Dallas
Urban Heat Island Management Study

Dallas 2017
Urban Heat Island Management Study

A regional climate and health assessment conducted by the Urban Climate Lab of the Georgia Institute of Technology for the Texas Trees Foundation

urban climate lab

Texas Trees Foundation

Foreword

Urban forests create healthy communities, and trees are two times more effective at mitigating the challenges of urban heat than other identified strategies. Trees are considered an important part of our communities' infrastructure and provide many economic, social, environmental, and health benefits when properly placed, planted, and maintained.

The City of Dallas is a thriving metropolitan area and BIG things happen in Dallas. But Dallas is facing a big, HOT, and dangerous challenge! The City of Dallas, with 386 square miles, is the 9th largest city in the country and, according to Dr. Brian Stone, author and professor with the School of City and Regional Planning of the Georgia Institute of Technology, Dallas is heating up faster than any other large city in the country, except for Louisville, Kentucky, and Phoenix, Arizona. Why? There is more than 35% impervious surface in the city, and not even the 23,464 parkland acres nor the Great Trinity Forest provide enough shade to lower ambient air temperatures and mitigate the urban heat island effect.

The ***Dallas Urban Heat Island Management Study*** shows the extent to which the City of Dallas is warming due to urban development, and estimates to what extent rising temperatures will have an impact on public health. This study is one of the largest urban heat assessments in the US, with data from more than 4,000 points across the city, and models heat exposure and the potential impact from various heat management strategies.

In his book, ***The City and the Coming Climate – Climate Change in the Places We Live***, Dr. Stone states that "cities do not cause heat waves – they amplify them." Human impacts on climate at the city and regional scale, accounting for both land surface changes and emissions of greenhouse gases, may be twice as great as the impacts of greenhouse gases alone. The type of urban landscape plays a big role in the intensity of heat.

The warming trends reported by climate science often do not reflect the impact of the urban heat island effect, and the magnitude of warming that urban populations are confronting is profoundly underestimated because of the urban heat island effect.

The ***Dallas Urban Heat Island Management Study***, combined with the ***State of the Dallas Urban Forest Report***, completed by the Texas Trees Foundation in 2015, provide the needed data to mitigate Dallas's urban heat. Texas Trees Foundation has the expertise and resources to move toward a greener, cleaner, and cooler Dallas. By monitoring the growing urban heat island, especially in our most vulnerable neighborhoods, and adopting an urban heat management plan that includes existing and future infrastructure projects, green infrastructure and canopy cover goals, cool roofs and pavement goals, emergency management planning, and a strategic urban forestry master plan, we can mitigate the urban heat island effect in Dallas.

These actions will change our weather patterns and cool our city. Incorporating urban heat management strategies into decision-making will allow for effective policy based on priorities for a greener, cleaner, cooler Dallas.

The Texas Trees Foundation, August 2017

Executive Summary

The Dallas Urban Heat Island Management Study, commissioned by the Texas Trees Foundation, is among the first comprehensive heat management assessments focused on a major city and constitutes one component of a broader effort to enhance environmental quality, improve health and livability, and reduce heat mortality in Dallas.

This study assesses the extent to which the Dallas area is warming due to urban development and deforestation, estimates the extent to which rising temperatures are impacting public health, and provides a scientific foundation for the development of urban heat management plans and programs.

The study is presented in four sections, through which we: 1) Provide an overview of the science of the urban heat island phenomenon, its implications for human health, and how urban temperatures can be moderated through urban design, urban forestry, and other strategies; 2) Present our methodology for estimating the potential benefits of specific heat management strategies for lowering temperatures across Dallas and lowering the risk of heat illness during periods of extreme heat; 3) Report the results of our heat management assessment; and, 4) Provide a set of neighborhood-specific findings on the potential for lessened heat risk through the adoption of cool materials, vegetative, and integrated strategies.

Study Highlights

- Tree planting and preservation in Dallas can change the weather – producing cooler days and nights than will occur if tree canopy continues to be lost.
- The benefits of greening strategies can be as high as 15°F of cooling in some areas on hot summer days.
- Tree planting and preservation can save lives when implemented in concert with more reflective roofing and paving materials, with these combined strategies found to reduce the number of deaths from hot weather by more than 20%.
- Tree planting and preservation was found to be more than 3.5 times as effective in lowering temperatures as cool materials strategies.
- Dallas can achieve significant cooling and health benefits by planting 250,000 trees.

Acknowledgments

This study is the result of a collaborative project between the School of City and Regional Planning and the School of Civil and Environmental Engineering at the Georgia Institute of Technology and the Texas Trees Foundation. Professors Brian Stone and Armistead Russell co-directed the study with support from Dr. Marcus Trail, Evan Mallen, and Kevin Lanza, who carried out key elements of the study's modeling, analysis and mapping components. We thank Dr. Jason Vargo, at the University of Wisconsin, for serving as a consultant on the health impact analysis.

Study Sponsors
Alliance Data
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Texas Trees Foundation
The Texas Trees Foundation was established in 1982 as a 501(c)(3) as a resource to support the Dallas parks system. In 1998, the Foundation merged with Treescape/Dallas, Inc., a project funded by the Dallas Junior League and the Central Dallas Association. In 2003 the Foundation was renamed the Texas Trees Foundation to expand the area of focus from Dallas to the North Texas region to better address the environmental challenges. The Texas Trees Foundation has a rich history and is positioned to build on the established traditions by its founders and nurtured by its stewardship of the many foundations, corporations, agencies, and organizations dedicated to making our cities "greener, cleaner, and cooler."

Contributors
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Contents


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1 Introduction

Large cities like Dallas have long been known to exhibit higher temperatures than the surrounding countryside, at times in excess of 10°F, due to the intensity of heat-absorbing materials in their downtown districts and the relative sparseness of tree canopy and other vegetative cover, which provides evaporative cooling and shading.

Known technically as the “urban heat island effect,” the heating of the urban landscape through development is further accelerating the rate at which cities are warming due to the global greenhouse effect, with increasing implications for public health and critical infrastructure failure.

Through this report, we assess the extent to which the City of Dallas is warming due to urban development and deforestation and estimate the extent to which rising temperatures may impact public health through heat-related mortality and changes in regional air quality. Commissioned by the Texas Trees Foundation, this study represents the first comprehensive heat management assessment for Dallas and constitutes one component of a broader effort to enhance livability, health, and sustainability in the Dallas metropolitan region.

This report is structured as four sections. In this first section, we provide an overview of the science of the urban heat island phenomenon, its implications for human health and quality of life in cities, and how urban temperatures can be moderated through urban design and other regional strategies. The report next presents our study methodology for estimating the potential benefits of specific heat management strategies for lowering temperatures across Dallas and lowering the risk of heat illness during periods of extreme heat. The third and fourth sections of the report present the results of our heat management assessment and include neighborhood-specific findings on the potential for lessened heat risk through the adoption of tree planting, preservation, and cool materials strategies.

