's effect on green versus impervious surfaces.................................................................................................................. 93
Table 5.11: Visualization of altering urban form's location efficacy. ................................. 94
Table 5.12: Visualization of altering urban form's positive impact on equity...................... 94
Table 5.13: Visualization of increasing vegetation's expected cumulative effects. ............ 96
Table 5.14: Visualization of modifying surface materials and color's expected cumulative effects. ..................................................................................................................... 97
Table 5.15: Visualization of altering urban form's expected cumulative effects. moderate urban height's and width's expected cumulative impacts. ............................................. 97

## List of Figures

Figure 4.1: New urbanization in MA by census tract, 2001-2019. .................................... 57
Figure 4.2: Increased urbanization in MA by census tract, 2001-2019. ............................ 57
Figure 4.3: Clustering of new urbanization in MA by census tract.................................... 59
Figure 4.4: Clustering of increasing urbanization in MA by census tract. .......................... 59
Figure 4.5: Distance to class 3 road's MGWR coefficient and spatial significance. ........... 64
Figure 4.6: Distance to class 1 road's MGWR coefficient and spatial significance. ........... 64
Figure 4.7: MGWR intercept's coefficient and spatial significance. .................................. 65
Figure 4.8: Distance to class 3 road's MGWR coefficient value raster.............................. 65
Figure 4.9: Distance to class 1 road's MGWR coefficient value raster.............................. 66
Figure 4.10: The distribution of major roads in MA by functional classification. ................ 68

# Chapter 1. Introduction

Cities and the urbanization processes that create them have the potential to change the course of human history (Georgescu et al. 2021, 1). This has happened repeatedly, from Uruk, which was arguably the first major city-state known to history and also provided a model for how citizens and rulers may cooperatively build and sustain a complex society; to Rome, which mass-produced modern infrastructure still in use today and whose historical image fueled contemporary Western hegemony; to Paris, which was the first site of public transit and has been claimed as the most important city for the evolution of socio-cultural modernity (Tilly 2010, 265; Osland 2023, 3; Arnason and Raaflaub 2011, 7-8; Glaeser et al. 2007, 21; Harison 2020, 3).

Across space and through time, cities such as these have altered human history by making possible things which have never been done before. Underlying these advancements are processes such as the spatial concentration of people and the creation of infrastructure networks, which have ultimately resulted in cities becoming centers of knowledge, social and cultural creation, economic development, and innovation (Han et al. 2018, 402; Chester et al. 2014, 534; Maparu and Mazumder 2017, 46).

As a counterweight to these seemingly positive identities, such increasingly dense concentrations of people and objects have also enabled negative externalities such as traffic congestion, pollution, and the loss of vegetated land cover (Das et al. 2024, 966-967). Infrastructural shortcomings and behavioral choices, such as energy-inefficient buildings and the importation of goods and foods, respectively, have led to 75% of the global stock of natural resources and 60%-80% of global energy production being consumed in urban areas (Nizic and Baresa 2013, 326). This equates to cities being responsible for over 70% of global carbon dioxide ($CO_2$) emissions, exacerbating anthropogenic climate change and contributing to environmental degradation (Gurney et al. 2015, 180; Das et al. 2024, 963).

The body of academic literature on the role cities can play in global issues such as climate change has steadily increased in the past two decades, and in August 2020, the academic journal Urban Studies even published a special issue exploring the popular thought that cities can save the planet (Miller and Mossner 2020, 2245; Angelo and Wachsmuth 2020). Along similar lines, this thesis first explores the effects of transportation infrastructure on urbanization processes using data from the state of Massachusetts. It then explores the impacts resulting from both systems, such as the surface urban heat island effect (UHI), which has significant implications for several major topics in the field of urban policy and planning including sustainability, social equity, and public health, among others.

## Introducing Urbanization

Urbanization is a demographic megatrend and has significant impacts on land use, human welfare, social equity, and sustainability (UN 2019, 3; Ahern 2011, 341; Kasraian et al. 2016, 788). Urbanization is a socio-economic process that involves the spatial redistribution of populations and their dominant socio-cultural attributes, such as occupations, lifestyles, cultures, and behaviors (UN 2019, iii).

In the year 1950, approximately 30% of the global human population was living in areas that were considered urban (UN 2019, 1). Then, sometime during the year 2007, the balance of the global population shifted from being predominantly rural to predominantly urban (Ahern 2011, 341). By 2018, the percentage increased further still to 55% and is expected to continue climbing in the future, reaching 68% by 2050. In terms of absolute population, these percentages represent an observed shift from 751 million urban inhabitants in 1950 to 4.2 billion in 2018 (UN 2019, 1).

Urbanization has typically bolstered economic growth and the production of social and technological infrastructure while reducing poverty levels (UN 2019, 3). As public and private investments are made in buildings and infrastructure, urban centers increasingly become hubs for transport, trade, and information while offering greater access to high-quality, basic public services, e.g., education and healthcare, compared to surrounding areas (UN 2019, iii). These trends have led many countries to view urbanization as a crucial tool for the overall well-being of their citizens, particularly as a means of enabling rural and marginalized communities to have better access to social services and opportunities such as higher-wage jobs (Pradhan et al. 2021, 1).

Other experts view the process of urbanization more cautiously, concerned that its potential benefits may not manifest if infrastructural improvements which enable the provision of amenities such as better transportation and knowledge access do not keep up with the rate of urban population growth. In this scenario, diseconomies of scale may arise instead, resulting in negative externalities like over-crowding and higher costs of living, further impacting social equity and public health outcomes (Pradhan et al. 2021, 2).

Moreover, as a geographic area grows, its systems of land use, land cover, and environmental material composition are all modified, which can secondarily result in alterations to local climatic conditions (Heris et al. 2020, 1; Kong et al. 2016, 1,429). The typical outcome of this process is an increase in the local heat levels of urban areas compared to the suburban and rural areas surrounding the urban core (Ulpiani 2021, 2). This difference in heat between urban and rural areas, known as the urban heat island effect (UHI), has been observed in cities around the world, regardless of location or size (Hashemi et al. 2023, 2).

Heat exposure has increasingly become a public health risk and is expected to be exacerbated even further as global climatic conditions continue to be altered (R. Li et al. 2023, 2). It also presents issues of equity and environmental justice by more greatly affecting impoverished populations (Das et al. 2024, 964). This can be seen when examining the co-location of populations earning incomes below the poverty line and the greatest heat levels.

Voelkel et al. (2018) discuss the presence of this trend wherein certain socio-demographic groups will be concentrated in neighborhoods that experience more pronounced heat levels than other, nearby areas (9-10). They point out that lower-income people are one such socio-demographic group, which agrees with the findings of Hsu et al. (2021) that heat is one of multiple environmental stressors unequally distributed across populations based on income levels (Voelkel et al. 2018, 6; Hsu et al. 2021, 1-2). In contrast, wealthier populations are more likely to live in neighborhoods with lower temperatures and to receive heat-ameliorating infrastructure, such as vegetation (Voelkel et al. 2018, 9-10).

There is even further support for this phenomenon of co-location. First, multiple sources have corroborated a positive relationship with the density of urban infrastructure and greater heat levels (Voelkel et al. 2018, 1; Taleghani et al. 2016, 1; Zhou et al. 2017, 3). Second, Glaeser et al. (2007) provide a detailed account of the concentration of poor citizens in metropolitan statistical areas (MSAs) throughout the United States, calculating that 19.9% of central city populations lived in poverty in the year 2000 compared to 7.5% of the surrounding suburban populations (1-2). They found that, not only are lower-income households over-represented in every MSA in the U.S., but members of this socio-economic status are also being continuously attracted to cities, further centralizing their locations and thus their exposure to extreme heat (Glaeser et al. 2007, 4, 7).

## Research Questions and Key Terms

Urbanization and urban heat are phenomena that exist at multiple scales simultaneously, presenting global, regional, and local challenges and opportunities (Zhou et al. 2017, 7). As urbanization becomes increasingly entangled with climate change, urban planning is likewise becoming increasingly entangled with sustainability and equity planning (Chester et al. 2014, 544; Angelo and Wachsmuth 2020, 2216).

Within this frame, this thesis explored how policy and planning efforts may increase social equity outcomes and reduce negative externalities. Specifically, spatial data spanning the timeframe 2001-2019 was gathered for the state of Massachusetts. This data was then combined with qualitative indicators to derive policy and planning recommendations meant to increase social equity outcomes for low-income, urban populations. The working definition this thesis used for "social equity increase" was the potential for reducing public health risks via the mitigation of UHI effects in addition to co-benefits such as increased thermal comfort and lower energy usage (Das et al. 2024, 964; McGeehin and Mirabelli 2001, 187).

This thesis was driven by three research questions:

1. What is the influence of major roads on urbanization in Massachusetts between the years 2001 and 2019?
2. How do road transportation infrastructure and urbanization influence the surface urban heat island effect in Massachusetts?
3. How can policy and planning efforts increase equity and decrease public health risks in MA, given challenges associated with the interplay between road transportation infrastructure, urbanization, and the surface urban heat island effect?

To answer these questions, spatial data collection and analyses were used to explore the correlations between road networks and urbanization in Massachusetts over time. The term "road networks" was defined as major roads throughout the state that were classified as major collectors through interstates based on the United States Department of Transportation (USDOT) Federal Highway Administration's (FHWA) functional classification system (MassGIS 2024a; FHWA 2023a, 14-19).

Meanwhile, "urbanization" was defined as one of two types of land cover change for a given parcel: either reclassification from any non-urban designation to any urban designation or from a lower-intensity urban designation to a higher-intensity one. These designations were based on the classification system used by the National Land Cover Database, which the Multi-Resolution Land Characteristics Consortium (MRLC) noted was modified from the Anderson Land Cover Classification System (MRLC n.d.).

In addition to this spatial analysis, a qualitative analysis was used to determine the effects that road networks and urbanization systems may have on local urban climate conditions via the production and exacerbation of UHI effects. To answer the final research question, a comparative framework based on the qualitative data was applied to review potential policy and planning responses to these interrelated systems.

Road networks were chosen as a variable because they lower the required input cost of moving people, goods, and ideas between geographic spaces, which is a key requirement for urbanization (Bernard 2009, 24: Maparu and Mazumder 2017, 319-320). Moreover, urban areas can expand further following the development of transportation infrastructure (Zeng et al. 2019, 2). Land cover was chosen as a proxy for urbanization based on the availability of data and the ability to utilize the intensity of an area's built infrastructure to distinguish between areas that urbanized for the first time over the observed time period versus areas that were already urban but urbanized further.

For clarification, it should be noted that the term "urbanization" was used separately from the concept of an urban area or region throughout this thesis. Urbanization itself was considered a process, while an urban area or region was considered a manifestation of said process (Pandey et al. 2022, 2; Chester et al. 2014, 534). Also, "land cover" was used distinctly from "land use," wherein land cover referred to the type of primary physical matter that occupied a geographic area. Examples of cover types include vegetation, bare soil, developed structures such as buildings, and water (Loveland et al. 2012, 2). In comparison, "land use" referred to the primary function derived from a geographic area, such as agriculture (Loveland et al. 2012, 2).

This thesis used the same land cover classification system as the National Land Cover Database (NLCD), jointly provided by the United States Geological Survey (USGS) and the Multi-Resolution Land Characteristics Consortium (MRLC). This system was modified from the Anderson Land Cover Classification System and included nine categories with 20 specific classes. For example, one category was "Developed," which included four classes: developed, open space; developed, low intensity; developed, medium intensity; and developed, high intensity (MRLC n.d.).

Another key term used in this thesis was "poverty," which was a measure of economic well-being based on an individual's or family's annual monetary income (U.S. Census 2024, 1). The United States Census Bureau publishes poverty thresholds annually for households of various sizes and ages based on the then-current cost of living as defined by the Consumer Price Index for all Urban Consumers (CPI-U) (U.S. Census 2024, 2). When a person or family has an income at or below their corresponding poverty threshold, they are considered unable to afford a basic standard of living (U.S. Census 2024, 2). This thesis used the terms "poverty," "low(er)-income," and "poor" interchangeably.

## Major Findings

The major findings from the spatial analysis conducted in this thesis include the fact that road networks do correlate with the urbanization of surrounding land cover in Massachusetts, with roads classified as interstates having the most significant relationship with urbanization processes. Additionally, incorporation of qualitative data from the literature affirms that the interaction of these systems poses public health risks and social equity challenges via the exacerbation of inequitably distributed UHI effects (Das et al. 2024, 970-972; McGeehin and Mirabelli 2001, 185).

The qualitative analysis found that increasing urban vegetation; modifying surface colors and materials, such as through the implementation of cool pavements and roofs;

and altering urban form, such as through changing building heights, street widths, and the spatial distribution of these features; were all found to be effective for mitigating UHI effects and improving public health outcomes (Hsu et al. 2021, 2; Das et al. 2024, 988; Taleghani et al. 2016, 6; Zhou et al. 2017, 6). Vegetation increases and the modification of surface materials and colors were found to be more likely to directly improve social equity outcomes compared to alterations of urban form, however, due to being easier to implement closer to city centers (Chester et al. 2014, 535; Zhou et al. 2017, 2).

More specifically, four key takeaways emerged from the qualitative results that may help local and regional planning and policy efforts to decrease public health risks and increase social equity outcomes related to UHI effects and their driving factors. These include:

1. The location of any intervention is crucial for maximizing its efficacy and benefits,
2. Daytime mitigation of UHI effects is best provided by increasing the quantity and/or density of urban vegetation,
3. Nighttime mitigation of UHI effects is best provided by cool pavements, particularly when they are implemented in shaded areas, and
4. The benefits of any intervention strategy are increased when both air temperature and mean radiant temperature are reduced.

The final findings from this thesis follow from a disconnect between the spatial and qualitative analyses: the spatial analysis highlights the importance of interstates, which are definitionally macro-scale infrastructure that connect geographically disparate places (FHWA 2023a, 14). The academic literature that informed the qualitative analysis, however, often evaluated interventions under the assumption that they would occur within urban residential neighborhoods. Considered together, these findings point to geographic and political scalar conflicts between some of the major drivers of UHI effects, and current research on mitigation strategies.

### Thesis Structure

This thesis is organized into five subsequent chapters. The second chapter (2) consists of the literature review. The third chapter (3) begins with a brief review of the methods other researchers have utilized. It then discusses the data, data sources, and methods used for the novel quantitative and qualitative analyses conducted in this thesis. The fourth chapter (4) consists of a technical report of the results from each of the econometric and geoprocessing techniques utilized in the quantitative analysis as discussed in the methods section. The fifth chapter (5) includes the discussion of the implications of the quantitative results as well as the subsequent qualitative comparative analysis. The sixth chapter (6) concludes this thesis. It briefly reiterates the major takeaways from this academic work and provides recommendations for future studies.

## Chapter 2. Literature Review

In order to discuss the importance of transportation infrastructure networks (TINs) on urbanization processes in Massachusetts, how they both affect urban heat islands (UHIs), and how the three impact social equity and public health, an overview of each system is provided as part of this literature review. These overviews provide context for this discussion, including the historical basis for, drivers of, and challenges posed by these systems.

Once this background has been provided, the implications of these processes on matters of social equity and public health will be highlighted in addition to indicators other studies have used to measure equity and health outcomes, respectively. Finally, examples of existing frameworks will be mentioned to provide context for the framework used in this study.

## Availability of Literature

It is important to preface this section with a comment on the availability of relevant literature. As noted in a thorough meta-analysis by Kasraian et al. (2016), there are few long-term studies on the interactions between TINs and land use generally, including more specifically the urbanization of land cover and land use (773). With a total of 22 U.S.-based studies, their meta-analysis included just six which analyzed both roadways and land cover, with data spanning the years 1945-2007 (Kasraian et al. 2016, 778-779).

Therefore, many international sources were consulted herein to conduct a thorough literature review. A significant percentage of recent and relevant studies are based in China and other East Asian nations. China has the largest urban population in the world, with greater than 837 million people, and is undergoing rapid land development along with neighboring countries (UN 2019, 12). Studies in this region also tend to focus on land cover more frequently than population (Kasraian et al. 2016, 777).

## A History of Roads

### *The Evolution of Roads Over Time*

In discussing the effects of TINs and their influence on urbanization and urban heat, it is necessary to discuss both the purpose of TINs and their evolution. At their most basic, the purpose of TINs is to facilitate travel to or from a place. Additionally, TINs that enable effective and efficient travel provide citizens with benefits such as convenience and leisure while providing the governing entity that controls the TIN with increased economic and military capabilities (Bernard 2009, 24).

The earliest known transportation networks consisted of dirt paths surrounding the springs of Jericho, which date back to approximately 6,000 BCE. Paths were discovered to have later been made on the ridges between valleys. These areas were drier and allowed for longer-distance travel than what may be thought of as local routes closer to water sources (Bernard 2009, 1).

Evidence suggests that the invention of paved roads occurred in the city of Ur, in ancient Mesopotamia, where stones were used to pave streets (Bernard 2009, 2). Several significant roads were subsequently paved as surrounding societies matured, including the Egyptian Kings Highway and the Silk Road. The purpose of these roads, and most others at the time, was either to extend a ruling power’s military presence or to participate in long-distance trade networks (Bernard 2009, 5-9).

As time continued, the Roman Empire built a road network that became the first known wide-scale example of a complex TIN designed for land transportation. This was the first time that a standardized process was used for road construction, which included utilizing multiple material layers rather than a single topping material, such as stones. This is also the first known example of roads being built with specific, varying widths, such as 40 feet for major highways and 20 feet for regular streets. This resembles an early version of the functional classification system used in the United States today. To put this era further into perspective, there were approximately 50,000 miles of paved roadway at the peak of the Roman network compared to the U.S. Interstate System's official length of 46,876 miles as of June 2023 (Bernard 2009, 11-17; FHWA 2023b).

### *Mode Shifts in Land Transportation*

The earliest paths and roads were all traveled on foot. Although there is not a single agreed upon date, there is a general consensus that the wheel was not invented until the fourth millennium BCE, with the oldest known wheel specifically designed for transportation dating to between 5,100 and 5,350 years ago (Bondár 2018, 281; Alacoque et al. 2024, 5-6).

Even after the invention of wheeled transportation, its utilization for human travel was not common until relatively recently. The city of Paris pioneered urban public transportation with its omnibus lines in 1828, but only people with considerable wealth could afford to utilize them. Everyone else walked to work (Glaeser et al. 2007, 21). This is significant because older cities such as Paris, Boston, and New York, which were already large by the year 1900, were designed first for walking and then built out according to the design of their public transportation infrastructure (Glaeser et al. 2007, 21).

Newer cities, in comparison, have been designed to accommodate personal automobile traffic. As noted by Lugo (2014), more space has been devoted in modern cities to infrastructure for automotive traffic than other means of transportation (311). This infrastructure includes features such as highways, local roads, and parking lots. In the United States, this has happened largely due to political choices that focused on minimal trip times and disproportionately funded roadways for personal vehicle travel in conjunction with tax policies in the mid-1900s that incentivized larger home sizes outside of urban cores (Chester et al. 2014, 534). This version of urban design that supports driving as the main method of transportation is known as "automobility" (Lugo 2014, 311).

In the 1920s, Los Angeles became the first community in the US to embrace personal automobile use over public transportation. Lacking the infrastructure to support the number of vehicles on the road, traffic congestion quickly ensued. Rather than see this as a problem based in car usage, however, the public largely saw this as an urban planning failure, beginning a new era of continuously striving to optimize the built environment for cars over nearly everything else (Lugo 2014, 310). Since 1969, passenger cars have been the most common means of transportation for U.S. commuters (Lugo 2014, 311).

## Defining Urbanization

### *Urban Definitions*

When discussing urbanization, it is possible to muddle the process of urban growth with the concept of urbanity—that which *is* urban. One way to conceptualize this difference is to think of cities as a product in both space and time of the cumulative effects of urbanization processes (Wachsmuth 2014, 76-77). Additionally, understanding the driving factors underlying the process of urbanization helps to explain why it exists in the forms that it does and the benefits and drawbacks of those forms.

For an adequate discussion, some terms must be defined. Individual countries tend to have formal definitions for what constitutes an urban settlement and how they measure urbanization, but there is significant variation among different countries, making international comparisons difficult (Moreno 2017, 3). In the 2018 revision of the UN's

*World Urbanization Prospects* publication, the organization provides general guidelines for “urban agglomerations” and “metropolitan areas,” which are useful in this study.

The former is a contiguous area with a minimum urban residential density while the latter is the urban agglomeration in addition to the surrounding areas which may have lower residential densities but are strongly tied both economically and socially to the city or cities at the core of the urban agglomeration. Meanwhile, the central city or cities may only be a subset of the urban agglomeration (UN 2019, 16).

Moreover, a given area’s *level of* urbanization is often measured as the percentage of the total population considered to be living in urban portions of the overall area. Urbanization *itself* is typically used to refer to multiple types of growth: growth in both this relative urban percentage of an area’s total population as well as growth in the absolute number of urban dwellers in addition to increases in an urban area’s geographic footprint (UN 2019, iii). Finally, urban population growth can occur in three ways: via natural population growth, rural-to-urban migration, and reclassification of non-urban surrounding areas to an urban classification (UN 2019, 1-14).

### *Agglomeration Economies*

It has been argued that urbanization is the single most impactful thing on the planet, both socially and environmentally, since the beginning of civilization (Georgescu et al. 2021, 1). The urban areas that form as a result are renowned for many reasons. They are centers of employment, economic development, and both technological and cultural innovation (Maparu and Mazumder 2021, 46). Much as an urban area is the result of urbanization processes, these attributes of urban areas are results of higher population densities and the agglomeration economies that are formed (Moreno 2017, 2).