1.1 Climate Change in Cities

Climate change in cities is driven by two distinct phenomena, one operating at the scale of the planet as a whole and the other operating at the scale of cities and regions. The global greenhouse effect is a climate phenomenon through which the presence of “greenhouse gases” in the Earth’s atmosphere traps outgoing radiant energy and thereby warms the atmosphere (Figure 1.1). A natural warming mechanism, without the operation of a global greenhouse effect the temperature of the Earth would approximate that of the Moon, rendering the planet inhospitable to life. Since the beginnings of the Industrial Revolution, increasing emissions of carbon dioxide and other greenhouse gases have served to enhance the natural greenhouse effect, leading to an increase in global temperatures over time. This global scale warming phenomenon has resulted in an average increase in temperatures across the United States of about 1.5 to 2°F over the last century, an extent of warming experienced in both urban and rural environments [1].

In addition to changes in the composition of the global atmosphere, changes in land use at the scale of cities also contribute to rising temperatures. Known as the urban heat island (UHI) effect, the displacement of trees and other natural vegetation by the construction materials of urban development increases the amount of heat energy that is absorbed from the Sun and stored in urban materials, such as concrete, asphalt, and roofing shingle. Four specific changes in urban environments drive the urban heat island effect, including: 1) the loss of natural vegetation; 2) the introduction of urban construction materials that are more efficient at absorbing and storing thermal energy than the natural landscape; 3) high density urban morphology that traps solar radiation; and 4) the emission of waste heat from buildings and vehicles.

As illustrated in Figure 1.2, these four warming mechanisms in cities elevate the quantity of thermal energy retained and emitted into the urban environment

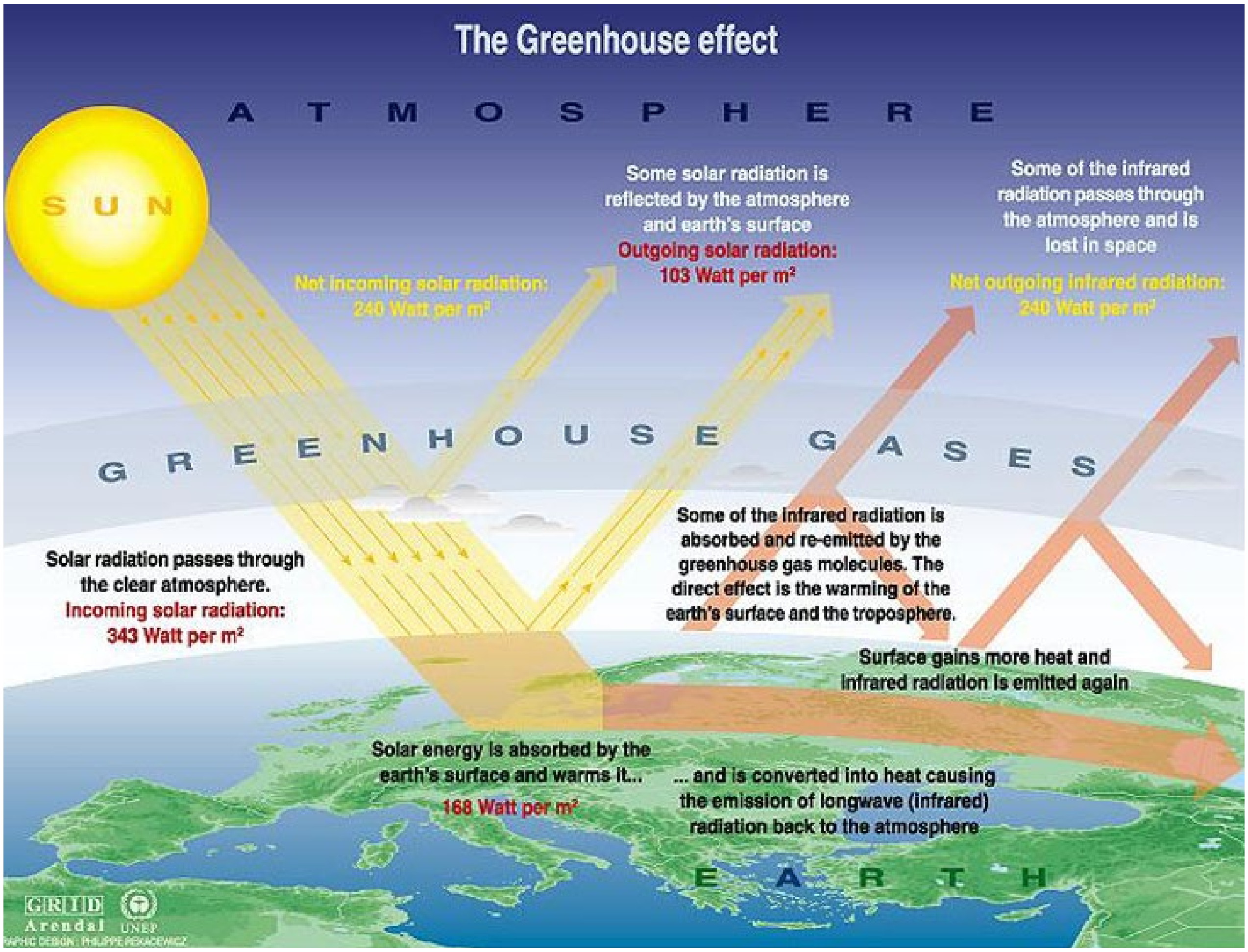


Figure 1.1 The global greenhouse effect

through distinct pathways. The loss of trees and other natural land covers contributes to a warmer environment through a reduction in shading and evaporative cooling – the process through which plants use solar energy to convert water to water vapor. As water is transmitted through plant cells and released to the atmosphere as water vapor, heat energy is also transported away from the land surface in a latent form that does not contribute to rising temperatures at the surface. As trees and other vegetation are displaced by urban development, less moisture is retained by the urban environment, resulting in less evaporative cooling.

Compounding the loss of surface moisture is the resurfacing of the urban environment with the bituminous and mineral-based materials of asphalt, concrete, brick, and stone – materials that contribute to higher temperatures through three mechanisms. First, urban construction materials such as asphalt are less effective in reflecting away incoming solar radiation, a physical property known as "albedo." As the albedo or reflectivity of cities is lowered through urban development, the quantity of incoming solar radiation absorbed and retained is greater. Second, mineral-based materials tend to be more effective in storing solar energy than the natural landscape – a property that results in the retention and release of heat energy in the late evening and into the night, keeping urbanized areas warmer than nearby rural areas. Lastly, urban construction materials such as street paving and roofing shingle are generally impervious to water, and thus

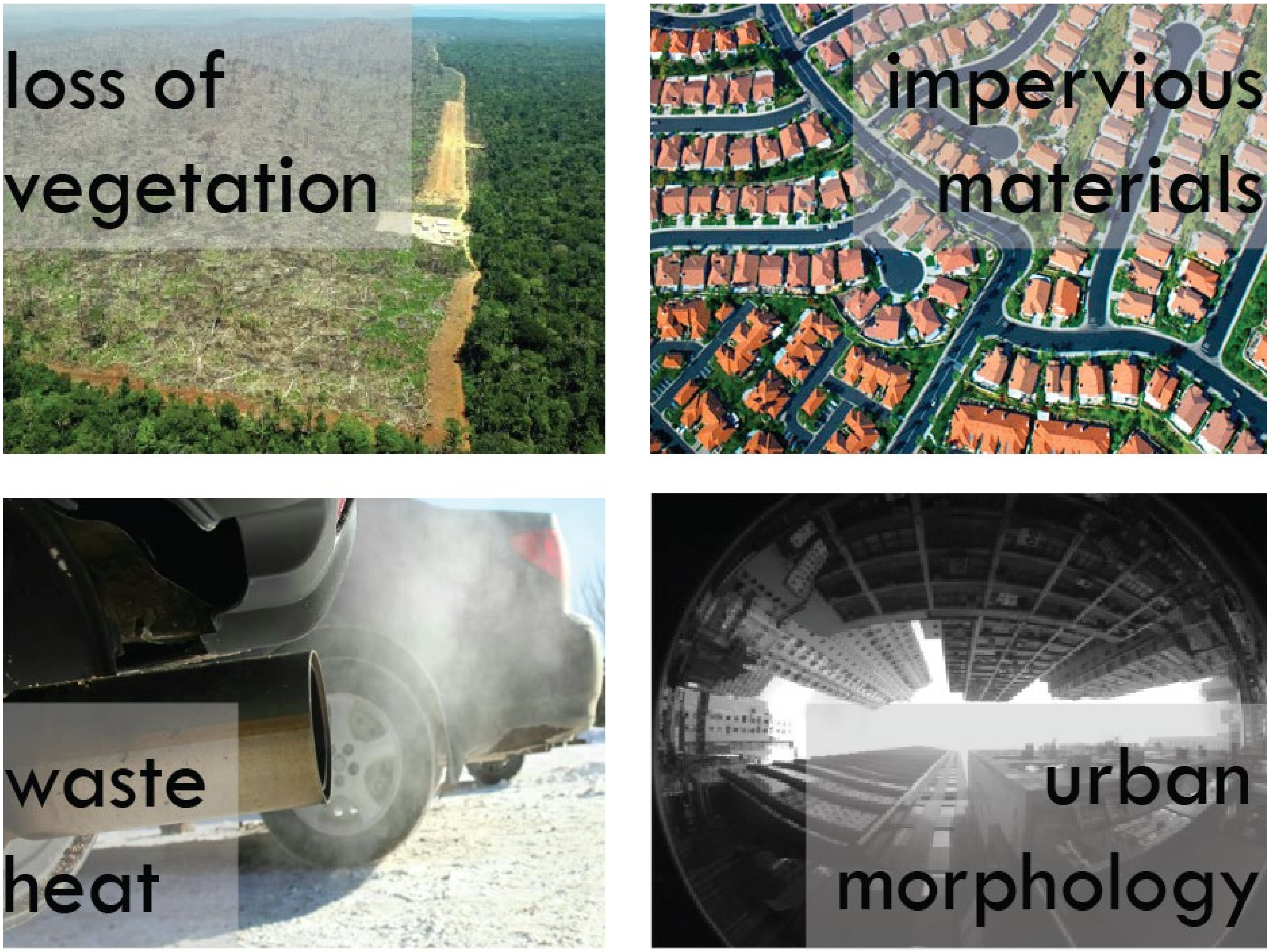


Figure 1.2 Drivers of the urban heat island effect

further reduce the amount of moisture that is absorbed and retained in cities for evaporative cooling.

A third physical driver of the UHI effect is the morphology or three-dimensional character of the urban landscape. In densely developed downtown districts, tall buildings and street canyons limit the extent to which reflected solar energy from the surface can pass unimpeded back to the atmosphere. As this reflected energy is absorbed by the vertical surfaces of the city, more heat is retained in the urban environment.

Lastly, cities are zones of intense energy consumption in the form of vehicle usage, the cooling and heating of buildings, and industrial activities. As immense quantities of energy are consumed in urban environments, waste heat is produced that is ultimately vented to the atmosphere, contributing to rising temperatures. In some US cities, waste heat from energy consumption has been estimated to account for about one-third of the UHI effect [2].

Research focused on the extent to which the global greenhouse effect and urban heat island effect contribute to warming in large US cities, including Dallas, finds the urban heat island effect to play a more significant role in warming trends since the 1960s. Figure 1.3 depicts average temperature trends in 50 of the largest US cities and in rural areas in close proximity to these cities. What these trends reveal is that urban areas not only tend to be hotter than rural areas – a manifestation of the UHI effect – but that the rate of warming over time is higher in urban areas. In addition, temperature trend data from large US cities shows that the UHI effect is a more significant driver of rising temperatures in cities since the 1960s than the global greenhouse effect. For most large cities of the United States, urban zones are warming at twice the rate of rural zones – and at about twice the rate of the planet as a whole [3].

Such rapid rates of warming have motivated an increasing number of municipal governments to develop heat management strategies designed to mitigate the urban heat island effect. Chicago, Illinois, for example, has planted over 500,000 trees over the last 15 years to offset rising temperatures through increased green cover, as well as to increase moisture retention and minimize flooding [4]. Los Angeles, California, adopted in 2014 a cool roofing ordinance designed to increase surface reflectivity, thus reducing the quantity of heat energy absorbed and retained by roofing materials [5]. Seattle, Washington, and Washington, DC, have recently adopted new zoning policies establishing minimum green area goals for all new development [6,7]. Building on this trend, The Texas Trees Foundation has undertaken comprehensive assessments of the region's tree canopy and urban heat island to lay the groundwork for new policies and programs to manage regional warming trends, among the first major US cities to do so.

1.2 Consequences of Rising Temperatures

With recent warming at both the global and regional scales projected to continue, the public health threat of heat is a national concern. The National Weather Service defines a heat wave as two or more consecutive days of daytime high temperatures ≥ 105°F and nighttime low temperatures ≥ 75°F [8]. When air temperatures rise above the temperatures to which people are accustomed, the body may not be able to effectively shed heat, causing health problems. Summertime, when air temperatures reach an annual high, is the season of greatest heat-related illness and death. In particular, heat waves during the beginning of the summer are the most dangerous because individuals have not yet acclimated to the warmer conditions [9].