Agglomeration economies are economic scenarios which affect the placement of firms and the access of both local firms and residents to markets, capital, ideas, and other people (Maparu and Mazumder 2017, 320).  Three types of agglomeration economies exist: internal scale economies, wherein a single firm concentrates its production; localized economies, wherein different firms within a similar industry concentrate geographically; and urbanization economies, wherein industries providing diverse goods and services concentrate geographically (Maparu and Mazumder 2017, 321).  These economies stem from higher population densities and lower transportation costs and, collectively, are the reason that many researchers view urbanization as the key to economic development (Maparu and Mazumder 2021, 46).

### *Urbanization and Infrastructure*

Just as the value of urbanization is tied to the agglomeration economies it produces, so, too, is urbanization tied to infrastructure.  Like cities, infrastructure systems are manifestations of urbanization processes.  Furthermore, as these processes evolve and respond to local conditions, they can give rise to various urban forms and infrastructure networks which then enable the continuation and evolution of the underlying urbanization processes (Chester et al. 2014, 534).

Improvements and breakthroughs in the many forms of infrastructure that enable urbanization, such as TINs, public services, and information and communication technology, have resulted in incredible advancements in economic growth and quality of life standards over the past two centuries (Chester et al. 2014, 535). That being said, only within the past few decades have efforts arisen to consider not just the immediate use of technology and infrastructure but also the potential unintended impacts of urbanization processes and their resultant infrastructural systems (Chester et al. 535).

This is significant because the philosophy behind the design of traditional infrastructure systems is typically to minimize the risk of failure by using components that are hard and resistant to chemical changes (Chester et al. 2014, 542). Several centuries of implementing this design philosophy have resulted in urban areas across the world that are built with systems that are not very flexible, that generally require fossil fuels in their construction and operation, and that are difficult to upgrade (Chester et al. 2014, 541).

These infrastructural characteristics are extremely common in areas that are often thought of as "developed," many of which are contemporarily struggling with infrastructural "lock-in" that makes it difficult to alter the existing infrastructure systems to meet modern needs using modern resources and technology (Chester et al. 2014, 534, 541). Beyond that, the types of infrastructure that are present can determine the structure of cities over time, and these urban morphologies are even longer lasting than the infrastructure systems on which they are based (Chester et al. 2014, 535; Glaeser et al. 2007, 23).

### *The Urban, Urbanization, and Sustainability*

Despite the reliance of many cities on fossil fuel-based infrastructure that continues to exacerbate alterations of the earth's climate systems, Angelo and Wachsmuth (2020) note in their meta-analysis on cities and sustainability that many researchers and policymakers hold assumptions that cities both can and should be "green" in addition to being the most likely answer to environmental problems (2,203). This is a significant shift in public opinions on urbanism from historically negative conceptions to ones that are not only positive but that may also increase the potential for impactful change (Angelo and Wachsmuth 2020, 2,204).

In practice, an area typically goes through several stages as it begins to undergo urbanization. First, motorized transport increases, replacing non-motorized transport modes and increasing overall energy consumption. As urbanization continues, urban features such as roadways and buildings increase in both quantity and density. This occurs in the urban core in addition to spreading out into the surrounding land. Residents begin to move to the outskirts of the urban area based upon factors such as environmental quality and the increasing price of land in the urban core. Businesses tend to stay in their established locations, however, so transport infrastructure is built for workers and consumers that have moved farther away, ultimately increasing total travel requirements and energy consumption. This last stage often then continues as an ongoing process of suburbanization (Z. Wang et al. 2019, 34,886).

The reason for the continuance of suburbanization, also called sprawl, is based on continually rising land costs and the housing market. In an economic context where prices are determined primarily by free market processes, sprawl becomes the de facto affordable housing policy. The effects of this are that commute times continue to rise, as do levels of energy consumption and greenhouse gas (GHG) emissions, undermining sustainability goals (Miller and Mössner 2020, 2,258).

Finally, the relationship between urbanization and sustainability is further complicated when considering the full geographic extent necessary to drive urban growth and industrialization. Deemed “extended urbanization,” this concept includes all the hinterlands necessary to produce the urban reality, including, for example, farmland from which food is imported that may be located adjacent to the city or may be located on the other side of the world (Castriota and Tonucci 2018, 515).

### *Urbanization and Inequality*

Inequality may be an inherent part of urbanization. Multiple types of inequality exist, one of which is infrastructural. Infrastructural inequality can be defined as unequal distributions in the availability, provisioning, or accessibility of infrastructure throughout the population of a geographic area when accounting for the total relative levels of these attributes (Pandey et al. 2022, 2). In other words, if the level of one of these attributes, say infrastructure provisioning, is low throughout the entirety of a study area, then the fact that a specific segment of the area’s population exhibits low provisioning is not a sign of infrastructural inequality at that scale. If, however, the study area typically has a high level of infrastructural provisioning, but one segment of the population exhibits low provisioning, then infrastructural inequality may be present at that scale.

These attributes of infrastructure can be thought of as a progression of planning, building, and maintaining individual components. As an example, think about building a new road. First, the road needs to be planned, including designating where the road will go, what it will be made of, and who will build it. Next, the site needs to be prepared, the materials and builders brought in, and the road constructed. This whole process may be thought of as infrastructure provisioning. When the road is opened for use, it may be considered as available. Finally, the ability of a person or group to actually utilize the infrastructure, such as having access to a vehicle as well as entrance and exit ramps to the road, may be considered as infrastructure accessibility.

As urbanization continues and drives increases in both population and the scale of the built environment, it necessitates greater quantities of physical assets like roads, electrical grids, and water pipes to provide basic services to the new residents and across the greater spatial extent (Pandey et al. 2022, 1). The buildout of these infrastructural systems is subject to both physical and resource constraints, which may result in unequal and inequitable scenarios (Pandey et al. 2022, 1). For example, consider the plans for building an auxiliary interstate around the Boston area. The interstate was meant to connect U.S. Route I-93 with Routes I-90 and I-95 in order to alleviate traffic on local roads (Moss et al. 2014, 1,054). The provisioning for the highway, which was known as the Inner Belt and officially designated as Interstate 695 (I-695), began in 1948 with a plan for a loop route around Boston proposed by the Massachusetts Department of Public Works (DPW), and it was eventually cancelled in 1971 (Moss et al. 2014, 1,054).

Completion of the interstate as it was proposed would have involved massive clearing projects; the demolition of existing infrastructure including homes using municipal rights-of-way (ROWs), which are publicly owned areas reserved for transportation purposes; and the acquisition of adjacent, privately-owned land via eminent domain (Moss et al. 2014, 1,054-1,055; MassDOT 2025c). Parts of the route for the highway divided existing communities, and in total, approximately 7,000 residents would have been immediately displaced by the physical constraints of implementing this infrastructure, i.e., the need for land (Moss et al. 2014, 1,059). This does not include further displacement and disinvestment impacts over time. As noted by Kasraian et al. (2016), living near highways may be unattractive to residents as evidenced by lower residential densities within a third of a mile of highways compared to surrounding areas (782, 786).

Although the highway was never made available due to its cancellation, it would have provided an infrastructural benefit to those with access to it (Gerritse and Arribas-Bel 2017, 1,146). Some of these beneficiaries would include, for example, people who simultaneously: A. were not displaced, B. had vehicle(s) to travel the road, and C. had travel requirements, such as commutes to work, that would have been shortened due to the higher speeds allowed by interstates compared to local roads (Moss et al. 2014, 1,059). Meanwhile, people who were displaced or did not have access to the road would have faced social inequities and an overall increase in infrastructure inequality. This agrees with Pandey et al.'s (2022) finding that, as infrastructure provisioning and availability increase, so do infrastructural inequalities (3-4).

Additionally, Pandey et al. (2022) discovered that, not only were inequality levels higher in areas with more infrastructure, but also there was an emerging trend of inequalities between urban centers and their peripheries (3). One of the areas they studied was India, where they found that, while greater infrastructure inequality existed in urban areas compared to rural areas by around 4%, any urban resident still had greater access to infrastructure on average than a rural resident by approximately 569.4% (Pandey et al. 2022, 3). Although the degree to which these interactions between urbanization processes and infrastructural inequalities are understood remains limited, these relationships display the complexity in equitable urban and regional planning efforts (Pandey et al. 2022, 1).

There are effects from high levels of inequality regardless of an area's status as urban or rural, though. Some examples of these effects include lower economic productivity, meaning businesses and services operate less efficiently; reductions in social capital, meaning lower levels of both inter- and intra-personal well-being; inequitable distributions of environmental burdens, meaning some groups of people are more greatly exposed to health and quality-of-life risks from factors such as pollution and noise compared to other groups; and greater variation in the distribution of disruptions caused by shock events, meaning certain groups of people face severer consequences from events such as economic recessions over other groups (Pandey et al. 2022, 1).

### *Conclusion*

Despite these inequalities and in conclusion of this background on urbanization, it is important to highlight the ongoing shift in public perception of the city from an environmental and social problem to a solution. This is a relatively recent development, occurring in the past few decades as climate change has linked two significant models of urbanization: sprawl and informal settlements. Over the past couple decades, the former has commonly been practiced in the Global North, while the latter has typically been practiced, at a continually increasing rate, in the Global South, though both have exceptions (Angelo and Wachsmuth 2020, 2,204). The typical perception of sprawl over this time period has been that it is dangerous to the environment and is expected to lead to resource depletion (Leffers 2015, 332; Angelo and Wachsmuth 2020, 2,204). Meanwhile, the typical perception of informal settlements has been that they are disdainful for their unprecedented levels of rapid growth and public health concerns (Angelo and Wachsmuth 2020, 2,204, 2,206). The focus on both shifted from sources of copious GHG emissions to sites for emissions reductions (Angelo and Wachsmuth 2020, 2,204).

These models of urbanization pose unique challenges. For cities that have already undergone considerable suburbanization, their ability to transition to sustainable development will be hampered by excessive dependence on high levels of energy in lower-density neighborhoods (Nizic and Baresa 2013, 326). This is exacerbated by infrastructural lock-ins that make transitions to lower-impact, "cleaner" infrastructure more difficult (Chester et al. 2014, 540-541). Finally, urban areas with high levels of informal settlements will face challenges from uncontrolled population growth mixed with poor infrastructure and management systems (Nizic and Baresa 2013, 326).

## Impact of Roads on Urbanization

Prior to mentioning anything else about roadways, it is imperative to understand that every single road, from dirt paths to interstates, is part of a larger network, hence the term "transportation infrastructure network." When an urban landscape is considered in its entirety, on a basic level it can be thought of as a system that performs functions. The specific function TINs perform as a subsystem of this greater superset is to provide connectivity. As will be shown, connectivity is at the center of the capacity of urbanization processes to provide benefits to individuals and societies (Ahern 2011, 342-343).

### *Causality (and Its Direction) Versus Correlation*

It is also important to mention the distinction between studies which examine correlation among variables versus causality. When studies are correlational, it is possible to miss feedback effects and endogeneity among the variables (Pradhan et al. 2021, 2). In other words, correlational studies may not discern when variables, considered independent from one another, may actually be related, meaning that changes in one “independent” variable cause another variable to also change rather than just the dependent variable. This may lead to biased results in an analysis, in turn causing incorrect assumptions about the relationships among the variables being studied.

### *Production of Agglomeration Economies and Spatial Spillover Effects*

Agglomeration economies were briefly mentioned above. To reiterate, they are economic scenarios that underlie urbanization processes and make certain areas more attractive to firms, resulting in greater employment densities and diversification of both employment opportunities and available commercial services (Chaneiabate et al. 2023, 4; Maparu and Mazumder 2017, 321). The reason TINs are so important for the production of these agglomeration economies is because the cost of transportation is a key consideration when firms decide where to locate. Moreover, urbanization occurs sooner when the costs of transportation are lower (Maparu and Mazumder 2017, 319-321).

TINs also produce both direct and indirect effects. These include spatial spillover effects, wherein a stimulus in one area produces effects in neighboring areas. For example, besides lowering transportation costs, a direct effect of roadways is the need for labor to initially plan and build them and then to maintain and repair them over time

(Chaneiabate et al. 2023, 5). In comparison, an example of an indirect effect is an increase in knowledge transfer among residents and firms due to increases in intra-urban interactions (Gerritse and Arribas-Bel 2017, 1,136). Both direct and indirect effects can promote urbanization (Chanieabate et al. 2023, 15; Zeng et al. 2019, 8).

The presence of road networks has also been shown to increase the likelihood of altering the surrounding land cover. This may consist of general changes, i.e., movement from one cover classification to another, but often the change is specifically from a non-urban classification to an urban one (Kasraian et al. 2016, 782-783). This begins a positive feedback loop of urbanization, wherein the expansion of existing urban areas allows for greater total urban populations, promoting further urbanization (Zeng et al. 2019, 2).

Roadways can be divided into functional classes that provide design guidelines and define the expected function of a given road including the corresponding vehicle capacity it can handle without excessive traffic. In the United States, classifications include design guidelines and range from local streets to roads incorporated into the federal interstate system (FHWA 2023a, 14-19). While many studies consider roads as a single variable without discerning among functional classifications, it has been shown that different functional classes provide varying levels of agglomeration benefits and spatial spillover effects, which themselves may be based on travel time more than the effects of urban population density (Gerritse and Arribas-Bel 2017, 1,146-1,147).

Specifically, highways have greater spillover effects than other transportation methods and have been shown to lead to land cover urbanization, increased employment densities, and to attract commercial and industrial developments in addition to increasing worker productivity (Zeng et al. 2019, 2; Kasraian et al. 2016, 786; Gerritse and Arribas-Bel 2017, 1,146-1,147). Zeng et al. (2019) found that the two highest functional classes were the most integrated in China's Wuhan urban agglomeration, i.e., expressways and national highways provided travelers with the greatest ability to easily travel between two separate locations in the study area (5-6). They also found that the urban core and its immediate surroundings were more integrated than areas on the periphery of the urban agglomeration, providing evidence for why agglomeration benefits may be higher in city centers if those benefits are indeed based on travel time.

### *The Congestion Effect*

As mentioned, functional classes help define the level of service a road is expected to provide. When a road is operating inside the level of service for which it is designed, an increase in users corresponds with an increase in economic interactions, productivity, and spillover effects. Once the capacity of the road network has been exceeded due to either too high a demand or to disrepair lowering the network's efficacy, though, the cost of using the road network increases with each additional vehicle on the road. This is known as the congestion effect (Chanieabate et al. 2023, 4; Han et al. 2018, 402).

Multiple consequences arise from the congestion effect. For residents, some effects include increases in costs of living, longer commute times, and decreases in net income. For businesses, some negative outcomes from congestion include decreases in labor productivity and decreased knowledge spillover effects (Han et al. 2018, 401-402).

The congestion effect also has spatial spillover effects. As an example, take two cities, Somerville and Boston, which are relatively close together. John is a Somerville resident. As part of the agglomeration benefits from Boston's ongoing urbanization processes, John was able to find a better job in Boston than Somerville. His daily commute was three miles long and initially took him 15 minutes in one direction driving his own car.

As the neighborhood around John's job location continued to urbanize, however, congestion increased. His commute time continued to grow, until traveling the same three miles took 45 minutes in one direction compared to 15 minutes. For John to continue to work his job for the same pay rate, he had to then sacrifice an additional hour of his time each workday as well as pay for increased expenses, such as additional fuel costs and charges incurred from accelerated wear on his vehicle. These negative externalities to which John has been exposed are examples of the potential consequences from the spatial spillover of congestion resulting from the urbanization processes in a nearby area. It is important to remember, though, that while such negative externalities may occur, they are not guaranteed to do so (Han et al. 2018, 405).

### *Transport Infrastructure's Relocation of Populations*

Finally, TINs support the relocation of populations, which is one of the major drivers of urbanization (Kasraian et al. 2016, 781; UN 2019, 1-14). Specifically, the main method of urbanization in North America over the past couple decades has been through rural-to-urban migration (Heris et al. 2020, 1). The development of TINs during early phases of urbanization allows for greater integration between rural and urban markets, facilitating both the transfer of goods and services as well as the transfer of labor (Chanieabate et al. 2023, 5-6). In later phases of urbanization, the expansion of road networks aids suburbanization processes (Kasraian et al. 2016, 781).

## Surface Urban Heat Island Effect

### *What is Urban Heat*

To talk about the impacts of urbanization and TINs on the surface urban heat island effect (UHI), it is important to define urban heat islands themselves. Heat islands are a phenomenon seen in urban areas across the globe. Zhou et al. (2017) note in their own in-depth literature review on UHI that the phenomenon has multiple underlying causes which operate simultaneously (1). These causes include human-induced material and design modifications to natural landscapes, as well as supporting causes such as the cumulative waste heat from transportation activities and buildings' heating, ventilation, and air-conditioning (HVAC) systems.

The material modifications consist of replacing land surfaces that are typically permeable and vegetated with compounds such as asphalt and concrete. The design modifications include the construction of typical urban infrastructure, like buildings, roadways, and parking lots. These materials and the spatial arrangements that are created with them alter the urban boundary layer both atmospherically and thermophysically, collecting and storing solar radiation over the course of each day (Taleghani et al. 2016, 1; Zhou et al. 2017, 1). This stored solar radiation combines with the waste heat from anthropogenic activities to result in higher air temperatures in city centers compared to surrounding areas (Taleghani et al. 2016, 1-2).

There are multiple metrics that can be used to measure urban heat levels. The two most common are air temperature, which is what most people think of when they think about the weather, and mean radiant temperature (MRT). This latter metric is measured as the sum of both shortwave and longwave radiation fluxes in a given area to which a person or object may be exposed (Taleghani et al. 2016, 2). To understand the difference, consider two areas: a spot receiving direct sunlight in a city square surrounded by buildings and another spot 200 feet away in the shade of a tree overhead. Both locations would have a similar air temperature, but the spot in the shade would feel much cooler than the one in the sun due to a lower radiative load. This example portrays how MRT is better associated with outdoor thermal comfort than air temperature and is often used as the main measurement for studying UHI (Taleghani et al. 2016, 2).

### *Land Cover and UHI*

Land cover plays a significant role in either mitigating or exacerbating urban heat levels. Moreover, urban microclimates are affected by an array of factors, including both the composition and spatial arrangement of land cover and land use (Kong et al. 2016, 1,429). Vegetated land cover, or green space, influences the local area's microclimate both horizontally and vertically, i.e., across the ground's surface and from the surface into the air. This has resulted in difficulties for researchers attempting to measure the full extent of the capacity of land cover to regulate local temperatures (Kong et al. 2016, 1,429).

That being said, it is agreed that green space does provide temperature regulation services, sometimes referred to as cooling effects, through both shading and evapotranspiration (Kong et al. 2016, 1,429). Shading, also known as radiation interception, is the reason given above for why a person would feel cooler under a tree than in direct sunlight. Evapotranspiration is a combination of evaporation, wherein a subset of liquid water in an environment turns to vapor and is dispersed, and transpiration, wherein the leaves of plants lose water vapor to the atmosphere. The combined effect of these processes is a cooling of the local environment due to heat being dispersed with the lost water vapor (EPA (Environmental Protection Agency) 2008b, 3).

It is possible for feedback loops to form between land cover and microclimate conditions, and alterations to said cover can then alter these loops (Loveland et al. 2012, 3-4). Take, for example, an area of vegetated land cover that is then altered into a roadway. As mentioned above, this roadway is most likely constructed with either asphalt or concrete, both of which are impervious surfaces. Two results are immediate: the first is that evapotranspiration processes are stopped due to loss of vegetation and an impervious layer capping the underlying soil, and the second is the roadway itself collects and stores solar radiation throughout the day. Now, not only is the local area not being cooled, but it is also additionally being warmed (Kong et al. 2016, 1,438). This leads to higher air temperatures which are then further stored by the road.[1] This is worsened by the increased likelihood of land cover urbanization near roadways (Kasraian et al. 2016, 782-783).

### *Urbanization and Responses to UHI*

General urbanization has been shown to increase the yearly average surface temperature of urban areas by between 0.19-2.6$^0$ C. Additionally, as noted by the Intergovernmental Panel on Climate Change (IPCC), urbanization exacerbates heat waves by between 1.22-4.0$^0$ C (IPCC 2019, 2-74). Furthermore, urban morphology, or the spatial

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[1] Unrelated but of note, soils underneath urban surfaces store less water than uncovered soils. This increases the risk of flooding in urban areas and may require adaptation measures to avoid damages to health and property. Levels of stored carbon are also reduced in urban land (IPCC (Intergovernmental Panel on Climate Change) 2019, 2-75).

characteristics of an urban area, affects UHI intensity. Some examples include city size, wherein doubling the size increases UHI by approximately $0.4^0$ C; fractal dimension as a measure of city compactness, wherein increased fractality, or a less-compact form, lowers the city's experienced UHI but increases the surrounding area's; and anisometry as a measure of the city's overall shape from circular to elliptical, wherein higher anisometry, or a more elliptical shape, decreases UHI up to approximately 1.5 C (Zhou et al. 2017, 3).

Some moderate correlations have been found between these characteristics. More compact cities tend to also be more circular, so higher fractal dimensions correspond with lower anisometry. Additionally, city size is positively correlated with fractality, so larger cities tend to be more compact (Zhou et al. 2017, 3). This can be summed up as saying that the larger a city is as well as the more compact and the less stretched, the greater its UHI intensity tends to be (Zhou et al. 2017, 6).

Besides altering urban form, opportunities for which may be limited, there are two other main categories of UHI mitigation strategies. These include increasing vegetation and modifying the composition and color of surface materials (Zhou et al. 2017, 2; Heris et al. 2020, 2). The shading and evapotranspiration functions of vegetation have already been introduced. Studies have found that the effect of shading can equal a reduction in MRT equal to or greater than 20° C (Taleghani et al. 2016, 6-7). This effect has been observed from natural features, e.g., trees, in addition to engineered features, e.g., tall buildings (Heris et al. 2020, 2). It may still be worthwhile to prioritize vegetation over engineered sources, however, as increasing tree density was found to lower air temperature in addition to MRT while removal of green space resulted in increases in air temperature (Heris et al. 2020, 12-13; Kong et al. 2016, 1,438).