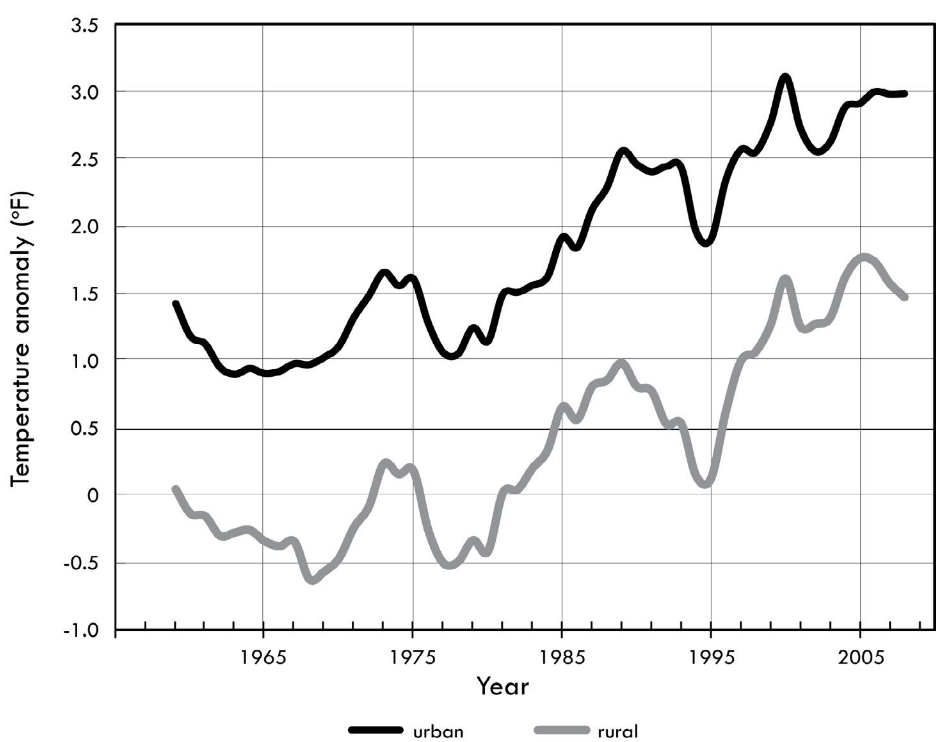


Figure 1.3 Urban and rural temperature trends in proximity to 50 large US cities (1961-2010)

The most serious heat-related illnesses are heat exhaustion and heat stroke. Common characteristics of heat exhaustion include nausea, muscle cramps, fatigue, and dizziness. If left untreated, heat exhaustion can progress to heat stroke, a more serious condition characterized by a core body temperature over 103°F and intense nausea, headache, dizziness, and unconsciousness. If fluids are not replaced and body temperature is not reduced in a timely manner, death can occur [10].

Regarding heat-related mortality, heat can either be the primary factor, i.e., heat stroke, or the underlying reason. Individuals with preexisting medical conditions, particularly cardiovascular and respiratory disease, are at higher risk for mortality during periods of high and/or prolonged heat. In a study of nine counties in California, each 10°F increase in temperature throughout the day corresponded to a 2.3% increase in mortality [11]. The 1995 Chicago heat wave, which lasted five days in July, resulted in more than 700 heat-related deaths [12]. Far more troubling was an intense heat wave that persisted for weeks across Europe and resulted in more than 70,000 heat-related deaths over the course of the full summer [13]. Global and regional temperature projections find that intense heat waves will be far more common in the coming years. By the end of the century, researchers project 150,000 additional heat-related deaths among the 40 largest US cities, including Dallas [14].

One consequence of extreme heat related to public health is its effect on outdoor activity. Heat waves can deter outdoor activity by lowering thermal comfort levels. Individuals are less likely to participate in outdoor activities when the weather is too warm, and those that do may experience symptoms of heat illness during periods of high temperatures [15]. This may have a negative impact on physical activity levels in the US, a country where one-third of adults and almost one-fifth of children are obese [16]. Extreme heat may also influence the work schedules of those in outdoor occupations, such as construction, as outside exertion during peak heat levels can be unhealthy [17].

Not all members of a community are equally affected by extreme heat. The ends of the age spectrum, i.e., the young and the old, are most vulnerable to heat waves due to lower physiological capabilities to regulate heat and a lack of mobility. The sick are vulnerable to elevated temperatures because of relatively weak immune systems compared to healthy adults, while low income individuals may lack the resources to escape high temperatures. And some minority groups carry an unequal share of the heat burden (those both older and less affluent than the general population), raising environmental justice concerns [18]. Additionally, individuals living in social isolation are more vulnerable to heat because of the absence of a social network to contact during heat waves [19].

With the continued aging of the US population combined with projected increases in urbanization and extreme heat, heat-related illness and death will become more prevalent over time. Since the public health effects of urban heat are largely preventable, health officials are developing heat response plans to prepare for the health consequences of rising temperatures. As these plans tend to be limited to actions taken during the onset of a heat wave, there is a further need for municipal and regional governments to develop heat management strategies that may lessen the intensity of heat both during heat waves and the warm season in general. This report provides the foundation for such a heat management plan in the City of Dallas.

1.2.1 Risks for Infrastructure and Private Property: While the health risks associated with extreme heat are of great importance,

Seniors are more vulnerable to heat illness than any other group.

risks to property and critical urban infrastructure can also be significant.

Urban transportation infrastructure is increasingly stressed with rising temperatures. Most transportation infrastructure is designed to last several decades, but with continued warming and an increase in the frequency, intensity, and duration of heat waves over time, significant stress will be placed on these systems [20]. For example, extreme heat increases the maintenance and repair costs for roads and railroad tracks. Prolonged exposure to high temperatures causes darkly hued surface paving to soften and expand, leaving potholes and ruts. The warping of both transit and freight railroad tracks has become increasingly common with heat waves of greater intensity over the last two decades [21]. Both roadway paving and railroad tracks can be engineered for higher heat tolerance, but each material has a maximum temperature threshold and little infrastructure currently in place is designed for the extremity of heat already experienced in recent heat waves [22].

Air transportation is impacted by extreme heat, as the lower density of hot air impedes aircraft liftoff climb performance, potentially requiring longer runway lengths as regional climates warm. The impact of extreme heat on a transportation system is far reaching because of the interdependent nature of these systems. For example, heat-related flight delays or cancellations may lead to increased roadway or rail system congestion [23].

Extreme heat can cause electricity and water delivery systems to fail during periods of peak demand. Extreme heat causes metal power lines to expand and impedes the efficiency with which transducers shed heat, lowering the overall efficiency of the system. The increased demand and inefficiency of the power system may

Prolonged exposure to extreme heat can produce kinking in the steel tracks of freight and urban transit rail systems.

overwhelm the power generation capacity of a region, leading to unplanned blackouts or intentional power outages by electric utility companies referred to as rolling blackouts. From 1985-2012, the number of major blackouts, i.e., those affecting more than 50,000 homes or businesses, increased tenfold [24].

Similar to electrical demand, residential and industrial water demand tends to rise with increasing temperatures. In US cities, temperatures above 70°F have been found to elevate water use above normal levels, while temperatures in excess of 86°F lead to significant increases in water demand [25]. As climate change and regional development lengthen periods in excess of these temperature thresholds, water delivery systems may be increasingly stressed, resulting in potential water main breaks and increasing the cost of managing these systems. Mitigation of the urban heat island effect provides a set of management strategies that can extend the life and efficient performance of critical urban infrastructure.

1.3 UHI Management Strategies

Several classes of heat management strategies have been demonstrated to lower air temperatures through small-scale experiments and larger scale modeling exercises. These strategies include the preservation and planting of trees and other vegetation, and the engineering of roofing and surface paving materials to reflect away incoming solar radiation. Two additional sets of heat management strategies, increasing the area of surface water and wind ventilation achieved through a redesigning of the built environment, are not explored through this study due to concerns over near-term feasibility and cost. In this section, we explore the potential benefits of urban "greening" and "cool materials" strategies.

1.3.1 Greening Strategies: Trees, grass, and other vegetation in cities provide a wide range of environmental and public health benefits, one of which is a cooling of the ambient air. Green plants can lower air temperatures through the processes of evaporation (the transfer of water to water vapor on plant surfaces) and transpiration (the transfer of water to water vapor in plant cells), referred to in concert as "evapotranspiration," which makes use of solar energy to convert water to water vapor, thus limiting the quantity of solar energy available to increase surface temperatures. A single oak tree transpires up to 40,000 gallons of water a year, while an acre of corn transpires up to 3,000 to 4,000 gallons of water a day [26], returning large quantities of water to the atmosphere and lowering air temperatures in the process (Figure 1.4).

In addition to evapotranspiration, trees cool the surfaces of the surrounding environment through shading. Tree branches and leaves block incoming solar radiation from reaching land surfaces beneath the canopy. Generally, trees are effective at blocking 70 to 90% of solar radiation in the summer and 20 to 90% in the winter [27]. The position of a tree impacts its effectiveness in cooling buildings, as trees located on the west or southwest sides of a building block the most solar radiation from reaching the building [28].

Trees are added to the urban forest through open space planting to shade surfaces like grass and curbside planting to shade impervious surfaces, such as streets and parking lots. Studies have found significant increases in tree canopy to be associated with measurable reductions in ambient temperatures. Through climate modeling studies focused on New York, Philadelphia, and Baltimore, for example, a 40% increase in urban tree cover was found to decrease air temperatures by an average of 1.8 to 3.6°F, with some areas experiencing temperature reductions in excess of 10°F [29].

Similar to tree canopy cover, the displacement of impervious materials by grass has also been found to lower urban temperatures. Conversion of commercial roof areas to green roofs is an increasingly common heat management strategy in large cities, with over 20% of all rooftops in Stuttgart, Germany, for example, now planted with various species of grass, sedum plants, or even shrubs and trees [30].

Research shows that the surface temperatures of green roofs can be up to 90°F cooler than conventional roofs during the summer [31]. While the benefits of green roofs for citywide air temperatures are difficult to measure directly, one modeling study finds the conversion of 50% of all rooftops to green roofs in Ontario, Canada, to produce a cooling effect of 3.6°F [32]. While green roofs are more expensive than traditional roofing to install, long term cost savings in the form of reduced building energy consumption and increased roof membrane life fully offset these costs over time [33]. Due to the relative expense of green roof strategies, we limit our focus on vegetative heat management strategies in this study to tree planting and preservation.

1.3.2 Cool Materials: Cool materials are paving and roofing materials engineered for high surface reflectance, a thermal property technically known as "albedo." Albedo can be thought of as the whiteness of a surface material, as lightly hued colors are more reflective than darkly hued colors. In reflecting away incoming solar radiation, high albedo materials absorb less heat energy from the Sun and atmosphere, lowering surface temperature. In addition

A cool roof is an urban heat management strategy that pays for itself through reduced energy costs for air conditioning.

to albedo, a second thermal property known as “emissivity” can be engineered in cool materials to enhance the rate at which absorbed solar energy is re-emitted to the atmosphere. High emissivity materials tend to store less heat energy, which also contributes to a lower surface temperature. While the first generation of cool roofing and paving materials were white or off-white in color, a full palate of colors, ranging from white to dark gray, are commercially available today.

Cool materials can significantly lower the surface temperatures of roofing shingle and surface paving. While the difference between surface and near-surface air temperatures above conventional roofing can be greater than 100°F, cool roofing products can reduce this differential by 50% or more [34]. Research has shown that large-scale implementation of cool materials can reduce air temperatures by more than 3°F at the urban scale [35]. Most suitable for flat or low sloping roofs, very high albedo materials may create undesirable glare issues if applied to surface paving.

Like green roofs, cool materials have higher initial costs per square foot than conventional materials, but these upfront costs are more than offset over the material lifespan by savings realized through reduced rates of weathering and, for roofing products, energy savings realized through lower air conditioning costs [36]. The Cool Homes Project in Philadelphia, for example, documented a 2.4°F reduction in indoor air temperatures after the installation of a cool roof [37]. Although cool roofing materials generally cost 0 to 10 cents per square foot more than conventional roofing materials, the average yearly net savings of 50 cents per square foot makes this a cost-effective roofing option [38].

In US cities, surface paving is a significant and, in some cases, dominant land cover type, elevating the potential for cool paving materials to reduce surface temperatures throughout a metropolitan region. While cool paving materials are engineered for a lower albedo than cool roofing materials to minimize glare, paving materials exhibiting a moderate reflectivity can significantly reduce urban temperatures due to their expansive surface area.

One property of cool paving that is distinct from cool roofs as an urban heat management strategy is porosity. By engineering paving materials for both a moderately high albedo (cool paving) and high porosity (pervious paving), newly surfaced streets, parking lots, sidewalks, and driveways can moderate air temperatures through two mechanisms. First, the higher albedo of cool paving reflects away a higher proportion of incoming solar radiation than conventional asphalt. Second, the ability of pervious pavement to allow the infiltration of rainwater through the material enables evaporation from water stored in the pavement and from the underlying soil, further reducing temperatures. Many cities are investing in cool and pervious paving as a strategy to manage both rising temperatures and flooding events with climate change.

In the following section of this report, we present the approach employed by our study to assess the potential benefits of vegetative and cool materials strategies for reducing summer temperatures and offsetting heat-related mortality during hot weather.