Concerning the second category of mitigation strategies, the value of material composition has been touched on in the example of building a roadway in a previously vegetated tract of land. To elaborate, part of the reason underlying the effects of material composition is due to the color of the materials. The darker something is, the lower its albedo and thus its ability to reflect the solar radiation that strikes it. The energy that is not reflected is stored and remains in the local environment (EPA 2012, 5). This continues throughout sunlit hours, and the stored energy is then emitted back into the environment at night, increasing nighttime temperatures (EPA 2012, 1; Taleghani et al. 2016, 8).

One potential response to this dynamic is the implementation of cool pavements which are brightly colored and reflect shortwave radiation during the day. This reflection results in lower levels of stored energy, leading to lower overnight temperatures (Taleghani et al. 2016, 8). There are tradeoffs to be considered, though. While these pavements have been shown to reduce local *air* temperatures compared to standard pavements, they simultaneously may increase *mean radiant* temperatures during the day due to the increased transmission of shortwave radiation (Taleghani et al. 2016, 6-7). Besides pavements, buildings themselves affect the amount of reflectivity and the heat storage capacity of urban areas (Heris et al. 2020, 2).

## Contextual Dependencies

Having provided these background sections on urbanization processes, the impacts of road networks, and the urban heat island effect, a word of caution needs to be given.

There is scientific and academic consensus on many of the relationships and effects that have been discussed, but most authors also point out that the results they reported were obtained within a given context, be it procedural, political, temporal, or geospatial (Maparu and Mazumder 2017, 335; 2021, 47, 53).

As noted by Gerritse and Arribas-Bel (2017), there is a breadth of estimates provided for the precise magnitude of many of these relationships, so none of the information provided should be taken for granted (1,147). Additionally, the spatial and temporal scales used for analysis may skew the results thereof, as may the variables that are considered (Maparu and Mazumder 2017, 324; Pradhan et al. 2021, 8).

## Equity Implications

### *Theories of Development*

The previous sections provided an overview of some of the major causes and effects of urbanization processes. While it is generally accepted that urbanization follows from socio-economic development and physical processes such as infrastructure construction, there remains a considerable amount of research needed to understand exactly how cities grow and which aspects, such as inequalities and carbon-intense activities, are truly necessary for that growth (Zeng et al. 2019, 3; Chester et al. 2014, 535, 540).

Multiple theories have been proposed to explain how economic development and urbanization occur. For example, two opposing theories are endogenous growth theory and Wagner's law. The former states that investments in infrastructure lead to economic development while the latter states that economic development leads to investments in public infrastructure (Maparu and Mazumder 2017, 320-324).

Some theories that attempt to explain the overarching mechanism by which urbanization occurs include dependency theory, urban-bias theory, and modernization theory. Dependency theory states that investments in the international export of goods leads to urbanization, showing that countries rely on the wealth of other nations. Urban-bias theory states that the key to urbanization lies in disparities between infrastructural investment between urban and rural areas, wherein rural residents move to urban areas based on the availability of better infrastructure. Finally, modernization theory states that investments in infrastructure lead to urbanization (Maparu and Mazumder 2021, 47).

The existence of these various theories showcases the difficulty in trying to determine the best leverage points to alter these systems. One conception of the relationship between urbanization and economic growth that is helpful herein is that of an inverted U-shaped relationship: urbanization first promotes economic development, but then, after a certain point, particularly when achieved rapidly, further urbanization impedes development. This effect is exacerbated when infrastructural capacity lags behind population growth (Pradhan et al. 2021, 2).

### *Agglomeration Economies vs. Diseconomies of Agglomeration*

The reason this depiction of urbanization and economic development is helpful in a conversation on equity is because it effectively summarizes the value of agglomeration economies versus diseconomies of agglomeration. Agglomeration economies are the true source of urbanization's value, and diseconomies arise from congestion, when an area's infrastructural capacity is exceeded by its population (Maparu and Mazumder 2021, 46; Han et al. 2018, 402).

The concept of infrastructural inequality may also be brought up once more. In Maparu and Mazumder's (2017) study on India, support was found for Wagner's law as causality was observed to run from economic development to several transport infrastructure variables (330-331). Ultimately, the areas that receive investment for infrastructure are the ones that can be expected to experience agglomeration benefits. On the other hand, areas that experience greater infrastructural inequality are more likely to experience the effects of congestion processes. Furthermore, the benefits from co-location can decline rapidly, even within one to two miles, so areas with inequitable access to infrastructure may not only experience fewer benefits but also fewer positive spatial spillover effects from surrounding areas (Gerritse and Arribas-Bel 2017, 1,134, 1,136).

### *Market Forces on Local Urbanization Processes*

Which areas receive investment versus which areas are at greater risk of experiencing infrastructural inequality is largely determined by market forces and inter-municipal competition (Miller and Mössner 2020, 2,246-2,247, 2,258). Due to municipalities' status as governmental actors and not businesses, it may seem strange to think of them being subject to market pressures. This relationship becomes more noticeable, however, when examining the effects of sustainability policies.

As climate change and its effects have become more prominent, it has become more common for municipalities to utilize sustainability principles in planning and policy goals. These goals, however, tend to be set by individual cities, and the policies that support them tend to stop at each city's borders (Miller and Mössner 2020, 2,242-2,243). Often, it is the central city in an urban agglomeration or metropolitan area that pushes for the most sustainability objectives. The municipalities surrounding this central city are often neutral towards or against these policies (Miller and Mössner 2020, 2,257).

This opposition is typically not idealistic. Rather, it is rooted in municipal differentiation. The purpose of differentiation is to attract assets like capital investment, jobs, and residents, ultimately providing a given town or city with a stronger tax base. Typical vectors for this process include housing costs; tax rates; the availability of neighborhood amenities; and ways of life, such as automobility versus the availability of public transit. In summary, when a neighboring municipality projects a brand of sustainability, a vacuum is created for other cities to fill as required by an encompassing economy that is itself largely run by market forces (Miller and Mössner 2020, 2,246).

There is a tendency for this process of inter-city and even at times intra-city competition to also correlate with polarization between social classes and cultures. This usually involves one portion of a metropolitan region experiencing ecological gentrification while another portion attempts to capture the displaced residents by offering basic resources at lower price points. For people living in these typically outlying municipalities, commute times tend to increase; services become harder to reach; and fewer amenities, such as access to transportation and entertainment, are usually available in the local area (Miller and Mössner 2020, 2,247; Han et al. 2018, 401).

An example of this overall dynamic as described by Kasraian et al. (2016) is in the potential expansion of public transit systems. If transit is not well-funded through the municipality and is instead dependent on fare revenue, only the routes that are projected to be the most profitable are likely to be built or expanded. This disincentivizes service providers from branching out into lower-income neighborhoods and municipalities (Kasraian et al. 2016, 784). Another example of market influence comes from green space. Despite the ecological and public health benefits derived from its temperature regulating capacities, these services are non-marketable, providing policymakers and developers with the illusion that there is little incentive to protect them (Kong et al. 2016, 1,438).

This market-based outcome is not inevitable. It results from two main factors: 1. societal markets prioritizing exchange value over human and ecological well-being and 2. scalar differences between the varying territorial boundaries of governmental institutions and the spatial extents of the people affected by the decisions of said governmental institutions at various levels (Miller and Mössner 2020, 2,258).

## Public Health Implications

There are many factors that can negatively affect public health outcomes in urban areas. A list offered by Nizic and Baresa (2013) includes "…overcrowding, transportation systems designed for cars, poor air quality, under-developed drinking water supply infrastructure, unsatisfactory sanitary conditions, waste disposal, and poor housing conditions" (325-326). This list is not exhaustive but manages to portray some of the complexity embodied in the planning and maintenance of urban regions that are meant to be safe and beneficial to their residents, workers, and visitors.

### *Urbanization Includes Public Services*

Thus far, the only type of infrastructure discussed in depth is that of road networks for land-based transportation. This has been a simplification, as there are multiple types of infrastructure that manifest from urbanization processes. Zeng et al. (2019) note that transportation networks by themselves are unable to account for the total effects that infrastructure construction has on urbanization processes (10).

While TINs support a diverse array of benefits, what has yet to be mentioned is that the physical connectivity they embody increases both urban and rural access to essential services (Chanieabate et al. 2023, 1). These services comprise a considerable portion of infrastructure's total effect on urbanization (Zeng et al. 2019, 8, 10). Some examples of this type of infrastructure include schools, public libraries, medical centers, and areas for leisure such as parks and ball fields (Z. Li et al. 2021, 681).

There is a reciprocal relationship between public services, roadways, and other urban factors. While roadways provide the initial accessibility for residents to reach the facilities that offer these services, the services themselves have been found to alter the nearby distribution of urban land use (Z. Li et al. 2021, 681-682). Specific examples include a correlation of medical facilities and governmental buildings with higher road densities and educational and cultural centers with increased densities of built-up area (Z. Li et al. 2021, 687). Moreover, when two or more services are close together, knowledge crossover are possible, displaying a spatial spillover effect of co-location (Zeng et al. 2019, 5).

The distribution of these facilities can also affect health outcomes. Urban areas with more open space, such as parks and water sites, are expected to be beneficial for residents' health (Das et al. 2024, 965, 980; Ulpiani 2021, 19-20; Z. Li et al. 2021, 686). Open spaces are also negatively related to road densities (Z. Li et al. 2021, 687). Access to medical facilities also results in improved public health outcomes (Das et al. 2024, 982).

### *UHI Risk and Active Mobility Co-Benefits*

Average temperatures around the world have been slowly increasing, and heat waves are occurring for longer periods of time. This is expected to escalate further with the ongoing impacts of climate change (R. Li et al. 2023, 2). This is particularly poignant in cities that include concentrated population levels and, consequently, concentrated human activities that intensify heat levels in areas that already trap significant amounts of naturally occurring heat (Taleghani et al. 2016, 1-2; Zhou et al. 2017, 1).

The public health consequences that occur in response to prolonged exposure to high temperatures range from thermal discomfort to heat stress and mortality (Heris et al. 2020, 1; IPCC 2019, 2-74). These consequences present both public health and social equity concerns due to urban heat levels being elevated the most in city centers, which is also where populations living in poverty tend to be concentrated (Glaeser et al. 2007, 2, 5).

In response to these adverse outcomes, many cities have begun promoting active mobility as a substitute for personal automobile use. This is because increasing active mobility levels reduces GHG emissions, reducing not only anthropogenic contributions to urban heat levels, but also mitigating further impacts on the global climate. Additionally, active mobility results in co-benefits for participants, such as increased general health and reductions in chronic disease rates (R. Li et al. 2023, 2; Lugo 2014, 325).

The density of cities and co-location of businesses and activities allow for significant opportunities to shift travel behaviors towards more active modes (R. Li et al. 2023, 11). Switching from automobile use to active transportation involves a behavioral change, which as an overall technique has been found to be highly effective in cooling trips compared to implementing cooling infrastructure for commuters. That being said, the study on the comparative potential of the two methods in reducing heat exposure during commutes was conducted on travelers already engaging in active transportation via either walking or cycling (R. Li et al. 2023, 7-8).

Encouraging *new* travelers to engage in active transportation must overcome at least two problems. The first is the increase in participants' acute exposure to elevated heat levels compared to their baseline mode of transportation. The second is in convincing said new travelers to physically exert themselves over the course of the trips in question, which they are presumably not accustomed to doing. This can even result in greater levels of heat-related ailments and death (R. Li et al. 2023, 2, 11).

Besides the behavioral challenges related to increasing participation levels in active mobility, a social equity challenge needs to be considered: the novel implementation of the infrastructure for this mode shift increases the potential for gentrification in the immediate vicinity. This can result in pushing out the residents of neighborhoods that were meant to be helped (Lugo 2014, 325). Supporting this dynamic of active transportation being more accessible to populations with greater economic means, Glaeser et al. (2007) found a positive correlation in income and walking as a means of transportation during their study on the concentration of poverty in U.S. metropolitan statistical areas (MSAs) (19).

### *Urbanization, UHI, and Urban Pollution*

Given the challenges associated with widescale behavioral shifts, other types of interventions must also be considered for mitigating the adverse effects of urban heat levels. As mentioned above, one alternative type of intervention is increasing the size and distribution of open, green spaces. Public amenities such as parks and urban forests have been found to reduce UHI levels and to improve air quality through mechanisms such as providing shade, evapotranspiration, and ventilation (Das et al. 2024, 983-984; Hsu et al. 2021, 6-7; Ulpiani 2021, 14-15).

It is significant that open and vegetated spaces can simultaneously reduce UHI and improve air quality because there is a growing body of literature on the connection between UHI and an emerging concept of UPI, standing for “urban pollution island” (Ulpiani 2021, 2). These two phenomena share many of the same drivers, such as changes in land use and land cover as well as increases in both energy use and transportation (Ulpiani 2021, 2). In turn, these drivers are all exacerbated by rapid urbanization (Das et al. 2024, 964).

Moreover, elevated temperatures can result in higher levels of pollution and decreased air quality due to the acceleration of chemical cycles in the atmosphere, causing, for example, increases in the formation of ground-level ozone (Das et al. 2024, 970-972; Ulpiani 2021, 2). This is exacerbated by a tendency for lower amounts of air movement in and out of urban areas based on factors such as both the height and configuration of buildings as well as average street widths (Zhao et al. 2020, 10,332). The air stagnation that then occurs effectively traps additional heat and pollution rather than dispersing them to areas outside the urban environment (Das et al. 2024, 970; Ulpiani 2021, 14-15, 17). Ulpiani (2021) points out, however, that if an open space is sufficiently large, it can help generate local breezes and thus restore dispersion effects (19-20).

Thus, green open spaces present opportunities not only for direct cooling effects via shading and evapotranspiration, which on their own can increase thermal comfort and decrease public health risks, but also to both remove existing pollutants from the urban environment and to decrease the rate at which new pollutants are formed via increasing wind turbulence and decreasing the photochemical reactions between primary pollutants (Das et al. 2024, 965, 983-984; Hashemi et al. 2023, 13; Ulpiani 2021, 14, 19-20).

There is one final mechanism that makes open, green spaces another reasonable consideration alongside active mobility. As mentioned, one of the primary benefits of replacing automobile trips with active forms of transportation, such as walking and cycling, is the reduction in GHG emissions (Lugo 2014, 325). Vegetation has a similar ability, except, rather than reducing emissions from vehicles, it can reduce emissions from buildings (Ulpiani 2021, 2, 19). This is possible when vegetation is close enough to a building that it reduces the ambient temperature. In turn, lower anthropogenic emissions are necessary, in the form of air-conditioning, to achieve a comfortable indoor environment, thus avoiding additional anthropogenic GHG and particulate emissions (Das et al. 2024, 976; Ulpiani 2021, 2, 19).

## Frameworks for Determining “Success”

This literature review has provided background context for the three major systems with which this study is concerned. Several of the relationships and most pressing challenges among them have also been presented. Scientists and, in turn, cities and communities, have been called upon to respond to these as well as other issues related to climate change in the face of national and state inaction (Keil 2020, 2,358). In order to do this, however, there needs to be an appropriate definition of “success” for individual actions and policies in addition to a framework that helps stakeholders and policymakers determine the best choices for their local contexts.

### *Example Frameworks*

A majority of the “frameworks” that exist in the current literature are schemas that help researchers describe the results they find and clarify different types of relationships. For example, in trying to define the complexity of urbanization and its inequalities, Pandey et al. (2022) proposed three axioms to characterize urbanization and its inequalities: first, urbanization is multidimensional, with demographic, economic, environmental, institutional, socio-cultural, and technological aspects; second, multiple dimensions manifest physically; and third, urban inequalities stem from unequal expressions of these dimensions at various scales (Pandey et al. 2022, 2). They then used four infrastructure types to create a composite index, namely: water, sanitation, housing, and electricity.

This example shows how the extent of a framework in the literature is really a process of defining a study’s subject matter and then both deriving methods and communicating results in terms consistent with that definition. Another example of this is in Maparu and Mazumder’s (2021) study between transport infrastructure and urbanization across the states in India. They used 11 distinct variables to describe four types of infrastructure: roads, railways, ports, and airways. Their “framework” is to stratify the Indian states into three categories based upon income: leading, intermediate, and lagging (Maparu and Mazumder 2021, 49). This again shows the blurring of methods with the concept of an adherence to a framework to understand the results.

Part of the reason for this phenomenon is that many studies focus on creating methods to determine what kinds of conditions or relationships exist in their respective study areas. Many studies are highly technical and utilize computer software and advanced econometric techniques to improve models that help explain what conditions currently exist. At this point in the field, few researchers venture a step further to conduct a carefully considered analysis on potential responses to the relationships they uncover. Recommendations tend to be simple continuations of a study's results or grounded only in the magnitude of a particular intervention's effect.

For example, Z. Wang et al. (2019) found that the expansion of urban areas and roadways resulted in greater energy consumption, so they recommended planning urban areas that required only short trips between residences and businesses (34,893). While this recommendation provides some policy insight, there is not a framework to weigh the recommendation against potential risks or shortcomings that may be associated with its implementation, nor is it weighed against other potential recommendations.

Szeto et al. (2013) created one of the few frameworks that do exist to try and determine the multi-dimensional sustainability inherent to a particular road network's design. Therein, they built an optimization model for road network design that is capable of simultaneously considering the impacts of design changes on economic, social, and ecological indicators (Szeto et al. 2013, 791). Specifically, they chose four indicators to showcasetheir model, namely: total vehicle emissions (as an environmental indicator), change in consumer surplus (as an economic indicator), variance of discounted landowner profit (a social indicator that measures landowner inequity), and variance of discounted generalized user cost over time (another social indicator, this time measuring intergenerational inequity) (Szeto et al. 2013, 794). This model is also highly technical, however, and it requires specific knowledge to use meaningfully.

Other researchers have similarly noted the absence of readily accessible resources that can assist stakeholders and policymakers in handling matters of urbanization and its entangled processes, such as TINs, UHI, and inequality. Chester et al. (2014), for example, state that there is not currently a framework to determine when and how investments may be made during urbanization processes to optimally avoid indirect impacts and the implementation of infrastructural components which may act as barriers to positive changes in the near future (540).

## Conclusions and Next Steps

This chapter has laid out the foundational literature that forms the basis of both the quantitative and qualitative arguments made throughout the thesis. Following this exploration of the global and local effects from the interactions of TINs, urbanization processes, and UHI effects, the question remains how these systems are uniquely related in any given location. This is specifically explored for the state of Massachusetts in the spatial analysis portion of this thesis (chapter 4). In light of the lack of user-friendly frameworks for evaluating the complexities of roads, urbanization, UHI, and the implications of these factors for equity and public health outcomes, this thesis develops a novel analysis framework for considering these issues. This framework is laid out in the methods chapter (chapter 3) and populated in the discussion chapter (chapter 5).

# Chapter 3. Methods

Now that background information has been provided for the systems that are analyzed in this thesis, namely urbanization, land-based transportation infrastructure networks, and the urban heat island effect, this section will explain the methods used herein to respond to the research questions laid out in chapter 1. The research questions explored in this thesis are:

1. What is the influence of major roads on urbanization in Massachusetts between the years 2001 and 2019?
2. How do road transportation infrastructure and urbanization influence the surface urban heat island effect in Massachusetts?
3. How can policy and planning efforts increase equity and decrease public health risks in MA, given challenges associated with the interplay between road transportation infrastructure, urbanization, and the surface urban heat island effect?

This research relied on a literature review, spatial analysis, and qualitative evaluation framework to respond to the research questions.

## Conducting the Literature Review

To conduct the literature review, the major search terms included "the effects of roads," "defining urbanization," "transportation and urbanization," "road networks and land use," "urban heat island effect," "roads and urban heat," and "urbanization and heat." Over the time period from April 2022 through December 2023, these terms were primarily entered into the "Jumbosearch" function offered by Tuft University's Tisch Library. This function simultaneously searches the library's physical and digital resources in addition to the catalogues of other libraries and several dozen research databases.

The top 100 hits for each term were reviewed for relevance and priority given to peer reviewed articles published after the year 2000. Articles that provided insight on the driving factors and impacts of urbanization processes, TINs, and UHI were considered relevant. Where appropriate, articles were also reviewed from the reference lists of other sources.

## Methods Others Have Used

There are not a significant number of studies to use as models on the relationship, and how the relationship may change, between the development of infrastructure and urbanization (Maparu and Mazumder 2017, 321). This kind of research, requiring a mix of spatial analytical data and demographic information within an overall socio-cultural context, has become significantly easier to perform, however, over the past several decades. This is due to developments such as better linking between ground-based measurements and satellite-based remote sensing data; growth in the quantity and quality of data on systems such as transportation networks, land cover, and land use; and advancements in both econometric techniques and software packages capable of handling and analyzing these data (Gurney et al. 2015, 180; Kasraian et al. 2016, 773).

The extent of the study area in the existing literature ranges from a neighborhood to an entire country, with intraregional studies potentially using very fine spatial units, e.g., parcels, while larger interregional studies use units such as census tracts, municipalities, or counties. Some examples include Heris et al. (2020), which compares two land parcels that were formerly indoor shopping mall sites and uses two-meter grids as the spatial unit, and Chaneiabate et al. (2023), which covers all of China with provinces as the spatial unit.

Larger-scale studies tend to look at the effects of infrastructure networks on developmental processes or regional changes in characteristics such as employment rates while smaller-scale studies more often look at alterations to local characteristics (Kasraian et al. 2016, 775-776). Consistent with this observation, Chanieabate et al. (2023) examines the urban-rural income gap in each Chinese province while Heris et al. (2020) compares the effects of different zoning requirements on each parcel's microclimate.

## Data

In order to answer the first research question guiding this thesis, four datasets were gathered that characterized transportation infrastructure networks and urbanization in Massachusetts between the years 2001 and 2019. These datasets and their sources are summarized in Table 3.1 below.