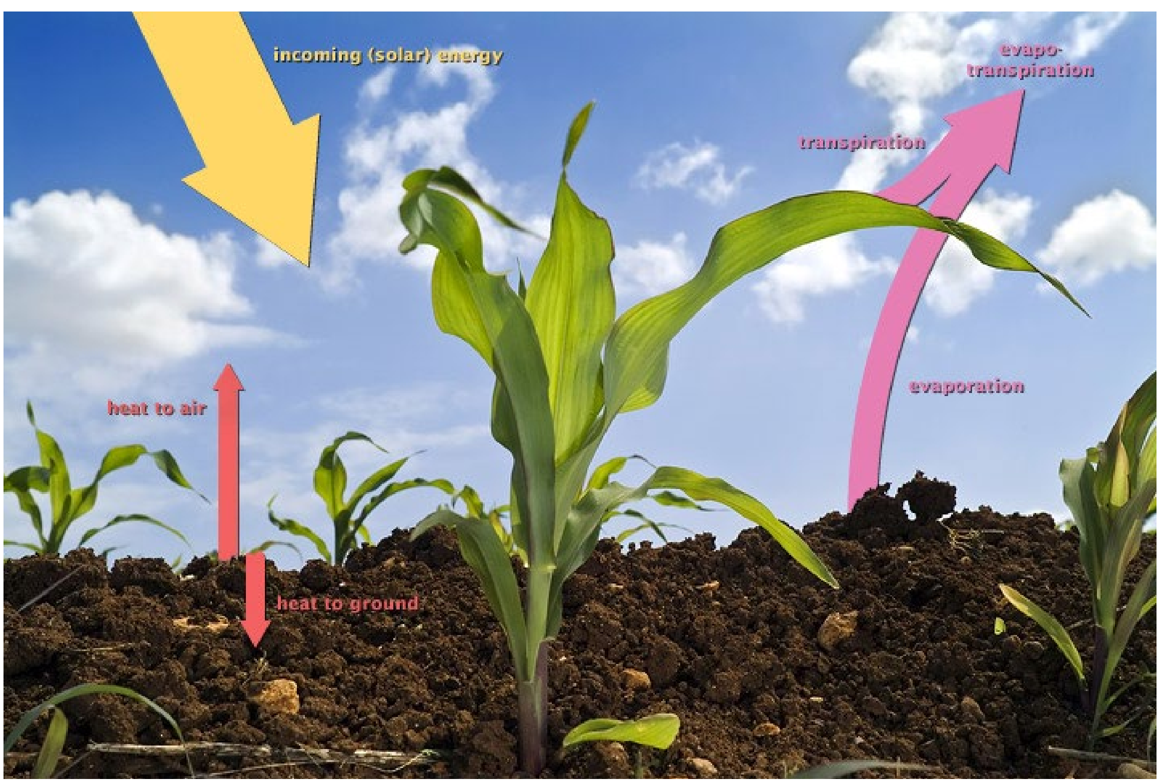


Figure 1.4
Evapotranspiration in green plants uses solar energy to convert water to water vapor and cools the air (NASA)

2 Heat Management Scenarios

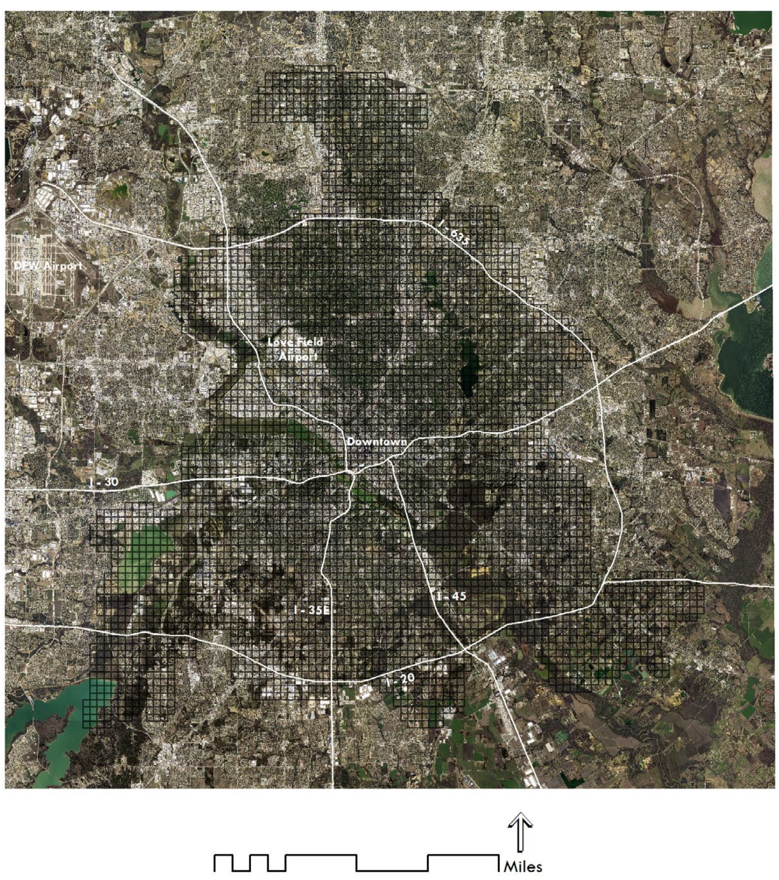
How effective would the implementation of heat management strategies be in cooling Dallas? Prior to developing a heat management plan for the City of Dallas, it is important to assess the potential benefits of such strategies for both reducing summertime temperatures throughout the city and for preventing heat-related illnesses, such as heat exhaustion and heat stroke, which are most pronounced during periods of very hot weather.

Through the use of a regional climate model, this study estimates the impact of the two classes of heat management strategies discussed above – preservation and expansion of the urban forest, and cool materials strategies - to assess how regional temperatures might change were these strategies to be implemented widely throughout the City of Dallas. We then make use of a health impact model to assess how any estimated changes in temperatures could reduce heat-related illness at the scale of individual neighborhoods. The results of this modeling study provide a basis for targeting heat management strategies to the areas of the region most vulnerable to health impacts resulting from extreme heat.

Why does this study make use of a computer model to estimate the benefits of heat management across Dallas? Regional climate models provide an essential tool for estimating temperatures in all areas of a metropolitan region. At present, only a handful of National Weather Service stations are routinely collecting temperature data in Dallas. As a result, it is not possible to accurately gauge heat exposure within areas of the region that lack a weather station, as is the case for most neighborhoods. The use of a climate model enables air temperatures to be estimated for every ½ by ½ kilometer area (equivalent to about six city blocks) across the entire city – effectively increasing the number of temperature measurements from a few to more than 4,000. Figure 2.1 presents the climate model grid developed for this study. The use of a climate model enables heat exposure in all areas of the city to be estimated.