TINs were represented by major roads with a functional classification of one, U.S. interstate, through four, major arterials and collectors. The Massachusetts Bureau of Geographic Information (MassGIS) offered both a dataset of these roads on their website, encoded as a vector layer composed of lines, and a supplemental data dictionary (MassGIS 2024a, 2024b). The dataset, as it was last accessed, was updated as of May 2022. MassGIS also offered a vector layer composed of polygons representing the census tracts throughout the state, which acted as the spatial unit of analysis (MassGIS 2022). This layer was consistent with the 2020 Decennial Census.

The two remaining datasets consisted of land cover rasters for the years 2001 and 2019 with a resolution of 30 meters. These data were from the 2019 release of the National Land Cover Database (NLCD), hosted by the United States Geological Survey (USGS) and the Multi-Resolution Land Characteristics Consortium (MRLC) (Dewitz and USGS 2021).

Each dataset distinguished among 16 land cover classifications, four of which denoted varying levels of development. Specifically, these included developed, open space; developed, low intensity; developed, medium intensity; and developed, high intensity (MRLC n.d.). Changes in these developed land cover classifications were used to represent changes in urbanization.

| ***Factor*** | **Source** | **Format** | **Date** | **Link** |
|---|---|---|---|---|
| *MA Census Tracts* | MassGIS | Polygon Vector | 2020 | https://www.mass.gov/info-details/massgis-data-2020-us-census |
| *Major Road Segments* | MassGIS | Line Vector | May 2022 | Layer:<br>https://www.mass.gov/info-details/massgis-data-massachusetts-department-of-transportation-massdot-roads<br>Supplemental Data Dictionary:<br>https://www.mass.gov/doc/road-inventory-data-dictionary/download |
| *Contiguous US Land Cover* | NLCD | Raster | 2001 | https://doi.org/10.5066/P9KZCM54 |
| *Contiguous US Land Cover* | NLCD | Raster | 2019 | https://doi.org/10.5066/P9KZCM54 |

Table 3.1: Datasets and their sources for this study.

## Spatial Data Analysis

Processing and analyzing these data began by clipping the land cover datasets to the extent of the census tracts layer so that all four datasets were specific to Massachusetts and then reclassifying the two rasters so that only the developed land cover data relevant to this study were included. Subsequent use of the Raster Calculator function combined the two datasets into a single raster that depicted the type of developed land cover change over the time period. Two further reclassifications of this master index resulted in one dataset that depicted areas that underwent urbanization for the first time, i.e., areas that were not classified as developed in 2001 but were classified as developed in 2019, and a second dataset that depicted areas that underwent an increase in urbanization, i.e., areas that were classified as developed in 2001 but were reclassified as more intensely developed in 2019.

Information from the land cover rasters was then combined with the census tracts layer to determine the percentage of each census tract that fell into each urbanization category. Similar to the methods of Wu (2023) and Hu et al. (2018), Local Moran's I, a tool that shows the types of relationships between neighboring units, was run to determine if there was any clustering within the datasets (Wu 2023, 2; Hu et al. 2018, 39-40).

Following this review of urbanization trends, the major roads layer was imported to determine the average distance between each type of road and urbanization. These distances were then used as separate regression variables to determine each road type's level of statistical significance in the two types of urbanization experienced throughout Massachusetts. Considering the larger spatial extent of the study area, two regression methods were chosen: ordinary least squares (OLS), a ubiquitous linear regression method in econometrics, and multiscale geographically weighted regression (MGWR), a newer method for working with data that exhibits spatial variation, known as spatial heterogeneity.

As noted by Kasraian et al. (2016), these regression methods are consistent with those used by other researchers when modeling the probability of land cover conversion (777). This is also consistent with the methods other authors have used when working with large spatial scales, particularly in the presence of spatial autocorrelation (Pandey et al. 4; Wu 2023, 2-4; Zeng et al. 2019, 3). In addition, Wu (2023), for example, similarly used OLS as a reference prior to determining that the random effect Spatial Durbin model was most appropriate for their data, while Hu et al. (2018) used OLS prior to geographically weighted regression (GWR) (Wu 2023, 3; Hu et al. 2018, 40).

The purpose of using OLS first was to determine baseline values for each variable. The technique does not allow the relationship between the regressors and the dependent variable to change over the study area, however, which can lead to inaccurate values for the dependent variables (Wu 2023, 4; Hu et al. 2018, 40). MGWR, on the other hand, allows the values of each variable to change over the geographic extent of the study area akin to Hu et al.'s (2018) GWR technique, which can provide more accurate values even over a large spatial region (Hu et al. 2018, 40). Values from these regressions as well as the clustering data from running Local Moran's I are reported in the following Chapter 4. and provide the answer to the first research question.

## Qualitative Analysis

There are a significant number of challenges and opportunities related to the interactions among urbanization processes, road networks, and urban heat. Research question two asks how urban heat is affected by the other two systems, and the third question focuses on how these systems may collectively be altered to increase equity and decrease public health risks in policy and planning.

To effectively answer these two remaining research questions, the focus of the discussion will be on 1. how to mitigate UHI effects to improve public health outcomes, and 2. how potential interventions may affect equity outcomes, specifically for lower-income populations. A novel comparative analysis framework, developed from academic literature (chapter 2), was used to systematically explore the expected direct effects on both public health and social equity outcomes from the implementation of several intervention options (chapter 5). Comparative analysis is an appropriate method to employ in this study because of the interest here in understanding how characteristics such as urbanization, land-based transportation infrastructure networks, and urban heat island effects, can influence public health and equity outcomes (Pickvance 2001, 11).

The comparative framework uses four indicators, visualized in Table 3.2 below. Two measure the expected physical impacts of an intervention, and two measure the expected value of an intervention's implementation. Specifically, the two physical indicators include: 1. the expected effects on mean radiant temperature (MRT) and air temperature (AT) and 2. the expected effects on green space (GS) and impervious surfaces (IS).

The first indicator was chosen because it accounts for the potential effects of an intervention on both outdoor and indoor thermal comfort. Under sunny outdoor conditions, MRT has repeatedly been found to be the single greatest factor in determining the radiative load and consequently the perceived thermal comfort of a pedestrian at ground level (Hashemi et al. 2023, 9; R. Li et al. 2023, 3; Taleghani et al. 2016, 2).

AT is a measure of heat exposure without considering radiance, unlike MRT. AT also does not account for wind and humidity, both of which are relatively controlled in indoor environments (R. Li et al. 2023, 3). Thus, outside AT is a helpful indicator for determining the amount of artificial cooling necessary, such as through the use of air conditioners, to achieve indoor thermal comfort. Specifically, reductions in ambient AT have been found to lower the amount of anthropogenic energy use in buildings by lowering the demand for air conditioning (Sanchez and Reames 2019, 1-2).

The second indicator was chosen due to the tendency for GS and IS to be dichotomous land cover types, with similarly dichotomous effects on UHI (IPCC 2019, 2-75). This is similar to the model created by Kong et al. (2016), wherein a binary classification system was created that categorized land as either vegetated or concrete (1,438). Green spaces have been found to lower ambient temperatures and increase air quality, while impervious surfaces have been found to increase temperatures and to be correlated with decreases in air quality (R. Li et al. 2023, 2; Kong et al. 2016, 1,438).

In addition to these physical indicators, the two value indicators included in this comparative framework are a gauge of location efficacy and the expected equity impacts from an intervention's implementation. Both of these are measured by the distance between the site of an intervention and the city center, wherein interventions that occur closer to the city center are considered more effective. This assessment is based on the fact that UHI intensity is typically greatest in the center of urban areas (Zhou et al. 2017, 6).

Similarly, people living in poverty tend to be concentrated in the center of U.S. cities (Glaeser et al. 2007, 23). Thus, one of the driving factors behind the greater exposure of lower-income populations to UHI effects is due to co-location, and greater equity impacts may occur when interventions are similarly co-located with UHI effects and lower-income communities (Das et al. 2024, 964; Hsu et al. 2021, 5; Sanchez and Reames 2019, 1-2). Therefore, the distance intervals for the expected implementation site of an intervention, upon which both the third and fourth indicators are based, are derived from the distribution of poverty in new and old cities discovered by Glaeser et al. (2007). These include: 1. seven-to-ten miles from the urban center, 2. four-to-six miles, and 3. zero-to-three miles.

<table>
<tr><th colspan="15">Qualitative Comparative Analysis Framework</th></tr>
<tr><td colspan="15">Indicator 1<br>Expected Effect on Mean Radiant Temperature (MRT) and Air Temperature (AT) (+, 0, -)</td></tr>
<tr><td colspan="3">+ MRT<br>+ AT</td><td colspan="3">+ MRT *or* AT<br>0 AT *or* MRT</td><td colspan="3">+ MRT *or* AT<br>– AT *or* MRT</td><td colspan="3">– MRT *or* AT<br>0 AT *or* MRT</td><td colspan="3">– MRT<br>– AT</td></tr>
<tr><td colspan="15">Indicator 2<br>Expected Net Effect on Green Spaces (GS) and Impervious Surfaces (IS) (+, 0, -)</td></tr>
<tr><td colspan="5">– *or* 0 GS<br>+ IS</td><td colspan="5">No Net Impact</td><td colspan="5">– *or* 0 IS<br>+ GS</td></tr>
<tr><td colspan="15">Indicator 3<br>Expected Location Efficacy (Distance from City Center) (miles)</td></tr>
<tr><td colspan="5">Low Efficacy (7+)</td><td colspan="5">Moderate Efficacy (4-6)</td><td colspan="5">High Efficacy (0-3)</td></tr>
<tr><td colspan="15">Indicator 4<br>Potential Positive Equity Impact (Distance from City Center) (miles)</td></tr>
<tr><td colspan="5">Low-to-No Impact (7+)</td><td colspan="5">Moderate Impact (4-6)</td><td colspan="5">High Impact (0-3)</td></tr>
</table>

Table 3.2: A visual representation of the comparative analysis framework in this thesis. This qualitative framework can be applied to a potential intervention in TIN, urbanization, and UHI systems. Four indicators are included with a range of potential outcomes. The farther an outcome is towards the right of the table, the more beneficial it is expected to be in equity and public health results.

The MRT/AT indicator has five possible values: 1. the intervention is expected to increase both MRT and AT, 2. either MRT or AT is expected to increase while the other is unaffected, 3. neither are affected or one is expected to increase while the other is expected to decrease, 4. one is expected to decrease while the other is unaffected, and 5. both MRT and AT are expected to decrease.

The GS/IP indicator has three possible values: 1. the intervention is expected to increase the quantity of impervious surfaces that are typical of urban areas, 2. no land cover change is expected, and 3. green spaces are expected to increase.

The third and fourth indicators each have three possible values based on the expected distance between an intervention and the city center. The possible values for the third indicator, as a gauge of location efficacy, are: 1. low efficacy, 2. moderate efficacy, and 3. high efficacy. Finally, the fourth indicator provides an idea of the value to lower-income communities that simultaneously face greater exposure to urban heat due to co-location. Its possible values include: 1. low-to-no equity impact, 2. moderate equity impact, and 3. high equity impact. The respective values for both the third and fourth indicators are based on decreasing distance to the city center.

The expected impact from each type of potential intervention will be estimated using these indicators. While this framework is far from perfect, its simplicity makes it accessible to other researchers and stakeholders to gain a general sense of how a given intervention may reasonably affect public health and equity outcomes in a range of social, political, economic, and ecological environments without requiring extensive technical knowledge similar to the few existing resources available in the literature thus far.

# Chapter 4. Results

This chapter reports the results from the spatial analysis conducted as per the data and techniques as described in the methods section (chapter 3). Recall that the first research question guiding this thesis is: What is the influence of major roads on urbanization in Massachusetts between the years 2001 and 2019? In order to determine the answer, two datasets were created for this thesis. The first was census tracts in Massachusetts where land cover became classified as urban for the first time between 2001 and 2019, and the second was census tracts where land cover was already classified as urban in 2001 but was reclassified to a higher intensity urban classification by 2019. For ease, these will be referred to as “newly urban” and “increasingly urban” datasets, respectively, and are depicted in Figure 4.1 and Figure 4.2 below.

By creating these two datasets, it was possible to determine not only overall urbanization patterns in Massachusetts, but also nuances in those patterns. By exploring areas undergoing increasing urbanization, information can be gleaned about urbanization processes prior to the time period included in the time series data analyzed in this quantitative analysis. Meanwhile, the exploration of areas that are undergoing early stages of urbanization, as depicted in the newly urban dataset, may provide insight on contemporary spatial shifts in population and construction patterns throughout the state. Differentiating between these two urbanization types also can allow for more precise recommendations, as these two types of areas in Massachusetts may be experiencing different pressures and challenges, thus requiring different solutions.

Results from the cluster analysis using Local Moran's I are given along with the outcome of running summary statistics. Following these are the results from ordinary least squares (OLS) regression. Finally, the results from executing multiscale geographically weighted regression (MGWR) are provided. All techniques were run twice: once on each dataset. Of particular note in the latter section, is that the technique failed to run on the newly urban dataset, so results are only given for the increasingly urban dataset.

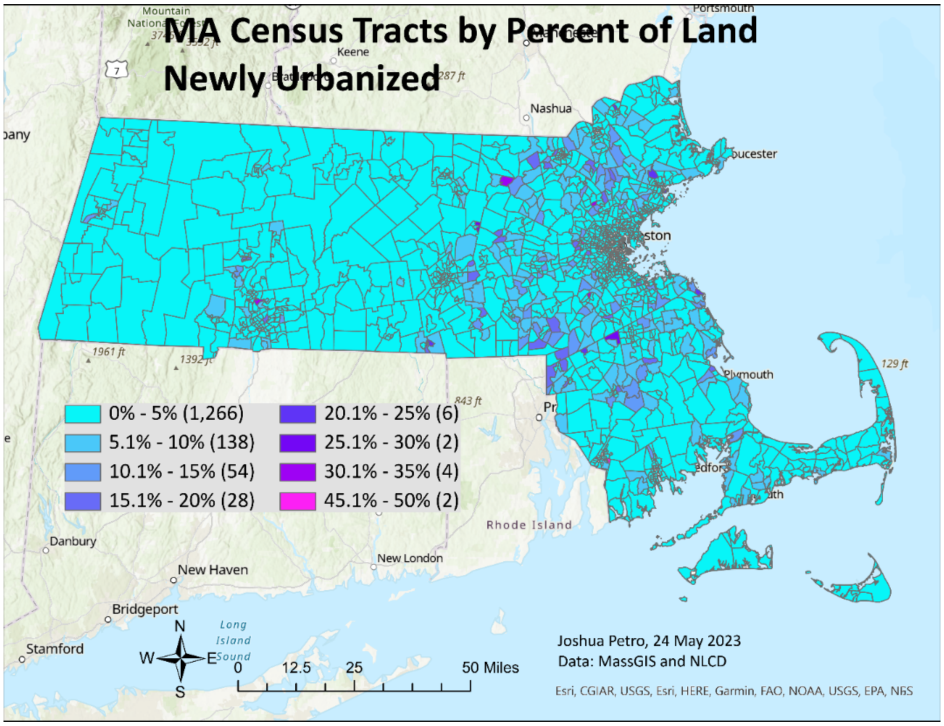


Figure 4.1: New urbanization in MA by census tract, 2001-2019. Tracts are stratified by percentage of land cover.

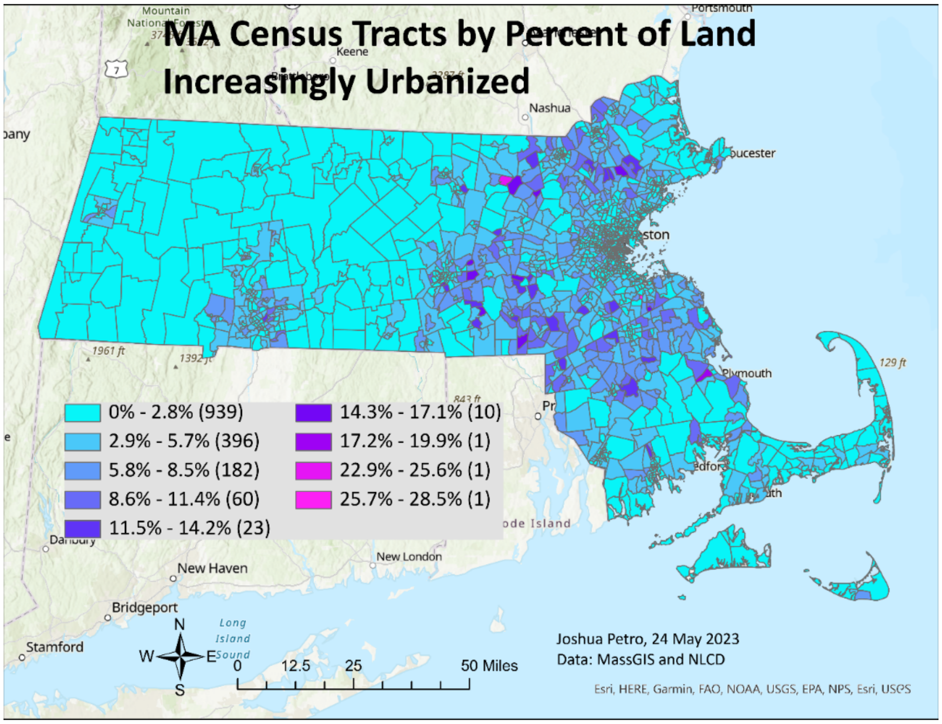


Figure 4.2: Increased urbanization in MA by census tract, 2001-2019. Tracts are stratified by percentage of land cover.

## Local Moran's I and Summary Statistics

Local Moran's I is a technique to determine spatial clustering within a dataset. The output for the newly urban dataset is depicted in Figure 4.3 below. The results suggested that most of the data were unrelated, with approximately 50.87% of the 1,500 identified clusters labeled as insignificant. These clusters are primarily located in central and western Massachusetts and Cape Cod. The clusters that were considered significant were mostly concentrated in the eastern portion of the state, notably forming two loose rings around the city of Boston.

The first ring included the city itself and the census tracts abutting it, most of which were classified as Low-Low clusters: areas exhibiting relatively low levels of urbanizing land cover surrounded by areas exhibiting similar trends. A buffer of insignificant tracts surrounded that ring, followed by a second ring mainly composed of Low-High clusters and High-High clusters. Other notable clusters included a primarily High-High grouping along the shore south of Boston and a mix of Low-Low and High-Low clusters near Springfield.

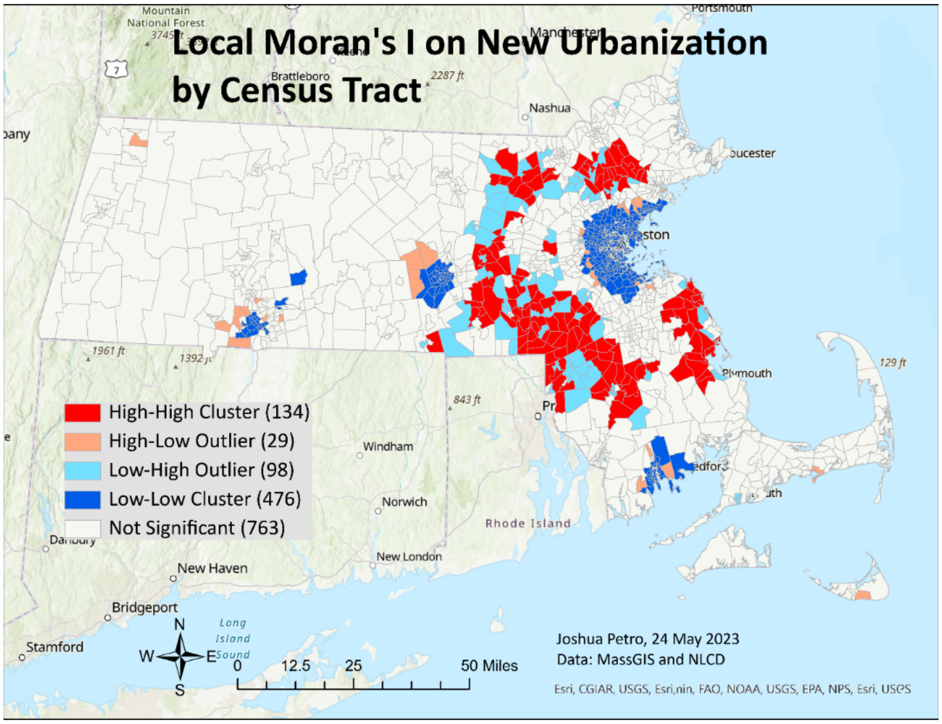


Figure 4.3: Clustering of new urbanization in MA by census tract.

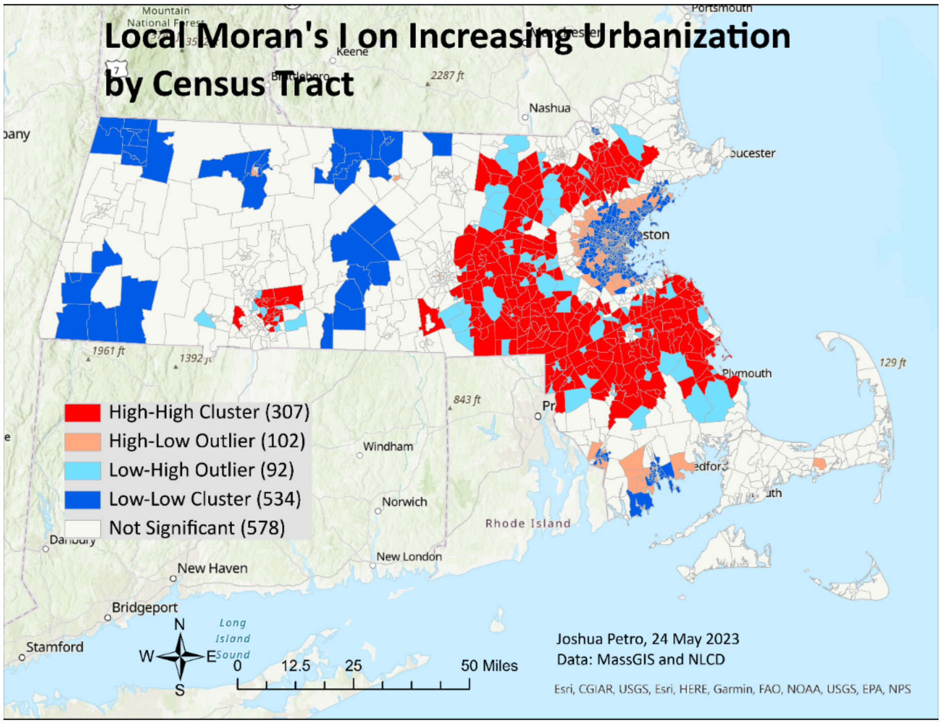


Figure 4.4: Clustering of increasing urbanization in MA by census tract.

The Local Moran's I output for the increasingly urban dataset is depicted in Figure 4.4 above. The appearance of the results was relatively similar to that of the newly urban dataset, but most of the data were significant: 64.17% of the 1,613 identified clusters. Some of the census tracts located in the cluster including Boston were classified as High-Low rather than Low-Low, and the secondary ring increased in size and density of High-High tracts while the amount of unrelated data separating the ring from the city decreased.

Additionally, six Low-Low clusters were identified in central and western portions of the state that were not present in the results for newly developed areas. The cluster along the shore south of Boston was incorporated into the secondary ring, and the cluster around Springfield is present but composed mainly of Low-High and High-High clusters.

After Local Moran's I was run for both datasets, the results were spatially joined to the census tracts layer so that summary statistics could be run. The results show the distance from each cluster type, e.g., Low-Low, to the nearest instance of each major road class. The process was executed a total of three times: once for each dataset and once for both sets of data combined. For brevity, the results for newly urban and increasingly urban data are depicted in Table 4.1 and Table 4.2, respectively. The combination of data is in appendix 1 of the supplementary materials, available at https://perma.cc/E4LG-KQ4H.

| ***Cluster/Outlier Type*** | **Frequency** | **Mean Distance to Class 4** | **Mean Distance to Class 3** | **Mean Distance to Class 2** | **Mean Distance to Class 1** |
|---|---|---|---|---|---|
| | 741 | 42.375 | 425.369 | 2,529.820 | 2,630.788 |
| *HH* | 151 | 28.544 | 39.496 | 2,090.320 | 1,323.141 |
| *HL* | 44 | 54.051 | 317.383 | 964.009 | 6,267.718 |
| *LH* | 96 | 12.493 | 42.029 | 1,523.823 | 1,365.444 |
| *LL* | 581 | 1.833 | 438.649 | 613.560 | 1,213.380 |

Table 4.1: Summary Statistics of the clustering distribution of the newly urban data. The table includes Local Moran's I cluster types, which were determined for each MA census tract, and the average distances of each cluster type to the nearest major road of each functional classification.

| *Cluster/Outlier Type* | Frequency | Mean Distance to Class 4 | Mean Distance to Class 3 | Mean Distance to Class 2 | Mean Distance to Class 1 |
|---|---|---|---|---|---|
| | 577 | 23.905 | 509.371 | 2,315.571 | 2,297.382 |
| *HH* | 302 | 37.228 | 82.675 | 1,852.660 | 1,539.724 |
| *HL* | 140 | 0.334 | 398.742 | 517.146 | 1,049.048 |
| *LH* | 83 | 33.913 | 59.066 | 2,019.590 | 1,842.212 |
| *LL* | 511 | 24.375 | 419.600 | 1,173.782 | 2,290.974 |

Table 4.2: Summary Statistics of the clustering distribution of the increasingly urban data. The table includes Local Moran's I cluster types, which were determined for each MA census tract, and the average distances of each cluster type to the nearest major road of each functional classification.

## Ordinary Least Squares Regression

OLS regression was run for both datasets using the distance from each census tract to each major road class as the independent variables to explain the two urbanization processes. The regression outputs followed a similar trend as the outputs from Local Moran's I, wherein stronger relationships were found among the increasingly urban data than among the newly urban data.

The model of the percentages of newly developed land cover found the intercept to be significant and the distances to roads labeled as classes one through three significant under robust calculations. The multiple R-squared = 0.00592, and the adjusted R-squared = 0.003261. The regression table is provided in Table 4.3 below. Additional outputs from the OLS regression on newly urban data are provided in appendix 2 of the supplementary data, available at https://perma.cc/E4LG-KQ4H.

The model of the percentages of increasingly developed land cover found the intercept and the distance to class one roads to be significant, making class one roads the only explanatory variable in both datasets to be significant under normal calculations. The multiple R-squared = 0.009782, and the adjusted R-squared = 0.007132. Both the multiple and adjusted R-squared are close to double that of the model for newly developed areas, so although fewer numbers were found to be statistically significant, the model was able to fit nearly twice the data. The regression table is provided in Table 4.4 below. Additional outputs from the OLS regression on increasingly urban data are provided in appendix 3 of the supplementary material, available at https://perma.cc/E4LG-KQ4H.

| ***Variable*** | **Coefficient** | **Standard Error** | **t-Statistic** | **p-value** | **Robust SE** | **Robust t** | **Robust p-value** | **VIF** |
|---|---|---|---|---|---|---|---|---|
| *Intercept* | 2.133 | 0.148 | 14.413 | 0.000* | 0.147 | 14.511 | 0.000* | |
| *Distance to Class 4 Roads* | 0.000 | 0.001 | 0.038 | 0.970 | 0.000 | 0.058 | 0.953 | 1.087 |
| *Distance to Class 3 Roads* | -0.000 | 0.000 | -1.541 | 0.123 | 0.000 | -2.093 | 0.036* | 2.209 |
| *Distance to Class 2 Roads* | 0.000 | 0.000 | 1.958 | 0.050 | 0.000 | 2.078 | 0.038* | 2.047 |
| *Distance to Class 1 Roads* | -0.000 | -0.000 | -1.863 | 0.063 | 0.000 | -3.348 | 0.001* | 1.617 |

Table 4.3: A summary of the OLS regression output for the newly urban dataset. An "*" denotes statistical significance.

| ***Variable*** | **Coefficient** | **Standard Error** | **t-Statistic** | **p-value** | **Robust SE** | **Robust t** | **Robust p-value** | **VIF** |
|---|---|---|---|---|---|---|---|---|
| *Intercept* | 3.331 | 0.095 | 35.009 | 0.000* | 0.092 | 36.304 | 0.000* | |
| *Distance to Class 4 Roads* | 0.000 | 0.000 | 0.505 | 0.614 | 0.000 | 0.519 | 0.604 | 1.087 |
| *Distance to Class 3 Roads* | -0.000 | 0.000 | -0.042 | 0.966 | 0.000 | -0.047 | 0.963 | 2.209 |
| *Distance to Class 2 Roads* | 0.000 | 0.000 | 1.067 | 0.286 | 0.000 | 1.223 | 0.219 | 2.047 |
| *Distance to Class 1 Roads* | -0.000 | 0.000 | -3.512 | 0.000* | 0.000 | -5.864 | -0.000* | 1.617 |

Table 4.4: A summary of the OLS regression output for the increasingly urban dataset. An "*" denotes statistical significance.

## Multiscale Geographically Weighted Regression

The last step in this spatial analysis was using MGWR to account for spatial heterogeneity in the datasets. As with the other geoprocessing techniques, the intention was to execute MGWR for each dataset. The tool failed to execute for the newly urban data, however, due to too little variation in the data to generate at least one local group. Therefore, only one MGWR model was able to be produced, suggesting that the OLS model is a good way to summarize the effects of roads on new development.

The single model, however, was able to fit a considerably greater portion of the total data, yielding a multiple R-squared of 0.4995. The intercept as well as distances to class one and three roads were found to be significant overall. The distance to class three roads was significant throughout approximately one-third of the study area, depicted in Figure 4.5 below. Meanwhile, the distance to class one roads was found to be significant in over 98% of the study area with a single cluster of insignificance between Springfield and Worcester, depicted in Figure 4.6 below. A summary of the values is also provided in Table 4.5 below.

| ***Variable*** | **Significance Count** | **Significance Percent** | **Neighbor Count** | **Neighbor Percent** | **C Mean** | **C Standard Deviation** | **C Minimum** | **C Maximum** | **C Median** |
|---|---|---|---|---|---|---|---|---|---|
| *Intercept* | 522 | 32.362 | 31.000 | 1.922 | -0.031 | 0.610 | -0.999 | 1.674 | -0.144 |
| *Distance to Class 4 Roads* | 0 | 0.000 | 1,239.000 | 76.813 | -0.015 | 0.037 | -0.074 | 0.063 | -0.018 |
| *Distance to Class 3 Roads* | 540 | 33.478 | 1,613.000 | 100.000 | -0.068 | 0.032 | -0.139 | -0.029 | -0.052 |
| *Distance to Class 2 Roads* | 0 | 0.000 | 1,525.000 | 94.544 | -0.024 | 0.023 | -0.043 | 0.054 | -0.033 |
| *Distance to Class 1 Roads* | 1586 | 98.326 | 1,008.000 | 62.492 | -0.149 | 0.051 | -0.297 | -0.074 | -0.141 |

Table 4.5: A summary of the MGWR output for the increasingly urban dataset.

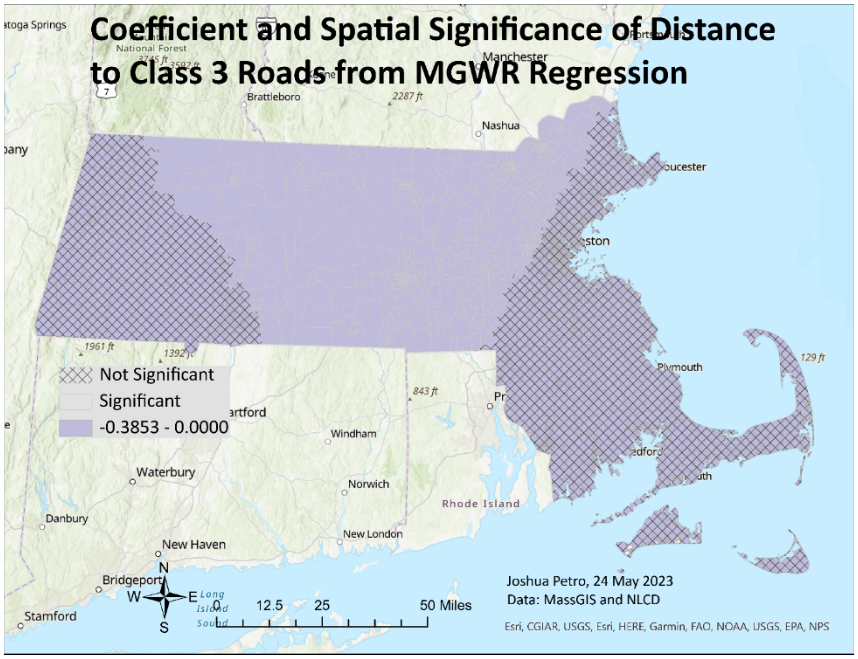


Figure 4.5: Distance to class 3 road's MGWR coefficient and spatial significance.

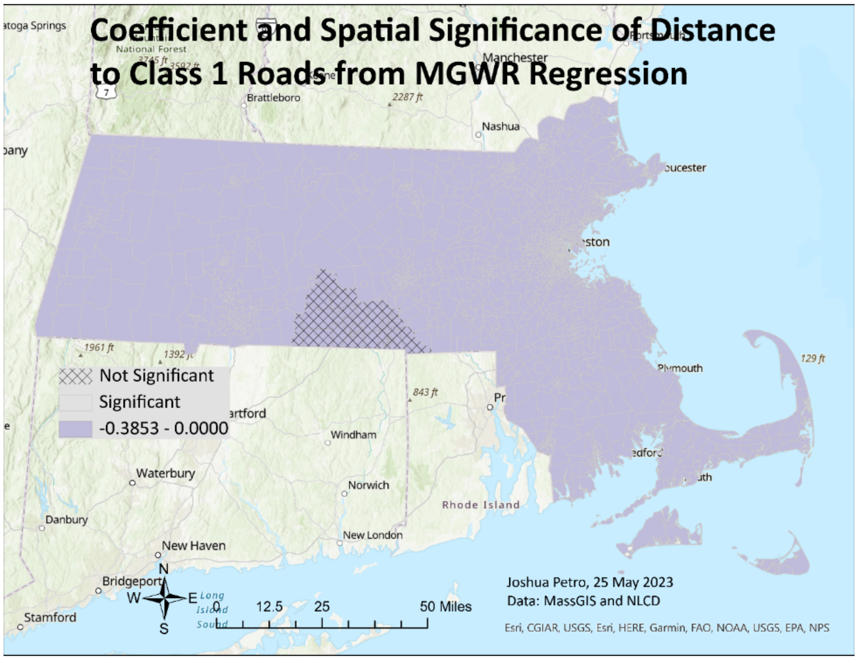
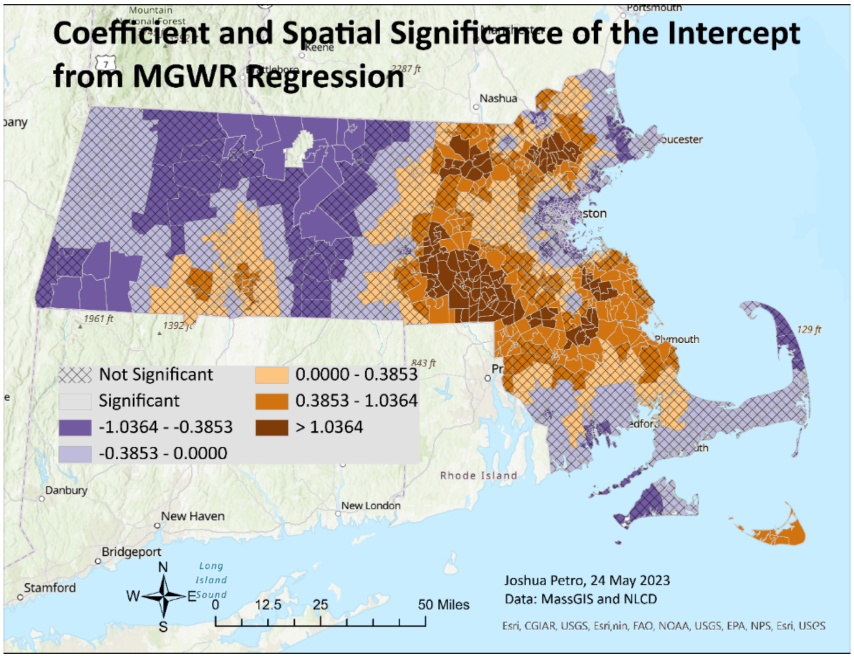


Figure 4.6: Distance to class 1 road's MGWR coefficient and spatial significance.

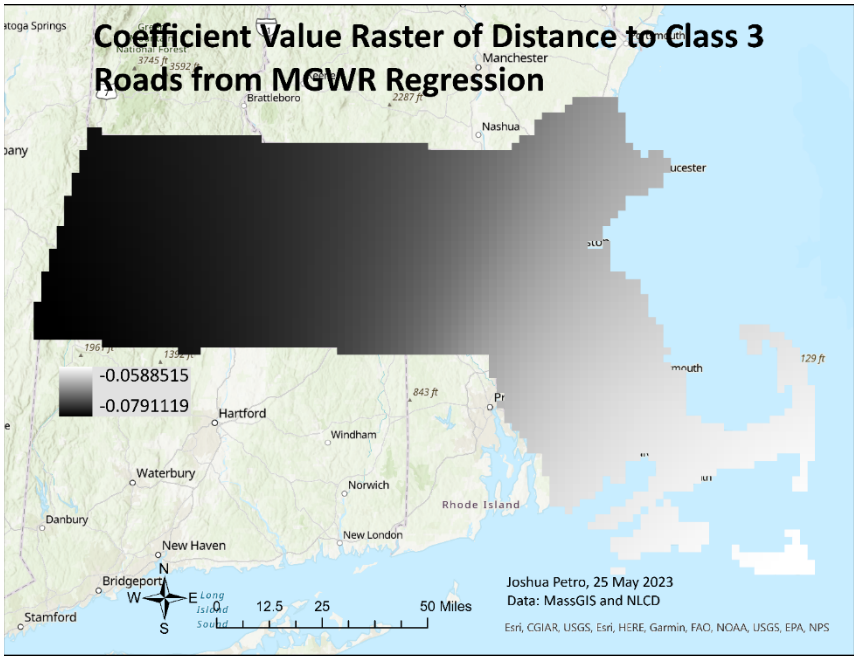
It is worth noting that the intercept was significant in central Massachusetts, approximately following Interstate 90 (I-90), depicted in Figure 4.7 below. Class three roads showed a similar trend of significance throughout central Massachusetts (Figure 4.5), and they exhibit the strongest effects in the western and central regions along I-90 and the near Springfield in the Connecticut valley, depicted in Figure 4.8 below.


Coefficient and Spatial Significance of the Intercept from MGWR Regression

Joshua Petro, 24 May 2023
Data: MassGIS and NLCD

Esri, CGIAR, USGS, Esri,nin, FAO, NOAA, USGS, EPA, NPS, Esri, USGS

Figure 4.7: MGWR intercept's coefficient and spatial significance.


Coefficient Value Raster of Distance to Class 3 Roads from MGWR Regression

Joshua Petro, 25 May 2023
Data: MassGIS and NLCD

Esri, CGIAR, USGS, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NPS

Figure 4.8: Distance to class 3 road's MGWR coefficient value raster.

In contrast, class one roads had nearly the opposite distribution in the spatial distribution of their effects. Class one roads had the lowest effect western Massachusetts, instead exhibiting the greatest influence on land cover change in the northern part of the state near the New Hampshire border and along I-495, depicted in Figure 4.9 below.

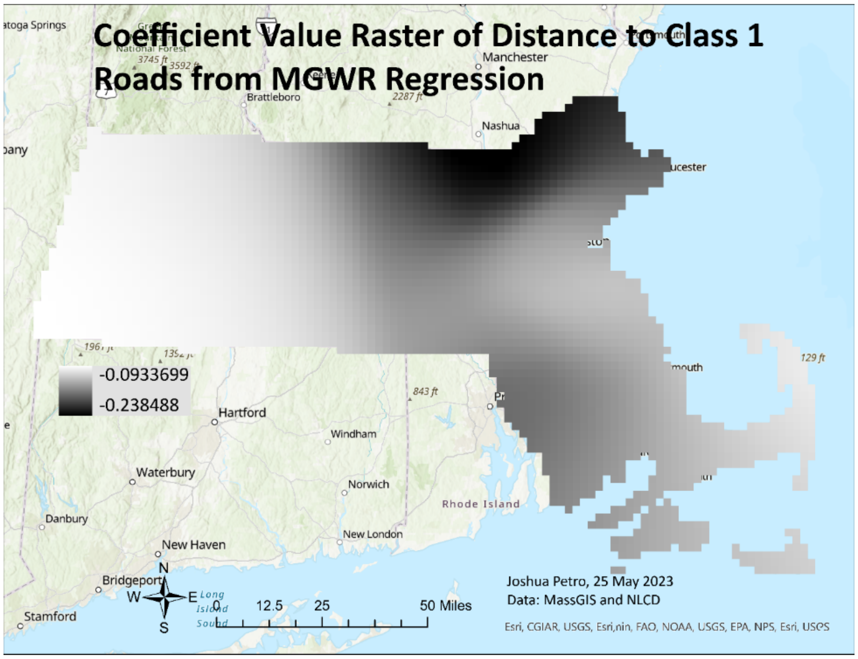


Figure 4.9: Distance to class 1 road's MGWR coefficient value raster.

Overall, this variation in the distribution of the two variables' coefficient values suggested that the influence of major roads on land cover change can vary based on both the specific road type and the existing level of urbanization in the surrounding area. This potentially agrees with the findings of other researchers that the effects of a given road type on urbanization processes can change based on the pre-existing level of urbanization in the surrounding area (Kasraian et al. 2016, 787; Maparu and Mazumder 2021, 52-53).

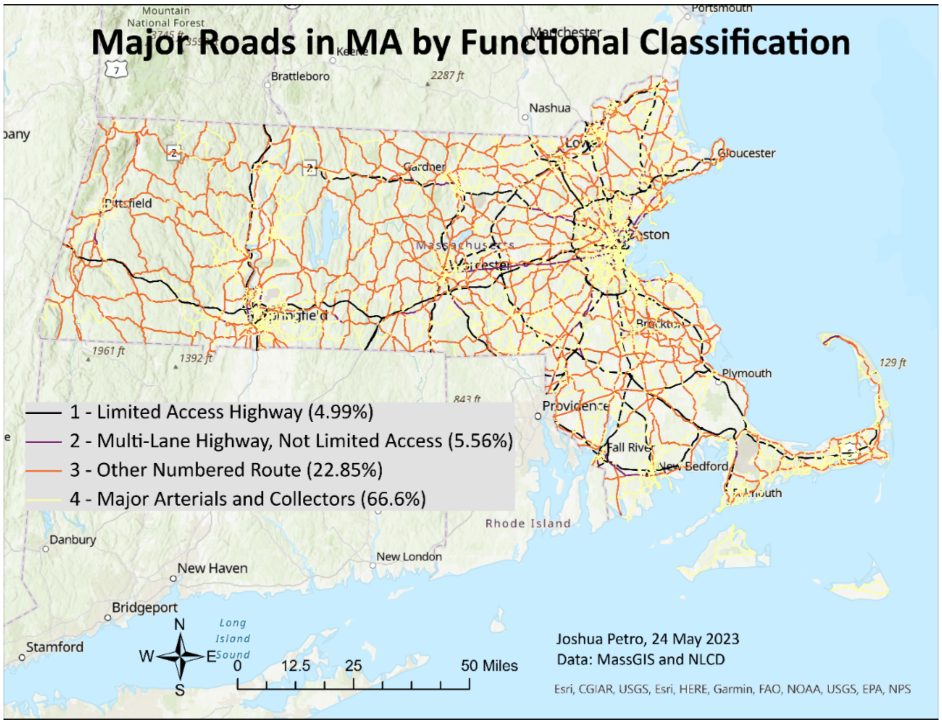
This would help explain why the eastern half of Massachusetts, which exhibited a more significant level of pre-existing and ongoing urbanization, was more greatly impacted by a higher roadway class, while the western half of the state, which exhibited relatively lower urbanization levels, was more greatly impacted by a lower roadway class. Additional outputs form the MGWR regression on increasingly urban data are provided in appendix 4 of the supplementary materials, available at https://perma.cc/E4LG-KQ4H.