A second benefit of regional climate models is that they enable the potential impacts of heat management strategies to be estimated. Even were there a large number of weather stations distributed across the Dallas area, such a network would only capture how

Figure 2.1 Climate model grid. The Weather Research and Forecasting regional climate model generates unique temperature, humidity, and wind speed estimates for each of 4,381 grid cells across the Dallas region. The Downtown district, regional airports, and regional interstate highways are labeled.



temperatures vary across the region under current development conditions. To better understand how temperatures might change in response to the implementation of heat management strategies, a regional climate model was run for current day conditions and then run again to assess how an increase in tree canopy and cool roofing and paving materials might change temperatures at the neighborhood level. Only a climate model enables such an assessment.

Do regional climate models estimate temperature with a high degree of accuracy? As our understanding of regional climatology has improved, along with continuing improvements in computer processing capacity, the accuracy with which regional climate models can simulate current day temperatures has increased substantially. Nonetheless, when run at high spatial resolutions, as required for a study of temperature change and human health at the neighborhood level, regional climate models are known to accurately capture the effects of evapotranspiration by trees on air temperature, while underestimating the effects of tree shading [39]. The reason for this outcome is that climate models such as the Weather and Research Forecasting model are only capable to simulating how trees influence air temperatures above the tree canopy itself, as opposed to underneath the canopy, where both shading and evapotranspiration can cool the air.

To most effectively simulate the benefits of tree shading in this study, we combine our climate model results with data from observational studies measuring the extent to which trees influence air temperatures through both evapotranspiration and shading. While both published work and current observations by the Urban Climate Lab at Georgia Tech find the ratio of cooling attributable to shading versus evapotranspiration to be 5 to 1 or greater [39, 40], we adopt in this study a more conservative ratio of 3 to 1. Due to the adoption of a shading effects ratio lower than observed in urban settings, the results of this study may underestimate temperature change associated with an expanded urban forest as simulated through the tree planting and preservation ("Greening") scenario.

Our approach to assessing the potential benefits of heat management in Dallas consists of four steps, including an inventory of land surface materials, the modeling of regional temperatures under current conditions, the modeling of regional temperatures in response to each of the heat management strategies, and, lastly, the estimation of health benefits associated with heat management planning across Dallas. In this section of the report, we describe each of these steps in the heat management study.

2.1 Inventory of Land Surface Materials

The regional climate model used in this study – the Weather Research and Forecasting Model (WRF) – is driven by three basic sets of climatic inputs. These include: 1) the weather conditions moving into the modeling area at the start of the modeling period; 2) the weather conditions of the modeling area itself at the start of the modeling period; and 3) the land surface characteristics of the modeling area, which are held constant during any single scenario run.

Based on these provided conditions, the WRF climate model estimates a series of weather variables, including air temperature, humidity, and wind speed, for every ½ kilometer by ½ kilometer (referred to as ½ km^2) grid cell across Dallas. These weather variables are estimated for every 1-hour interval over the period of May 1 through September 30 in the year 2011. We selected the 2011 warm season as the modeling period for this study as this was an unusually warm summer. Each of the heat management scenarios modeled in this study are based on regional weather, land use, and population characteristics consistent with the period of 2011 to 2015.

Development conditions around the Dallas area have a significant influence on air temperatures. As described above, the presence of expansive areas of surface paving in the form of roads and parking lots, in combination with building areas, tends to absorb large quantities of solar energy and to re-emit this energy as heat, raising air temperatures. Thus, zones of the city that are intensely developed, such as the Downtown district, will generate their own hotspots, in which air temperatures are measurably higher than in undeveloped or residential zones with ample amounts of tree canopy, lawn area, and other vegetation. The accurate modeling of air temperatures across the Dallas area thus requires information on the land surface materials found in each model grid cell.

Two sources of information are used to map land surface materials across the study area. First, we make use of parcel and roadway information provided by the City of Dallas, which maintains very detailed and high quality geographic information on all impervious surfaces throughout Dallas, including roadways, parking lots, and building footprint areas. To classify the non-impervious components of urban land cover, we make use of aircraft-measured land use information, also obtained from the City of Dallas. The availability of data on both impervious and non-impervious land use conditions across the City of Dallas enables the estimation of the percent coverage of each of eight classes of land cover (Table 2.1) within each grid cell, which may then be used to drive the WRF climate model.

Each of two heat management scenarios entails either the conversion of impervious areas (paving or roofing) to cool materials or an increase in total tree canopy across Dallas over time. The resulting land cover changes associated with each heat management scenario are presented in Section 3.

2.2 Heat Management Scenarios

Temperature and humidity were modeled across Dallas in response to five land development scenarios, including Current Conditions, Greening, Cool Materials, Tree Loss, and Combined Strategies scenarios. This mix of modeling scenarios was selected to assess the potential benefits of each heat management technique as a stand-alone

Table 2.1 Land cover classes used as inputs to WRF climate model

Class Number	Land Cover Type
1	Buildings
2	Surface Impervious
3	Parking Lots
4	Trees
5	Irrigated Grass
6	Non-Irrigated Grass
7	Bare Soil
8	Water

strategy and in concert with other heat mitigation tools. In addition, a scenario forecasting the climate effects of additional trees loss in areas of the region where rapid development is anticipated provides a means of estimating the impacts of heat management over a "business as usual" scenario. In this section, we present the policy-based assumptions driving each of the five heat management scenarios.

2.2.1 Current Conditions: The Current Conditions scenario models temperature and humidity in response to current day development patterns. As such, the mix of surface paving, roofing materials, tree canopy, grass, and other land cover characteristics found in each grid cell match as closely as possible the current day development patterns. The Current Conditions scenario is used in this study as a baseline set of temperature and humidity estimates against which the heat management and tree loss scenarios are measured. It is expected that increased levels of tree canopy and cool materials will be found to lower temperature and humidity levels, on average, across the Dallas study area.

2.2.2 Greening Scenario: Through the Greening scenario, the area of tree canopy is increased across Dallas to moderate temperatures through increased shading and evapotranspiration. The addition of new tree canopy is targeted toward areas of high development density, where vegetation tends to be most sparse. To direct where new tree canopy should be targeted, the study assumes two new land use policies to be in place in the region. The first is a requirement that 30% of all roadway surfaces be overlaid with tree canopy. The second is a requirement that 30% of all parking lots, driveways, sidewalks, and other surface paving be overlaid with tree canopy.

Minimum green cover standards in municipal codes are increasingly common around the United States. Both Seattle, Washington and Washington, DC, for example, have enacted in recent years "green area ratios" setting minimum green cover standards by zoning class. And many large cities, including Dallas, require parking lots for specific development classes to include a minimum area of tree cover. In light of these existing landscaping requirements, we assume the adoption of a 30% minimum green cover over paved surfaces across the city to establish new canopy in highly impervious zones where it can be most beneficial in moderating temperatures.

While a requirement that 30% of all paved surfaces be overlaid with tree canopy may seem ambitious, it is important to note that some areas across Dallas are already characterized by this level of canopy cover.