## Limitations of this Spatial Analysis

One serious limitation herein is the use of a single road network dataset. While land cover data was able to be retrieved and processed for two time periods, namely 2001 and 2019, only 2022 data was able to be retrieved for roads. This prevented the ability to analyze changes in the road network over the land cover time period, thus preventing accurate results on the correlation between the two types of data. Moreover, the time period of the road network data is inconsistent with both land cover datasets.

Several other types of error may have also affected this analysis. To begin with, the observed data were not normally distributed, with the levels of variation in the explanatory variables, i.e., the distances from each census tract to the closest segment of each major road type, skewed towards zero. This happened because nearly every census tract included at least one type of major road, with many including more than one. The resulting effect was that even relatively short, but non-zero, distances were more akin to outliers in the data rather than regular points. Again, OLS is a linear regression method and not designed to easily handle this type of bias, while the MGWR tool entirely failed to execute with the newly urbanized data. Histograms of the standardized residuals from the OLS regression are provided in appendices 2 and 3 of the supplementary materials, available at https://perma.cc/E4LG-KQ4H.

Another potential source of error is the failure to account for the inconsistency of road network density throughout the state, as depicted in Figure 4.10 below. Greater densities were typically observed in the eastern half of Massachusetts, and the highest density was concentrated around Boston on the eastern shoreline. Smaller clusters of road networks were observed around this epicenter, and the road network near Springfield was the western-most cluster, surrounded by areas of considerably lower density. The closest this thesis came to normalizing these data was in the use of MGWR itself, allowing the relationship among the variables to change throughout the study area.


Major Roads in MA by Functional Classification

Joshua Petro, 24 May 2023
Data: MassGIS and NLCD

Esri, CGIAR, USGS, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NPS

Figure 4.10: The distribution of major roads in MA by functional classification.

Finally, as noted by other researchers performing similar work, another major source of error is potential endogeneity of the explanatory variables (Hu et al. 2018, 44). The two urbanization indices herein may also exhibit endogeneity, thus affecting the results of this study, as the index of greater urbanization included newly urbanized areas as well.

# Chapter 5. Discussion

This discussion chapter considers the implications of the results from the spatial analysis (research question 1), including thoughts on the methods that were used. Qualitative data gathered in the literature review is then used to provide context to the analytical results, ultimately providing an answer to the second research question.

After determining the influence of both transportation network and urbanization systems on the urban heat island effect, possible interventions are identified from the qualitative data and the comparative analysis framework, which is used to project the equity and public health benefits and externalities associated with each intervention. Finally, the comparison results inform suggestions for ways in which policy and planning efforts may increase equity and decrease public health risks connected to the interactions among these complex systems, ultimately answering the third and final research question.

## Consideration of the Results

Regarding the output patterns from the Local Moran's I executions, the Low-Low formation around Boston for both datasets may be due to higher pre-existing levels of urbanization in the area prior to the timeframe that was analyzed in this thesis. As noted by Glaeser et al. (2007), Boston was already a large city by 1900, well before 2001, the date of the earliest data used in this thesis (21). Thus, it is possible that the pre-existing urbanization level in the region has resulted in a higher degree of developmental saturation. This has been shown to lead to decreases in the marginal effects of further development (Chanieabate et al. 2023, 5; Kasraian et al. 2016, 786; Zeng et al. 2019, 10). Further urbanization would still be possible in the area, though, which is consistent with the region’s two classification results: Low-Low for the newly urban data and mixed High-Low and Low-Low for the increasingly urban data.

Additionally, the ring of Low-High and High-High clusters around Boston in both datasets is consistent with urbanization patterns around central cities (Miller and Mössner 2020, 2,258; Z. Wang et al. 2019, 34,886). This is typically based on a mix of increased public transit options making commuting more affordable and the decentralization of employment, reducing residents’ needs to commute into the central city at all (Glaeser et al. 2007, 19-21). The area of insignificance between the two rings warrants further review.

The distribution of clustering in both newly urban and increasingly urban data revealed considerable spatial heterogeneity throughout the study area, with nearly all urbanization processes occurring within the eastern half of Massachusetts. This distribution is similar to the one discovered by Hu et al. (2018) in their analysis of the clustering of road density in China’s Fujian Province (40-41). Notably, for both Massachusetts and Fujian Province, the region with the highest level of clustering was located along the shore, potentially signaling the influence of exogenous variables such as water-based transportation or international trade access (Hu et al. 2018, 41).

Additionally, the visualization of clustering provided graphic evidence for which parts of the state may be considered as higher priority areas based on factors such as infrastructural lock-in and difficulties in altering urban morphology. Chester et al. (2014) note that local conditions can affect the urban forms and infrastructure systems that result from urbanization processes and simultaneously that these forms and systems are long-lived once they are built (Chester et al. 2014, 534-535). Knowing the intensity and maturity of urbanization processes across a spatial extent can thus help stakeholders determine which interventions are most appropriate for each location (Kasraian et al. 2016, 788).

Closer examination of the OLS regression results revealed trends that were not surprising. Both models fit less than one percent of their respective datasets. This was probably due to the inability of OLS to account for spatial variations (Hu et al. 2018, 40; Wu et al. 2023, 3). There was less variation in the newly urban dataset than the increasingly urban, but more road types were significant. This may signal that a greater diversity of road types affects initial urbanization processes or the novel geographic expansion of urban areas while increases in the intensity of an area's urbanization levels are more significantly affected by a narrower range of road types (Maparu and Mazumder 2021, 52-53).

In contrast, the MGWR results were surprising. To start with, the model failed when executed on the newly urban data. While the dataset did not present significant variation, there was still a certain degree. OLS, despite its shortcomings, was capable of generating a model that placed observations greater than one and a half standard deviations away from the average value. This may have happened, however, as a direct result of the low variation. It is possible that values that were even slightly different from the average appeared more like outliers when OLS was applied. In comparison, MGWR may have not run into this limitation due to its increased capacity to fit the observed data but then failed to execute after computing how little variation was actually observed.

Perhaps the largest surprise was the finding that the distance of a census tract to an interstate was not only generally significant in the model, but significant throughout nearly the entire model when the significance can change across space. A visual investigation of the single area of insignificance revealed the presence of multiple wildlife management areas, a state park, and a state forest, which may have had a combined effect almost like their own agglomeration economy that altered the typical effects of nearby TINs (Kasraian et al. 2016, 788; Z. Li et al. 2021, 687).

## Significance of Results

### *Answering Research Question One*

The results that were suggested by OLS and confirmed with MGWR provide the answer to the first research question guiding this thesis, which asks how major roads influence urbanization in Massachusetts.  First, major roads have been shown to influence urbanization processes in the state between the years 2001 and 2019.  More specifically, roads classified as state routes and interstates have a positive relationship with the urbanization of surrounding land cover.  Interstates in particular have a significant positive relationship on land cover urbanization throughout nearly the entire state.  This agrees with similar results other researchers have found (Chanieabate et al. 2023, 7; Gerritse and Arribas-Bel 2017, 1,145; Kasraian et al. 782-783; Zeng et al. 2019, 2).

There are several implications that follow from this.  While a number are outside the scope of this thesis, for completeness they will be mentioned.  Highways have been found to attract both commercial and industrial developments, which can explain the positive effects observed on employment growth (Kasraian et al. 2016, 782-783).  Moreover, while these major roads support suburbanization as the urban core becomes more accessible to the urban periphery, population density abutting highways may be lower than surrounding areas at least one-third of a mile away (McMillen and Lester 2003, 73-78).

This could be due to a degree of unattractiveness of living next to high-speed, high-traffic roads, potentially explaining why commercial and industrial developments may be attracted immediately adjacent to highways in lieu of residential ones (Kasraian et al. 2016, 783, 786). Overall, this dynamic succinctly depicts how transport technologies can determine the structure of cities (Glaeser et al. 2007, 23).

### *Answering Research Question Two*

The second research question builds on the first, asking what influence both major roads and urbanization have on UHI in Massachusetts. Now that the analytical analysis has shown roads to be significant on signaling urbanization throughout the state, qualitative data on the effects of both road networks and the resultant urbanization processes can reasonably be applied to answer this question.

Recall that increases in urban heat levels include more frequent and extended periods of higher daytime temperatures as well as reduced nighttime cooling (Das et al. 2024, 970). These are effects of atmospheric and thermophysical changes in the urban boundary layer (UBL) combined with anthropogenic emissions (Zhou et al. 2017, 1). This boundary layer encompasses the urban area and exists vertically from the ground level up, and the lower sublayers are directly affected by urban morphological features such as average building height and mean street width (Zhao et al. 2020, 10,332).

The reason the UBL is so important is because it affects wind patterns and concentrations of particulate matter, in turn influencing the intensity and distribution of systems such as urban heat and pollution (Zhou et al. 2017, 6; Zhao et al. 2020, 10,339-

10,441). This means that the presence and design of urban features, such as road networks, affects heat and pollution systems (Heris et al. 2020, 7-9; Zhou et al. 2017, 3).

Moreover, a positive feedback loop is often created in areas of developing land cover wherein the presence of roadways first increases the likelihood of urbanization, and second, the urbanization of land cover increases the likelihood of similar affects to the surrounding areas (Kasraian et al. 2016, 782-783). The result of this feedback loop is the ongoing introduction of urban elements, such as roadways, to undeveloped lands, which begets further urbanization and thus closes the loop. Given that urbanization has also been shown to increase heat and pollution levels in both the urban core and the surrounding areas similarly to urban features, though, UHI effects constantly increase as the cycle continues (IPCC 2019, 2-74; Loveland et al. 2012, 3-4; Ulpiani 2021, 9).

This is consistent with the findings from Clinton and Gong's (2013) global study on urban heat sources and heat sinks. They found that both urban area and vegetation, in addition to night light, were dominant factors in indicating the presence of either sources or sinks. Specifically, urban areas indicated the former while vegetation indicated the latter (Clinton and Gong 2013, 299-300).

This information provides the answer to the second research question guiding this thesis. Both road transportation infrastructure and urbanization are positively related to the surface urban heat island effect. As the quantity and scale of TINs and urbanization processes increase, they synergistically exacerbate the frequency and intensity of urban heat. This is globally applicable generally and applicable in Massachusetts specifically.

Now that the effects of these systems have been identified, the question remains what is to be done about them. For example, is there a single solution that will work? If these relationships among and effects from TINs, urbanization, and UHI are applicable for both Massachusetts and across the planet, then are solutions also applicable on both global and local scales? These are significant questions, particularly when considering that the general question "what can cities do," regardless of the subject matter, is typically, though not always, a question of scale (Janos 2020, 2,286). The remainder of this thesis is dedicated to answering the question of what is to be done.

## Qualitative Comparative Analysis

### *The Necessity of the Framework*

Increases in urban heat correspond with serious equity and public health risks. Factors like morbidity and mortality increase while others, like labor productivity, decrease (IPCC 2019, 2-74; Voelkel et al. 2018, 1). Some of the most common symptoms of excess heat exposure include dehydration, heat exhaustion, and heat stroke, which can alter mental status and be fatal (Das et al. 2024, 970-972; McGeehin and Mirabelli 2001, 185).

The extent of risk from extreme urban heat levels can be taken even further when considering the effect of intense heat on pollution levels and air quality. Urban air quality is typically reduced from a non-urban baseline to begin with due to anthropogenic emissions, such as from transportation and industrial activities (Das et al. 2024, 979; Z. Li et al. 2021, 678). During heatwaves and under strong UHI conditions, the heightened temperatures promote ozone formation at the ground level by increasing reactions between primary pollutants such as nitrous dioxide ($NO_2$) and both biogenic and synthetic hydrocarbons (BVOCs and VOCs, respectively, for "volatile organic compounds") (Ulpiani 2021, 2, 14).

At the same time, both pollutants and heat are concentrated near the ground level due to a combination of temperature inversions and increased vertical stability in the UBL when aerosol levels increase (Ulpiani 2021, 3, 13). The elevated and sustained levels of various pollutants lower urban air quality even further and exposes urban residents to the risks associated with long-term pollution exposure on top of the risks of heat exposure already described (Nizic and Baresa 2013, 325-326). These additional risks include respiratory illnesses, cardiovascular diseases, and, once more, premature death, ultimately making the public health risks of UHI even more severe (Das et al. 2024, 979).

These risks portray the ways in which the ongoing intensification of urban heat levels, often noticed via phenomena like UHI, is literally a matter of life and death for urban residents in addition to potentially affecting their economic stability (Das et al. 2024, 964). When considering the entire United States, studies have projected that the Midwest and Northeast are going to experience the greatest increases in both morbidity and mortality from higher urban temperatures, making this information especially relevant to Massachusetts (McGeehin and Mirabelli 2001, 186).

Having now discussed the importance of this topic for public health, the other viewpoint this thesis is concerned with is the social equity component associated with the distribution and effects of UHI. Voelkel et al. (2018) provide a concise way to discuss these UHI characteristics using the concept of a person or group's vulnerability to any given stressor. They define vulnerability as a composition of three factors: exposure, defined as the likelihood of experiencing or interacting with a stressor; sensitivity, defined as the point at which exposure to a stressor becomes harmful; and adaptive capacity, defined as the ability of the person or group to alter their exposure or sensitivity (Voelkel et al. 2018, 1-2).

As mentioned in the literature review (chapter 2), there is a significant tendency for the densest portions of urban areas throughout the United States to simultaneously experience the highest UHI effects and to house a disproportionately high percentage of people living below the poverty line compared to surrounding census tracts (Taleghani et al. 2016, 1; Glaeser et al. 2007, 7). This results in people of lower socio-economic status being disproportionately exposed to extreme urban heat compared to their wealthier counterparts (Hsu et al. 2021, 1). This is the first sign that poverty is related to an inequitable increase in vulnerability to UHI (Voelkel et al. 2018, 6).

Das et al. (2024) provide the second sign that UHI and its effects are inequitably distributed and that people living below the poverty line are more vulnerable to these negative impacts. Specifically, they found that low-income communities are at higher risk of both experiencing and being harmed by elevated urban temperatures (Das et al. 2024, 975). This increase in harm shows an increase in the sensitivity of lower socio-economic populations to UHI compared to higher ones. Finally, another finding by Voelkel et al. (2018) provides the third sign of the poor's inequitable vulnerability to urban heat through their observation that a significant correlation exists between higher exposure levels and lower adaptive capacity levels (10).

In summary, the tendency towards an urban concentration of poverty in the U.S. exhibits a significant positive relationship with both experiencing and being physically and/or economically harmed by UHI effects (Voelkel et al. 2018, 1). This concentration of poverty also exhibits a significant negative relationship with the ability of these populations to access either technologies or environmental features, such as air conditioning or green spaces, respectively, that can ameliorate the consequences of heat exposure compared to comparable populations with greater economic means (Voelkel et al. 2018, 1-2; Das et al. 2021, 6-7; Hashemi et al. 2023, 10).

Finally, the inequity experienced in the typical co-location of poverty and UHI in the U.S. is exacerbated further by the significant co-location of urban heat and urban pollution. Due to this geographic relationship between the two phenomena, populations living below the poverty line face inequitable levels of vulnerability to pollution, including both increased exposure to it and probable harm from it, compared to the wealthy (Hsu et al. 2021, 2; Ulpiani 2021, 2; Y. Wang et al. 2024, 820).

As with the projected increases in heat-related morbidity and mortality, the disparity in heat exposure between low-income and wealthier populations is particularly notable in the Midwest and Northeast regions of the United States (Hsu et al. 2021, 5). This dynamic also mirrors that of other social and environmental stressors which have resulted in both higher concentration levels of poverty and decreases in standards of living for affected communities (Glaeser et al. 2007, 6-7; Voelkel et al. 2018, 1, 9-10; Das et al. 2024, 964).

Now, the major benefits and consequences associated with road networks and urbanization processes have been defined, as have the impacts of both systems on the formation and intensification of the urban heat island effect. Additionally, both the public health and social equity implications associated with the general distribution of UHI phenomena have been explored. The last remaining step for this thesis is to answer the third and final guiding research question: how can policy and planning efforts increase equity and decrease public health risks in Massachusetts considering the interplay among these three distinct but related systems?

### *Introducing the Qualitative Comparative Analysis*

Studies throughout the academic literature on TINs, urbanization, and UHI explore a variety of interventions that may be applied to either one or multiple systems to try to directly influence the outcomes of their interactions. These interventions vary in their levels of technicality and in the skill required to implement them, such as the difference between planting trees in an unused dirt lot versus altering the road network to create a space that could be turned from impervious surface into greenery.

Additionally, the effects of each intervention may seem fairly straightforward on the surface but may actually be very complex. For example, many studies have found trees and other green spaces provide significant benefits to their surroundings, such as reductions in both air temperature and MRT as well as increasing air quality (Das et al. 2024, 965; Hashemi et al. 2023, 13; Heris et al. 2020, 12-13; Kong et al. 2016, 1,429; Taleghani et al. 2016, 6-7). Ulpiani (2021), however, points out that not all trees and greenery provide the same level of benefits. Specifically, different tree species emit varying levels of BVOCs, affecting air quality to the point that it may actually be reduced with a simultaneous increase of pollution levels (Ulpiani 2021, 3, 14-15). On top of that, Hashemi et al. (2023) found that the height of the tree canopy also affects the overall cooling capacity, with higher canopies seemingly more effective at limiting exposure (13).

As noted by Voelkel et al. (2018), “methodological, conceptual, and pragmatic” approaches are needed to understand UHI trends on finer spatial scales than macro-national levels (2). Such approaches would need to identify both the communities that bear the greatest burdens from UHI as well as which strategies are most effective at reducing those communities’ vulnerabilities. While the methods employed by this thesis are not quite on the micro-scale, they do offer a model for how other researchers may explore which interventions are the most appropriate for their respective study areas.

A qualitative comparative framework has been created herein, described in the methods section (chapter 3), to explore which interventions may be the most appropriate for Massachusetts and answer the third research question. Succinctly covering every possible intervention across TINs, urbanization, and UHI would be difficult, so this thesis considers the most commonly cited types of UHI interventions. These include: 1. vegetation increase, 2. modification of surface materials and colors, and 3. alteration of urban form (Heris et al. 2020, 2; R. Li et al. 2023, 2; Taleghani et al. 2016, 2). They are considered individually and then their identified benefits and tradeoffs are compared.

### *Vegetation Increase*

As mentioned above, vegetation increase has widely been cited as beneficial in mitigating UHI effects. This intervention has also been referred to as increasing “green infrastructure,” a term which can be defined as vegetation in urban areas, often intentionally designed and maintained, that is beneficial due to the provision of ecosystem services (Das et al. 2024, 983-984; IPCC 2019, 2-76). These services are diverse and may include shading, evaporative cooling, ventilation, carbon storage and sequestration, and reductions of both primary and secondary pollutants (EPA 2008b, 6-7; Ulpiani 2021, 14-15).

The first indicator in the comparative analysis framework is the expected effect on both air temperature (AT) and mean radiant temperature (MRT). These variables were chosen based on their ability to define the scale of a given UHI effect compared to the surrounding region and the expected impact on the well-being of the affected populations.

AT represents the ambient amount of heat in an area without considering other factors such as wind, radiance, or humidity. Because these other factors are ignored, AT is helpful as a baseline value (R. Li et al. 2023, 3). MRT, meanwhile, is widely considered as the most significant variable in determining an individual's thermal comfort when outside during sunny conditions due to its measurement of the energy to which a body is exposed (Hashemi et al. 2023, 9; Heris et al. 2020, 2; R. Li et al. 2023, 3; Taleghani et al. 2016, 2).

Tree and grass coverage has been found to typically have a significantly negative relationship with both AT and MRT. The mechanisms behind these relationships are a combination of evapotranspiration, or evaporative cooling, and shading, respectively (Heris et al. 2020, 2; Taleghani et al. 2016, 1). Hashemi et al. (2023) measured the size of their effect to be a reduction of up to 1.5° C for AT and up to 31° for MRT (13). This is consistent with Heris et al.'s (2020) finding of an average AT reduction of 0.56° C when increasing the density of existing tree cover and with Taleghani et al.'s (2016) finding of a peak MRT reduction of nearly 30° C (Heris et al. 2020, 12; Taleghani et al. 2016, 6).

Given these findings, it would be reasonable to expect that the impact of increasing vegetation in an urban area would be a decrease in both AT and MRT. This is represented within the context of the first indicator of this comparative analysis in Table 5.1 below.

| Indicator 1<br>Expected Effect on Mean Radiant Temperature (MRT) and Air Temperature (AT) (+, 0, -) | | | | |
|---|---|---|---|---|
| + MRT<br>+ AT | + MRT *or* AT<br>0 AT *or* MRT | + MRT *or* AT<br>– AT *or* MRT | – MRT *or* AT<br>0 AT *or* MRT | – MRT<br>– AT |

Table 5.1: Visualization of increasing vegetation's effect on air and mean radiant temperatures. The effect is an estimated value based on data from the academic literature on the impacts of increasing both evapotranspiration and shading via urban vegetation.

The second indicator measures the expected impact of an intervention on green spaces and impervious surfaces. Green spaces provide urban areas with the various ecosystem services discussed above. Simultaneously, impervious surfaces do not allow for evaporative cooling of the local environment and instead store heat, exacerbating UHI effects (Taleghani et al. 2016, 1; Voelkel et al. 2018, 2). As such, these two types of land cover exhibit essentially opposite effects.

When considering the effects on land cover from increasing vegetation, the IPCC (2019) defines green infrastructure as non-sealed surfaces and their maintenance as a process of retaining said non-sealed surfaces (2-76). Thus, vegetation increases can be thought of as promoting green spaces and inversely related to impervious surfaces. This is graphically represented within the context of the second indicator in Table 5.2 below.

| Indicator 2<br>Expected Net Effect on Green Spaces (GS) and Impervious Surfaces (IS) (+, 0, -) | | |
|---|---|---|
| – *or* 0 GS<br>+ IS | No Net Impact | – *or* 0 IS<br>+ GS |

Table 5.2: Visualization of increasing vegetation's effect on green versus impervious surfaces. The effect is an estimated value based on data from the academic literature on the impacts of increasing both evapotranspiration and shading via urban vegetation.

The third indicator is a measure of the expected efficacy of a given intervention to directly address UHI effects based on where it is likely to be implemented compared to the city center. This indicator does not represent an aspatial consideration of the intervention's potential efficacy.

The location of an intervention matters because the greatest UHI effects tend to be concentrated in the urban core. This is because, for a given urban region, the core tends to be the area with the greatest percentage of landscape modifications, including the introduction of materials that collect and store radiative heat, and the highest amounts of anthropogenic emissions (Z. Li et al. 2021, 687; Taleghani et al. 2016, 1-2; Zhou et al. 2017, 1). Therefore, the closer an intervention is to the urban core, the greater its expected direct impact can be. While it is hard to predict where any specific city may choose to implement any of these interventions, some educated guesses can be made based on the typical accessibility of areas with varying proximity to the urban core.

There are several reasons that make increasing vegetation in areas closer to the urban center more difficult than in areas farther away for most cities. First, urban centers are typically the densest and most modified parts of an urban region, so land availability is typically the lowest (Z. Li et al. 2021, 680, 687). On top of this, not only would vegetation need to be cultivated, but the existing impervious land cover would potentially need to be removed first. This significantly increases the difficulty of implementing green space in city centers compared to other areas within an urban region that are both less modified and typically farther from the city center (Z. Li et al. 2021, 686; Mo et al. 2017, 1,009; Ulpiani

2021, 18). The result is that the contemporary modification of existing land use or cover is decreasingly likely to occur the closer land is to the urban core (Kasraian et al. 2016, 786).

This is confirmed by Z. Li et al.'s (2021) finding that the concentration of green spaces has a negative relationship with the concentration of roadways, the latter of which is simultaneously higher towards city centers (687). Thus, it can be concluded that any increase in vegetation is more likely to occur farther from the city center, which is graphically represented within the context of the third indicator in Table 5.3 below.

| Indicator 3<br>Expected Location Efficacy (Distance from City Center) (miles) | | |
|---|---|---|
| Low Efficacy (7+) | Moderate Efficacy (4-6) | High Efficacy (0-3) |

Table 5.3: Visualization of increasing vegetation's location efficacy. The efficacy is an estimated value based on data from the academic literature on the likely distance between the site of vegetation increases, which increase both evapotranspiration and shading, and the city center.

The final indicator in this comparative analysis is a measure of the expected positive impact on social equity from an intervention's implementation. Like the third indicator, this is based on the likely distance from the implementation site to the city center and is not an aspatial consideration of the capability of the intervention to provide equity impacts.

While this final indicator is very similar to the third, it is not the same. Where the third indicator discusses the expected efficacy of an intervention in mitigating physical UHI effects based on the likely distance between the site of the intervention and the city center, the fourth indicator goes one step further to discuss the potential positive equity impact an intervention may have. Like the third indicator, the fourth is based on the distance between an intervention and the city center due to the tendency for the co-location of populations below the poverty line and significant UHI effects (Das et al. 2024, 975; Voelkel et al. 2018, 1). In practice, interventions that are better able to mitigate increases in urban temperatures also tend to exhibit greater equity impacts by lowering the risks to which certain segments of urban populations, such as those with low incomes, are disproportionately exposed (Hsu et al. 2021, 1-2). This is not always the case, however, so separate indicators are included.

Based on the low likelihood of increasing vegetation in lower-income communities as described above, it is unlikely that such communities would benefit from either the heat mitigating attributes of the intervention or its co-benefits, such as the management of air quality and stormwater and the positive mental health effects (Das et al. 2024, 965, 980). This is graphically represented within the context of the fourth indicator in Table 5.4 below.

| Indicator 4<br>Potential Positive Equity Impact (Distance from City Center) (miles) | | |
|---|---|---|
| Low-to-No Impact (7+) | Moderate Impact (4-6) | High Impact (0-3) |

Table 5.4: Visualization of increasing vegetation's positive impact on equity. The positive impact is an estimated value based on data from the academic literature on A. the expected ability of increasing vegetation to mitigate UHI effects via increasing both evapotranspiration and shading, and B. the likely distance between the implementation site and the city center. This estimate does not include the intervention's potential for negative equity impacts.

It should also be noted that "vegetation" is a broad term. Most of the research on the effects of vegetation on AT and MRT focuses on trees. Some studies have explored alternative forms of greenery, such as green roofs and grasses, which have yielded different results. For example, Taleghani et al. (2016) found that green roofs had very minor impacts on surface AT largely because they modify energy balances above the areas where most pedestrians are affected (6). Additionally, Hashemi et al. (2023) found a potential MRT reduction of up to 31° C for greenery in general but that grass cover alone provided a negligible benefit compared to other vegetation, at most equaling a reduction of 2° C (10).

### *Modification of Surface Materials and Colors*

The second type of intervention considered in this comparative analysis is the modification of surface materials and colors. This intervention type includes the use of cool roofs and pavements as well as permeable materials (R. Li et al. 2023, 2). Cool roofs and pavements are typically created by finishing a surface with light colors rather than dark ones. This increases the surface's spectral emissivity, or albedo, and allows it to reflect a portion of the incoming solar radiation back into the atmosphere instead of storing it (Taleghani et al. 2016, 2; Hsu et al. 2021, 2).

An example of using permeable materials is the installation of green roofs, which overlaps with increasing vegetation. This method replaces materials that have high heat capacities, like asphalt, with others which have much lower heat capacities, like soil and biomass (Taleghani et al. 2016, 1; Ulpiani 2021, 19-20). The result is less heat being stored in the urban environment similar to the effects of increasing the percentage of heat reflected (Taleghani et al. 2016, 8). Although vegetated roofs can be categorized as both increasing vegetation and modifying surface materials and colors, for clarity, this analysis will consider increasing the albedo of surfaces as the main means of implementing this second intervention category (Heris et al. 2020, 2; Taleghani et al. 2016, 2).

When considering the effects of the modification of surface materials and colors within the context of the AT and MRT indicator, the reduction in heat storage has been shown to lead to decreases of up to several degrees Celsius in ambient AT (Heris et al. 2020, 2; Taleghani et al. 2016, 6; Ulpiani 2021, 16-17). This has been observed in both shaded and unshaded locations (Taleghani et al. 2016, 8-9). The impact of cool pavements on MRT is less favorable, though. Researchers have found that there is a greater amount of shortwave radiation above these surfaces when they are unshaded due to the increased reflection, rather than absorption, of incoming waves (Taleghani et al. 2016, 6-8). This results in a greater amount of radiation exposure and thus a higher MRT. This effect has been measured up to at least 7.8° C, reducing overall thermal comfort (Taleghani et al. 2016, 7-8). When the altered surfaces are in the shade, however, MRT largely remains unchanged while AT is still reduced (Taleghani et al. 2016, 9). These potential effects are graphically represented in Table 5.5 below.

<table>
<tr><td colspan="5">Indicator 1<br>Expected Effect on Mean Radiant Temperature (MRT) and Air Temperature (AT) (+, 0, -)</td></tr>
<tr><td>+ MRT<br>+ AT</td><td>+ MRT *or* AT<br>0 AT *or* MRT</td><td>+ MRT *or* AT<br>– AT *or* MRT</td><td>– MRT *or* AT<br>0 AT *or* MRT</td><td>– MRT<br>– AT</td></tr>
</table>

Table 5.5: Visualization of modifying surface materials and color's effect on air and mean radiant temperatures. The effect is an estimated value based on data from the academic literature on the impacts of increasing the reflection of solar radiation via surface modifications such as cool pavements and roofs.

Studies on the effects of this second category of interventions typically involve either the comparison of atmospheric data between either two similar points with differing albedos or the same point(s) before and after replacing the existing impervious surfaces, either at the ground or roof level, with cool surfaces (Hashemi et al. 2023, 13-15; Taleghani et al. 2016, 4-5). Computer programs such as ENVI-met, a detailed computational fluid dynamics (CFD) model that allows for the simultaneous spatial mapping of many climatic variables, are typically used to simulate these scenarios rather than researchers actually altering an urban area's existing infrastructure (Heris et al. 2020, 2; Taleghani et al. 2016, 3).

This is significant when considering the potential impact of these interventions on green space and impervious surfaces because it shows that there is no precedent for altering land cover during their implementation. In other words, when cool pavements and roofs are deployed, areas that were previously vegetated remain so, and areas that were primarily built up also remain so. The only major physical change is the albedo of surfaces. This lack of land cover alteration is graphically represented in Table 5.6 below.

| Indicator 2<br>Expected Net Effect on Green Spaces (GS) and Impervious Surfaces (IS) (+, 0, -) | | |
|---|---|---|
| – *or* 0 GS<br>+ IS | No Net Impact | – *or* 0 IS<br>+ GS |

Table 5.6: Visualization of modifying surface materials and color's effect on green versus impervious surfaces. The effect is an estimated value based on data from the academic literature on the impacts of increasing the reflection of solar radiation via surface modification such as cool pavements and roofs.

Currently, little is mentioned in the academic literature on the potential distribution of cool pavements and roofs. A few theoretical concepts can be considered. One follows from Hashemi et al. (2023), wherein they compared two census tracts with differing average socio-economic levels (3). They found that the lower-income tract had a significantly higher ratio of impervious surface to vegetated surface than the wealthier tract (Hashemi et al. 2023, 10). From this point of view, there is a potentially higher available stock of impervious surfaces to shift to cool surfaces in some lower-income areas.

That being said, Glaeser et al. (2007) point out, that lower-income populations tend to live in apartment buildings and other multi-unit structures, suggesting that they have less control over the exterior components of the buildings they live in, such as the roofing material (23). In contrast, Hsu et al. (2021) point out that homeowners may value cooler temperatures, which has been incorporated into market prices for housing and land (7). Following this train of thought, it is possible that said homeowners would be more willing or able to alter the construction materials in their immediate environments.

Given this data, it is possible that there is a greater opportunity for municipalities to incorporate cool surfaces publicly in lower-income areas while there is a greater opportunity for individuals to incorporate them privately in adjacent wealthier areas. Further research is needed to understand where these materials may be sited (Sanchez and Reames 2019, 1-2). This uncertainty is graphically represented in Table 5.7 below.

| Indicator 3<br>Expected Location Efficacy (Distance from City Center) (miles) | | |
|---|---|---|
| Low Efficacy (7+) | Moderate Efficacy (4-6) | High Efficacy (0-3) |

Table 5.7: Visualization of modifying surface materials and color's location efficacy. The efficacy is an estimated value based on data from the academic literature on the likely distance between the site of surface modifications that increase the reflection of solar radiation, such as cool pavements and roofs, and the city center

Finally, when trying to determine the potential equity benefit from the implementation of cool surfaces, there is again no agreed upon or suggested way to project where the infrastructure may be physically incorporated. Hashemi et al. (2023) chose the two sites they used for their simulation in Philadelphia by looking at two criteria: census tracts' social vulnerability index (SVI) as defined by the Agency for Toxic Substances and Disease Registry (ATSDR), which is part of the Centers for Disease Control and Prevention (CDC), and the amount of tree coverage (3-6). The tract with the lowest SVI and highest tree cover and the tract with the highest SVI and lowest tree cover were chosen.

Meanwhile, Taleghani et al. (2016), for example, used a single simulation site, which was chosen as a typical representation of the overall municipality of El Monte, California (4). While they mention that the general population of the municipality is on average lower-income than the national average, which the authors suggest increases the population's vulnerability, they make no mention of intentionally targeting a lower-income site (Taleghani et al. 2016, 4). These two examples suggest that neither lower- nor higher-income communities are prioritized in studying the effects on albedo-increasing cooling infrastructure. Again, this uncertainty is graphically represented in Table 5.8 below.

| Indicator 4 | | |
|---|---|---|
| Potential Positive Equity Impact (Distance from City Center) (miles) | | |
| Low-to-No Impact (7+) | Moderate Impact (4-6) | High Impact (0-3) |

Table 5.8: Visualization of modifying surface materials and color's positive impact on equity. The positive impact is an estimated value based on data from the academic literature on A. the expected ability of surface modifications, such as cool pavements and roofs, to mitigate UHI effects via increasing the reflection of solar radiation, and B. the likely distance between the implementation site and the city center. This estimate does not include the intervention's potential for negative equity impacts.

### *Alteration of Urban Form*

It is important to preface this section on the last category of UHI-mitigating interventions by saying that opportunities to alter an existing urban form are rare (Zhou et al. 2017, 2). This type of intervention is included in this comparative analysis, however, because unplanned urban expansion generally increases the likelihood of UHI effects, and significant value can be gained from implementing certain urban morphologies (Das et al 2024, 965). While studies such as Zhou et al. (2017) note that these principles are of the greatest value to developing countries that are currently experiencing rapid new urban development, these concepts can still be valuable for areas in Massachusetts that are undergoing earlier stages of urbanization, such as areas in the western half of the state, or in the redevelopment of a site which may be surrounded by any level of urbanization (2).

Both microscale and mesoscale factors of urban form can significantly impact AT and MRT (Heris et al. 2020, 10; Zhou et al. 2017, 3). Examples of microscale factors include the height of individual buildings and the width of streets, while some mesoscale factors include the size and compactness of an entire urban region. Buildings have multiple impacts on an area's microclimate, affecting characteristics such as reflectivity and heat capacity as well as air movement patterns and velocities (Heris et al. 2020, 2). Moreover, these impacts are often complex. For example, taller buildings have been found to provide greater shade, lowering MRT (Hashemi et al. 2023, 16). Simultaneously, tall buildings have been shown to create urban "canyons" that can trap heat and pollutants (Das et al. 2024, 970). Building density typically has similar effects. Hashemi et al. (2023) found that increased building density can result in improvements to thermal comfort by reducing MRT, but Zhou et al. (2017) found that higher density in cities correlates with increased UHI effects (Hashemi et al. 2023, 16; Zhou et al. 2017, 6-7).

The consideration of street widths and patterns further complicates alterations of urban form. As a baseline, they alter air movement, which can either increase or decrease AT depending on the heat present in upwind regions (Heris et al. 2020, 7, 9). Narrow streets typically exacerbate urban canyon effects, but wide streets increase the amount of impervious surface and may lead to increases in local heat storage (Heris et al. 2020, 2).

Other mesoscale factors also change local climate patterns. For example, increases in either total urban area or fractal dimension result in decreases in wind convection, i.e., air movement is reduced when the geographic extent of an urban region increases and when an urban region becomes less circular (Zhou et al. 2017, 6). The resulting air stagnation once more leads to higher temperature and pollution loads, intensifying UHI effects (Das et al. 2024, 970; Ulpiani 2021, 19; Zhao et al. 2020, 10,332).

It should be emphasized that these typically negative effects frequently occur from the unplanned expansion of urban areas (Das et al. 2024, 965). Urban form can also have beneficial effects on microclimate characteristics. For example, the weakened convection patterns caused by the built environment may be beneficial if the incoming wind has been heated already. The example given by Heris et al. (2020) is of a linear commercial corridor blocking the heated wind coming off a surface parking lot, keeping the area past the buildings cooler than it otherwise would be (10-12). Additionally, some studies have found that shade from engineered sources, such as buildings, may still be effective at lowering MRT similar to shade provided by vegetation, though further research is needed (Heris et al. 2020, 2; Hashemi et al. 2023, 16; Park et al. 2023, 2).

This analysis distinguishes between the broad category of potential microclimate effects of urban form and the more specific category of intentional alterations to urban form for the purpose of mitigating UHI effects. Examples of this latter category include using moderate street widths to minimize airflow restrictions and adjusting building heights so that they are tall enough to shade the street but not so tall that they restrict airflow or severely increase the heat storage capacity of the urban environment (Das et al. 2024, 970; Hashemi et al. 2023, 16). The expected range of effects from the implementation of these types of interventions on AT and MRT is graphically represented in Table 5.9 below.

| Indicator 1<br>Expected Effect on Mean Radiant Temperature (MRT) and Air Temperature (AT) (+, 0, -) | | | | |
|---|---|---|---|---|
| + MRT<br>+ AT | + MRT *or* AT<br>0 AT *or* MRT | + MRT *or* AT<br>– AT *or* MRT | – MRT *or* AT<br>0 AT *or* MRT | – MRT<br>– AT |

Table 5.9: Visualization of altering urban form's effect on air and mean radiant temperatures. The effect is an estimated value based on data from the academic literature on the impacts of increasing both airflow and shading and decreasing heat storage via forms such as moderate building heights and street widths.

It is possible that green space and impervious surfaces can be managed in the design of urban form, but the alteration in form does not inherently affect either. It is true that the size and placement of green spaces both affect UHI, with large areas allowing for local breezes and more significant local effects while a greater dispersion provides smaller benefits over a larger area (Ulpiani 2021, 19; Kong et al. 2016, 1,429). Likewise, the configuration of impervious surfaces is important and even integral to urban form as mentioned above, but these factors are not directly affected by altering urban forms such as the height of buildings or the direction of street patterns (Heris et al. 2020, 10-12). This relationship is graphically represented in Table 5.10 below.

| Indicator 2<br>Expected Net Effect on Green Spaces (GS) and Impervious Surfaces (IS) (+, 0, -) | | |
|---|---|---|
| – *or* 0 GS<br>+ IS | No Net Impact | – *or* 0 IS<br>+ GS |

Table 5.10: Visualization of altering urban form's effect on green versus impervious surfaces. The effect is an estimated value based on data from the academic literature on the impacts of increasing both airflow and shading and decreasing heat storage via forms such as moderate building heights and street widths.

As part of their concept of infrastructural lock-in, Chester et al. (2014) note that once a piece of infrastructure, such as a building, is created, it tends to be long-lasting due to factors such as high fixed costs and increasing rates of return (535). They also note that the morphology created by the formation of multiple pieces of infrastructure is even longer lasting than any single unit (Chester et al. 2014, 535). This helps describe the difficulty in altering an urban form once it has been established. Given that city centers are typically the densest, and thus most established, areas within an urban region, they are simultaneously the most difficult to alter (Z. Li et al. 2021, 680). Thus, implementation of these concepts of urban form are more likely to occur farther from the city center, which is graphically represented in Table 5.11 below.

| Indicator 3 | | |
|---|---|---|
| Expected Location Efficacy (Distance from City Center) (miles) | | |
| [✓ Low Efficacy (7+)] | Moderate Efficacy (4-6) | High Efficacy (0-3) |

Table 5.11: Visualization of altering urban form's location efficacy. The efficacy is an estimated value based on data from the academic literature on the likely distance between the site of urban form alterations that increase both airflow and shading and decrease heat storage, such as moderate building heights and street widths, and the city center.

With the likelihood of alterations to urban form being higher with increasing distance from the city center, they are inversely related with the typical concentration of lower-income populations in the urban core (Glaeser et al. 2007, 4). While many positive effects can result from changing urban morphological characteristics, such changes are not likely to occur in established, lower-income neighborhoods, and thus few positive equity impacts may be expected. This is graphically represented in Table 5.12 below.

| Indicator 4 | | |
|---|---|---|
| Potential Positive Equity Impact (Distance from City Center) (miles) | | |
| [✓ Low-to-No Impact (7+)] | Moderate Impact (4-6) | High Impact (0-3) |

Table 5.12: Visualization of altering urban form's positive impact on equity. The positive impact is an estimated value based on data from the academic literature on A. the expected ability of urban form alterations, such as moderate building heights and street widths, to mitigate UHI effects by increasing both airflow and shading and decreasing heat storage, and B. the likely distance between the implementation site and the city center. This estimate does not include the intervention's potential for negative equity impacts.

### *Comparison of the Results*

The expected effects of each type of intervention on the four indicators are displayed in Table 5.13, Table 5.14, and Table 5.15 below. Out of the three categories, interventions involving vegetation increases were found to be most likely to result in beneficial effects on AT, MRT, and the ratio of green spaces to impervious surfaces. However, this intervention is somewhat unlikely to be implemented very close to the city center, where it would have the highest impact on equity.

The modification of surface materials and colors was found to be likely to result in moderately beneficial impacts on AT and MRT without impacting the green space or impervious surfaces. This method also had the highest uncertainty in where it would be deployed, however, as most studies to date only simulate the effects of these techniques without many real case studies.

Finally, alterations of urban form were expected to result in moderate to significant benefits in AT and MRT with no direct effect on green space or impervious surfaces. However, like vegetation, these techniques were expected to be implemented farthest from the city center, thus offering the lowest potential for beneficial equity impacts.

While all three intervention categories examined here can be effective at reducing UHI effects as shown with the analysis indicators, each have unique effects and drawbacks. For example, increasing vegetation has been found to be the most effective technique for reducing AT and MRT during the day, but they provide much smaller effects at night (Taleghani et al. 2016, 8). In contrast, implementing cool pavements has been observed to produce the most benefits after sunset with mixed results during the day (Taleghani et al. 2016, 6-8; Ulpiani 2021, 16-17).

In terms of implementation, most of the interventions discussed herein do not have inherent effects on land cover, so existing cover prior to an implementation may also affect the capacity of a group or municipality to deploy a given intervention (Ulpiani 2021, 18). For example, it is easier to plant a tree in a park than it is to build the park itself. Other urban form characteristics such as average humidity and incline grades may also complicate the implementation of certain interventions (Ulpiani 2021, 18; Park et al. 2023, 12).

That being said, both increasing vegetation (Table 5.13) and modifying surface materials (Table 5.14) are generally easier to implement in dense urban areas than altering the form of the urban area (Table 5.15). One reason for this is because they can both be implemented on the rooftops of buildings without requiring the same level of complexity or expense as changing the form of the building itself (Sanchez and Reames 2019, 1-2).

Because of this, the first two intervention categories (Table 5.13 and Table 5.14) may be of greater interest to cities that are already dense and undergoing further urbanization, such as those in the eastern half of Massachusetts. Towns and cities that are starting to urbanize but have not yet already begun significant suburbanization may be better able to implement intentional morphological designs (Table 5.15), such as some areas in the western half of Massachusetts.

<table>
<tr><th colspan="15"><b>Vegetation Increase</b></th></tr>
<tr><td colspan="15"><u>Indicator 1</u><br>Expected Effect on Mean Radiant Temperature (MRT) and Air Temperature (AT) (+, 0, -)</td></tr>
<tr><td colspan="3">+ MRT<br>+ AT</td><td colspan="3">+ MRT <i>or</i> AT<br>0 AT <i>or</i> MRT</td><td colspan="3">+ MRT <i>or</i> AT<br>– AT <i>or</i> MRT</td><td colspan="3">– MRT <i>or</i> AT<br>0 AT <i>or</i> MRT</td><td colspan="3">– MRT<br>– AT</td></tr>
<tr><td colspan="15"><u>Indicator 2</u><br>Expected Net Effect on Green Spaces (GS) and Impervious Surfaces (IS) (+, 0, -)</td></tr>
<tr><td colspan="5">– <i>or</i> 0 GS<br>+ IS</td><td colspan="5">No Net Impact</td><td colspan="5">– <i>or</i> 0 IS<br>+ GS</td></tr>
<tr><td colspan="15"><u>Indicator 3</u><br>Expected Location Efficacy (Distance from City Center) (miles)</td></tr>
<tr><td colspan="5">Low Efficacy (7+)</td><td colspan="5">Moderate Efficacy (4-6)</td><td colspan="5">High Efficacy (0-3)</td></tr>
<tr><td colspan="15"><u>Indicator 4</u><br>Potential Positive Equity Impact (Distance from City Center) (miles)</td></tr>
<tr><td colspan="5">Low-to-No Impact (7+)</td><td colspan="5">Moderate Impact (4-6)</td><td colspan="5">High Impact (0-3)</td></tr>
</table>

Table 5.13: Visualization of increasing vegetation's expected cumulative effects. These effects are estimated values that correspond to the four indicators reviewed in this qualitative comparative analysis. They are based on data from the academic literature on the impacts of increasing both evapotranspiration and shading via urban vegetation.

<table>
<tr><th colspan="15">Modification of Surface Materials and Colors</th></tr>
<tr><td colspan="15">Indicator 1<br>Expected Effect on Mean Radiant Temperature (MRT) and Air Temperature (AT) (+, 0, -)</td></tr>
<tr><td colspan="3">+ MRT<br>+ AT</td><td colspan="3">+ MRT <i>or</i> AT<br>0 AT <i>or</i> MRT</td><td colspan="3">+ MRT <i>or</i> AT<br>– AT <i>or</i> MRT</td><td colspan="3">– MRT <i>or</i> AT<br>0 AT <i>or</i> MRT</td><td colspan="3">– MRT<br>– AT</td></tr>
<tr><td colspan="15">Indicator 2<br>Expected Net Effect on Green Spaces (GS) and Impervious Surfaces (IS) (+, 0, -)</td></tr>
<tr><td colspan="5">– <i>or</i> 0 GS<br>+ IS</td><td colspan="5">No Net Impact</td><td colspan="5">– <i>or</i> 0 IS<br>+ GS</td></tr>
<tr><td colspan="15">Indicator 3<br>Expected Location Efficacy (Distance from City Center) (miles)</td></tr>
<tr><td colspan="5">Low Efficacy (7+)</td><td colspan="5">Moderate Efficacy (4-6)</td><td colspan="5">High Efficacy (0-3)</td></tr>
<tr><td colspan="15">Indicator 4<br>Potential Positive Equity Impact (Distance from City Center) (miles)</td></tr>
<tr><td colspan="5">Low-to-No Impact (7+)</td><td colspan="5">Moderate Impact (4-6)</td><td colspan="5">High Impact (0-3)</td></tr>
</table>

Table 5.14: Visualization of modifying surface materials and color's expected cumulative effects. These effects are estimated values that correspond to the four indicators reviewed in this qualitative comparative analysis. They are based on data from the academic literature on the impacts of increasing the reflection of solar radiation via surface modifications, such as cool pavements and roofs.

<table>
<tr><th colspan="15">Alteration of Urban Form</th></tr>
<tr><td colspan="15">Indicator 1<br>Expected Effect on Mean Radiant Temperature (MRT) and Air Temperature (AT) (+, 0, -)</td></tr>
<tr><td colspan="3">+ MRT<br>+ AT</td><td colspan="3">+ MRT <i>or</i> AT<br>0 AT <i>or</i> MRT</td><td colspan="3">+ MRT <i>or</i> AT<br>– AT <i>or</i> MRT</td><td colspan="3">– MRT <i>or</i> AT<br>0 AT <i>or</i> MRT</td><td colspan="3">– MRT<br>– AT</td></tr>
<tr><td colspan="15">Indicator 2<br>Expected Net Effect on Green Spaces (GS) and Impervious Surfaces (IS) (+, 0, -)</td></tr>
<tr><td colspan="5">– <i>or</i> 0 GS<br>+ IS</td><td colspan="5">No Net Impact</td><td colspan="5">– <i>or</i> 0 IS<br>+ GS</td></tr>
<tr><td colspan="15">Indicator 3<br>Expected Location Efficacy (Distance from City Center) (miles)</td></tr>
<tr><td colspan="5">Low Efficacy (7+)</td><td colspan="5">Moderate Efficacy (4-6)</td><td colspan="5">High Efficacy (0-3)</td></tr>
<tr><td colspan="15">Indicator 4<br>Potential Positive Equity Impact (Distance from City Center) (miles)</td></tr>
<tr><td colspan="5">Low-to-No Impact (7+)</td><td colspan="5">Moderate Impact (4-6)</td><td colspan="5">High Impact (0-3)</td></tr>
</table>

Table 5.15: Visualization of altering urban form's expected cumulative effects. moderate urban height's and width's expected cumulative impacts. These effects are estimated values that correspond to the four indicators reviewed in this qualitative comparative analysis. They are based on data from the academic literature on the impacts of increasing both airflow and shading and decreasing heat storage via urban form alterations, such as moderate building heights and street widths.

### *Additional Considerations*

Each of these three types of interventions also have tradeoffs that must be considered. The typical effects of increased vegetation, for instance, include reductions in AT, MRT, and pollutants (Heris et al. 2020, 12-13; Park et al. 2023, 10-11; Das et al. 2024, 965). Depending on the species, however, AT and MRT may be reduced while pollution is exacerbated due to the release of BVOCs (Ulpiani 2021, 18). Cool pavements and roofs face a similar dilemma. When they are used in unshaded locations, they can increase daytime MRT, decreasing thermal comfort and potentially exacerbating ozone creation (Taleghani et al. 2016, 6-7; Ulpiani 2021, 16-17). This is further complicated, though, by the effects of reduced AT lowering the formation of other pollutants (Ulpiani 2021, 19).

A potential benefit shared by vegetation and cool pavements is a decrease in the need for air conditioning within buildings due to lower AT, which curtails a portion of anthropogenic emissions, reducing both heat levels and pollution loads (Das et al. 2024, 983-984, 988; Ulpiani 2021, 19-20). On the other hand, certain morphological changes may have an opposing effect. For example, lowering development density may result in lower UHI effects, but the tradeoff is longer commute times, which can increase vehicle use and ultimately increase anthropogenic emissions (Zhou et al. 2017, 6-7). This is one piece at the core of the sprawl-versus-density debate, as suburbanization is a particular alteration of the urban form (Kasraian et al. 2016, 777).

Another consideration when choosing which intervention is the most appropriate for a specific location involves maintenance and efficacy over time. Vegetation typically becomes more effective at providing UHI-mitigating effects over time due to the maturation and growth of the individual plants. In contrast, cool pavements and roofs break down over time and need to be repaired or replaced (Ulpiani 2021, 16-17). Long-term efficacy complicates these dynamics, though. Urban heat levels are projected to increase in the near future, and increases in heat can potentially damage vegetation, reducing the overall benefits each plant is able to provide (Das et al. 2024, 969). On the other hand, cool pavements are not necessarily affected by rising temperatures.

One last consideration prior to the implementation of any intervention regards the potential for ecological gentrification in lower-income communities. While it has been specifically associated with increases in vegetation, it is possible that any infrastructural change in or around these communities can result in rising property values and costs of living, in turn potentially displacing existing residents who cannot financially afford the higher costs (Hsu et al. 2021, 6-7). This can result in a scenario where the intervention that was implemented provides public health benefits, but those benefits do not go to the original residents of the community, causing further social inequities (Lugo 2014, 325).

## Reconciling the Two Models

### *Geographic and Political Scalar Conflicts*

The final significant finding from the two analyses conducted in this thesis is that there are scalar conflicts between the drivers of UHI effects and UHI mitigation strategies. The first conflict is on the geographic scale. The quantitative analysis (chapter 4) identified interstates, which are the highest roadway functional classification, as the most important major road type when considering urbanization processes and urban heat effects.

To understand how this presents a geographic conflict, first consider the fact that the U.S. Interstate System is composed of both urban and rural segments, which mainly facilitate intra-city and inter-city travel, respectively (FHWA 2023b). Then, consider that each UHI mitigation strategy which was identified for comparison in the qualitative analysis was studied in the academic literature under the assumption that it would be implemented at both the neighborhood level and in locations that were usually closer to the urban core than the urban periphery. While some of these neighborhoods may be near urban interstate segments, a significant percentage of the total interstate system would be ignored, both in Massachusetts and nationally, if UHI interventions are concentrated in inner-city neighborhoods (Kasraian et al. 2016, 782).

Second, a political scalar conflict exists between UHI drivers and mitigation strategies. When considering any alteration to a U.S. interstate, it is important to note that each segment is owned and operated by the state-level government with geographical jurisdiction, i.e., an interstate segment is owned by the government of the state in which the segment is located and operated by that state's department of transportation (DOT) (FHWA 2023b). Any modification attempt is complicated further as the Federal Highway Administration (FHWA) also has authority over the interstate system (FWHA 2023b).

In contrast once more, research on UHI mitigation strategies typically assumes smaller-scale control and oversight, with the local municipality usually having primary jurisdiction (Miller and Mössner 2020, 2,258). This level of governance generally has no direct control over interstate infrastructure and must instead coordinate with the state's DOT to affect any change (FHWA 2023b).

These scalar conflicts have been pointed out by several researchers. For example, both Pandey et al. (2022) and Miller and Mössner (2020) acknowledge geographic scalar conflicts. The former discusses the insufficiency of focusing on any single unit in planning for equitable urbanization, whether the unit is a metric of success, a location, a spatial extent, or something else (Pandey et al. 2022, 6). Miller and Mössner (2020), meanwhile, discuss how municipalities are shaped by processes and systems that exist both inside and outside their geographic borders, including transportation and other urban infrastructure networks (2,257). In turn, individuals and communities are affected by the presence and consequences of "outside" systems, like the capacity of rural interstates to drive local urbanization and UHI effects (Miller and Mössner 2020, 2,258).

MacKinnon and Derickson (2012) go a step further to emphasize that different political scales have varying capacities to provide for their own resilience in the face of challenges. In other words, municipalities may not have the ability to fully mitigate negative externalities from systems such as UHIs despite those externalities primarily existing at the scale of individual municipalities (MacKinnon and Derickson 2012, 261-262).

### *Potential Responses Considering These Conflicts*

For consistency with the discussion thus far, the focus will mostly remain on strategies that are available to local municipalities and communities, particularly considering that they face the greatest restraints from these scalar conflicts. While not discussed in-depth in this thesis, there are many interventions available to state and federal organizations, notably departments of transportation, which share both responsibility for and interest in mitigating the negative public health and social equity consequences from UHI effects.  Briefly, one example includes roadside revegetation within interstate ROWs,[2] which includes co-benefits such as habitat provision for native plants and pollinators, and another example is the implementation of cool pavements and roofs in interstate service plazas[3] (FHWA 2019, i; Project Service LLC 2025b).

For municipalities and local organizations, strategies such as increasing vegetation, modifying surface materials and colors, and altering urban form are still viable options for mitigating UHI effects.  The most significant difference from what has already been discussed is the site of implementation.  In practice, these strategies may include specific interventions like the adoption of tree ordinances (e.g., ordinances that require a permit to prune or fell a tree), participation in state DOT programs (e.g., MassDOT's Adopt-a-Visibility Site program), and the alteration of zoning codes (EPA 2008a, 10, 14; MassDOT 2025a).

It is beyond the scope of this thesis to go into any depth on these strategies. However, more information regarding tree ordinances can be obtained from EPA (2008a). MassDOT (2025a) specifically discusses the Adopt-a-Visibility Site program, and Mass.gov

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[2] Roadside revegetation campaigns have become popular in the U.S. at both federal and state levels in the past decade (Conniff 2013).  While these campaigns can be categorized as increasing vegetation and do help mitigate UHI effects, efforts have primarily focused on providing habitat for native animals and plants whose natural habitats have been replaced with TINs and other urban land covers and uses, with a particular emphasis on pollinator species whose populations have been significantly declining (Conniff 2013; FHWA 2019, i).  A comprehensive guide to the initiation, planning, implementation, and monitoring of these campaigns is offered by the FHWA (2019), and further resources are available on the state of Massachusetts's website: mass.gov (MassDOT 2025b).

[3] There are currently 18 service plazas throughout Massachusetts, which offer amenities such as food, fuel, and restrooms (MassDOT 2025b).  These plazas are currently operated by MassDOT, but efforts are underway to modernize them and move to a public-private partnership ($P_3$), similar to other states, wherein the plazas would be operated by a private contractor on behalf of the state's DOT (MassDOT 2024; Project Service LLC 2025a).  As part of this modernization, cool technologies, such as pavements and roofs, can be incorporated in these locations.  Comparable efforts are underway elsewhere, such as in Connecticut, which has 23 service plazas (Project Service LLC 2025b).

provides further webpages on relevant DOT programs. Finally, both EPA (2008aa) and Heris et al. (2020) extensively cover the alteration of zoning codes.

With the understanding that interstates increase the likelihood of nearby land cover and land use changes, a foundational long-term question for any municipality that either contains or is affected by one or more interstates is what kinds of changes are desirable (Kasraian et al. 2016, 782-783). For the mitigation of UHI effects driven by TINs and urbanization processes, the three major intervention categories that have thus far been primarily explored at the urban neighborhood level are still applicable when considering implementation near interstates, even despite geographic and political scalar conflicts.

The following and final chapter of this thesis will review key findings and conclusions in addition to recommendations for future efforts.

# Chapter 6. Conclusions and Recommendations

## Methods and Results

This thesis was guided by three main research questions concerning the interactions among land-based transportation infrastructure networks (TINs), urbanization processes, and the surface urban heat island (UHI) effect in Massachusetts. The first question specifically asked what influence TINs had on urbanization processes. To find an answer, publicly available time series data was gathered on land cover throughout the state in addition to the location of all major roads.

The spatial scale of analysis was the census tract level. Local Moran’s I was run first to determine the presence of any clustering in the data, and the results showed that the eastern half of Massachusetts exhibits significantly higher clustering among census tracts that are both newly urbanizing and undergoing further urbanization processes. The relationship between roadways and urbanization was still unclear, so both ordinary least squares (OLS) and multiscale geographically weighted regression (MGWR) methods were used to determine the correlation between the distance of each tract to the nearest instance of each major road class. The MGWR results were the most revealing, showing that interstates were the most significant type of road for urbanization processes and were related to the further urbanization of their surrounding areas. This provided the answer to the first research question.

The second research question asked about the influence of TINs and urbanization processes on the production and exacerbation of UHI effects in Massachusetts, and data from an extensive literature review was combined with the analytical results to determine an answer. Both systems promote the alteration of existing vegetated land cover to urban environments (Kasraian et al. 2016, 782-783; Miller and Mössner 2020, 2,258). These environments are typically composed of infrastructural components such as roads and buildings constructed from materials like asphalt and concrete (EPA 2012, 1). These materials affect microclimate processes such as wind patterns and the dispersion of solar radiation, resulting in higher temperatures and decreased thermal comfort in urban regions (Zhao et al. 2020, 10,332; Heris et al. 2020, 2; Ulpiani 2021, 18-19). This answers the second research question.

Finally, the third question asked how policy and planning efforts may increase social equity and decrease public health risks associated with the interactions among these systems in Massachusetts. To answer this, first the effects of these systems on social equity and public health were determined from the academic literature. Second, a qualitative comparative analysis was conducted on three different categories of techniques that could be used to directly ameliorate the public health risks and social inequities associated with UHI effects, which arise as manifestations of the interaction between transportation networks and urbanization processes (Hsu et al. 2021, 1-2).

The first finding was that the interactions among these systems do pose public health risks, including dehydration, heat exhaustion, heat stroke, and premature death (Das et al. 2024, 970-972; McGeehin and Mirabelli 2001, 185). The second finding was that lower-income populations are disproportionately exposed to these risks due to a trend of co-location that has been observed throughout the entire United States with a particular emphasis on the Midwest and Northeast regions, including Massachusetts (McGeehin and Mirabelli 2001, 186). Specifically, this trend of co-location includes both the fact that people with incomes below the poverty line tend to be concentrated in city centers and the fact that the greatest UHI effects in an urban region also tend to be located near city centers (Glaeser et al. 2007, 7; Taleghani et al. 2016, 1).

Finally, the three categories included in the qualitative comparative analysis were increasing vegetation, modifying surface materials or colors, and altering urban form. Each of these categories were found to be able to reduce local air temperatures and mean radiant temperatures, which would increase thermal comfort for citizens (Taleghani et al. 2016, 6-7; Park et al. 2023, 10, 12; Ulpiani 2021, 18-20; Heris et al. 2020, 12-13). None of the three were particularly likely to be implemented directly in city centers, however, with changes in urban form expected to occur the furthest away. This mismatch in the expected siting of these heat-ameliorating interventions and the locations of the greatest heat levels resulted in sub-optimal expectations for the social equity benefits that would occur from their implementation directly.

That being said, interventions that involved either increasing vegetation or replacing traditional impervious surfaces with either cool pavements or cool roofs were found to have the greatest potential for immediate and direct equity benefits based on the fact that such interventions would be less difficult to implement in dense city centers than changes in urban morphology. Thus, the answer to the final research question was that policy and planning efforts should focus on intentionally siting either of these two types of infrastructure in areas that are at the highest risk of exposure to and harm from UHI effects.

## Key Takeaways

The relationship among the systems studied in this thesis are complex, and any type of intervention that seeks to alter the effects from these systems needs to be carefully considered. While it seems that increasing vegetation and implementing cool pavements seem to be the most likely methods of directly reducing public health risks and increasing social equity for lower-income populations in urban regions, the site of implementation is crucial to maximizing these benefits. The farther away an intervention is, the lower its expected direct impact may be.

Additionally, negative consequences may result from the location of an intervention. For example, ecological gentrification has been observed following the implementation of green infrastructure, such as increases in vegetation, in lower-income neighborhoods (Hsu et al. 2021, 6-7). Planners, policymakers, and other stakeholders need to be aware of these risks prior to widescale deployment of any UHI intervention (Lugo 2014, 307, 325).

That being said, there is not currently a clear understanding of the indirect impacts of the interventions that were explored in this thesis. For example, the qualitative comparative analysis conducted herein would have considered any action taken on the edges of an urban area to be relatively ineffective at promoting public health and social equity outcomes. Given that interstates significantly drive urbanization, though, it is possible that a forward-thinking municipality that had proper zoning guidelines and tree ordinances in place, even at locations far from the city center, actually used a combination of the three intervention categories explored in this thesis to successfully mitigate future increases in UHI effects for populations close to the city center. Indirect interactions such as these will hopefully be considered more deeply in future research.

Indeed, future research may provide answers to many of the uncertainties that still remain about these various interventions. To date, most research on the effects of cool pavements and roofs has been via computer simulations, but there is little indication of where this type of infrastructure may actually be built. Additionally, while it is difficult to alter the existing morphology of an urban area, there are rare opportunities to do so during site redevelopments, such as the two former indoor shopping malls studied by Heris et al. (2020). There is no way to currently account for or take advantage of these opportunities when they do arise.

Another objective for future research is to find a way to refine a comparative framework, such as the one created in this thesis, even further. An improved method for comparing the various benefits and drawbacks of alternative interventions would ideally be accessible to policymakers, spatially applicable on a micro-scale, and flexible enough to account for the unique characteristics of multiple, diverse locations.

Finally, as noted by Chester et al. (2014), knowledge regarding the drivers of urbanization, and in particular how these drivers interact, is still very limited, and research is only just beginning (535). As our understanding of these drivers grows, perhaps some of the other questions that were raised in this thesis may also be answered, such as the meaning behind the intermediary ring of insignificance around Boston that was discovered during the quantitative cluster analysis discussed in the results section (chapter 4).

Given the information currently available, there are four key takeaways from this thesis. 1. The location of an intervention is crucial to reducing public health risks and increasing social equity. 2. Daytime mitigation of UHI effects are best provided by increases in vegetation. 3. Nighttime mitigation of UHI effects are best provided by cool pavements, particularly when they are in shaded areas. 4. Reductions in air temperature and mean radiant temperature are both crucial, as the former can reduce the indoor need for air-conditioning and thus curb anthropogenic emissions while the latter increases the thermal comfort of people who are outside.

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