In designing the Greening scenario for this study, we first estimated the area of unshaded surface paving - including roadways, parking lots, driveways, and walkways - for every ½ km^2 grid cell in Dallas. We next identified all grid cells for which less than 30% of the paved surface area was overlaid by tree canopy. Last, for any grid cell found to have less than 30% of the surface paved area unshaded, we increased the tree canopy percentage to achieve a minimum of 30% cover. In concert, these two policy assumptions were found to increase total canopy cover across Dallas from 29 to 35%, or an increase of 6%. This area of new canopy cover is equivalent to the addition of about 250,000 large trees.

2.2.3 Cool Materials Scenario: Roads, parking lots, and building roofs account for a large percentage of the total surface area in dense areas of Dallas. On average, grid cells in the city's Downtown district are more than 75% impervious, with the remainder typically occupied by grass, Tree canopy cover over a residential street in Dallas

trees, barren land, and water. Through the Cool Materials scenario, the reflectivity or "albedo" of roofing and surface paving is increased to reduce the quantity of sunlight absorbed by these materials and re-emitted as sensible heat. Surface albedos are measured on a scale of 0 to 1.0, with values of 1.0 approaching the reflectivity of a mirror. Dark materials with high surface roughness, such as new black asphalt roofing shingle, exhibit albedos as low as 0.05.

A second thermal property of impervious materials – the emissivity, or efficiency with which absorbed solar energy is re-emitted as sensible heat – is also increased through this scenario to reduce material temperatures. High emissivity materials quickly release absorbed solar energy, reducing the quantity of solar energy that is retained by these materials and thus lowering temperatures. Thermal emissivity is also measured on a scale of 0 to 1.0, with higher values associated with a more rapid release of absorbed solar energy.

Similar to the establishment of minimum green cover requirements, a number of US cities now require all new roofs to achieve a minimum level of reflectivity. The largest among these is Los Angeles, which adopted a cool roofing ordinance in 2014. Other cities with minimum albedo requirements include Houston, New York, and Philadelphia.

Through the Cool Materials scenario, different values of albedo and emissivity are applied to different types of surface materials. Because highly reflective materials, such as a bright white paving, can create glare problems for drivers and pedestrians, more moderate levels of albedo are applied to streets, parking lots, and other types of surface paving than to roofing.

2.2.4 Tree Loss Scenario
In contrast to the Greening and Cool Materials scenarios, which simulate the potential climate benefits of established heat mitigation strategies around Dallas, the Tree Loss scenario is intended to simulate a "business as usual" scenario, through which the effects of continued canopy loss in areas of the city experiencing development are estimated.

To do so, we use the results of a 2013 study carried out by Azavea and focused on districts across Dallas most likely to experience development over time. The results of this study find the projected loss of tree canopy in a set of south Dallas neighborhoods and the Downtown district to average 11% over the near to medium term. We find an 11% reduction in tree canopy in these neighborhoods alone to result in a city-wide reduction in tree canopy of 1.4%.

This simulation of a business as usual scenario accounting for likely tree loss due to development over time in Dallas provides a basis to assess two different futures for the region: one in which tree canopy is further reduced over time and another in which existing canopy is preserved and new canopy is added through a citywide tree planting campaign. As detailed Section 3, these two futures represent in shift in city wide tree canopy ranging from a 1.4% loss to a 6% gain.

2.2.5 Combined Strategies Scenario:
The fourth and final temperature change scenario carried out for this study entails the combination of the Greening and Cool Materials scenarios. While each heat management strategy is expected to yield temperature reductions, on average, when applied as a stand-alone strategy, prior work suggests that the combination of strategies will achieve the most significant reductions in regional temperatures. Through the Combined Strategies scenario, any required changes in tree canopy under the Greening scenario are applied first, followed by an increase in the albedo and emissivity of all building roofs and of all uncanopied surface paving. The resulting surface materials changes, including new tree canopy and higher levels of albedo and emissivity for all impervious materials by type, are then input into the climate model.

2.3 Health Impact Assessment

Frequent and prolonged exposure to high temperatures produces adverse health effects directly tied to climate and expected to worsen with climate change. To evaluate the health protection benefits of urban heat management strategies, we assess the population sensitivity to varying temperatures under each heat management scenario. An established relationship between temperature and mortality is used to evaluate the number of lives saved in Dallas following urban heat management actions, compared with current summer conditions.

Several basic elements of data are combined to perform our health impact modeling. First, population estimates were obtained from the US Census and allocated to each ½ km^2 grid cell in the region. Census information used in the health modeling includes number of people by age and sex.

Second, we obtained data on average daily mortality from the US Centers for Disease Control and Prevention (CDC). This data was acquired for the Dallas area from the CDC's Wide-ranging ONline Database for Epidemiologic Research (CDC-WONDER) and allocated to each grid cell in the study region.

Third, an exposure-response relationship between temperature and mortality was obtained from a recent study on extreme heat and heat-related mortality focused on global cities. The study provides data on the measured association between temperature and heat-related mortality for more than 384 cities around the world, including Dallas [41]. Using this information, the risk of heat mortality can be estimated for each day in the 2011 warm season (May through September) across each grid cell in the Dallas study area.

Finally, the grid cell daily temperatures from the climate scenario modeling are used to estimate the number of heat-related deaths in response to current conditions and each heat management scenario. As the heat management scenarios modify daily temperatures in different areas of Dallas, the estimated number of heat-related deaths will change as well. Importantly, the number of heat-related deaths in any area of the region will be a product not only of the corresponding neighborhood temperature but also of the population composition of the neighborhood. Neighborhoods consisting of larger populations, or of a disproportionate number of sensitive individuals (such as the elderly), will be found to have a higher number of heat-related deaths than neighborhoods with lower populations, assuming the same degree of temperature change in both areas. The results of the heat-related mortality assessment are reported in Section 4.

3 Heat Scenario Results

How might the implementation of heat management strategies moderate temperatures across the City of Dallas? In this third section of the report, we present the results of the heat management scenario modeling to assess how an enhancement in urban tree canopy and cool materials, alone and in concert, might reduce the urban heat island effect in Dallas. We also examine how a continued loss of tree canopy to development may influence temperature and health.

3.1 Land Surface Materials Inventory

Through the land surface materials inventory, eight distinct classes of land cover were estimated at the grid cell level throughout the Dallas area. Three of these land cover classes – tree canopy, building roofing, and surface paving – were changed through the climate simulations to assess how increased areas of tree canopy cover and cool materials, as well as a reduction in tree canopy, would modify temperatures across Dallas. In this section of the report, we present a series of maps detailing the present day distribution of these land cover materials throughout the study area and then illustrate how these land cover distributions were modified through each heat management scenario. The final component of this section presents the scenario results for warm season temperatures across Dallas.

3.1.1 Tree Canopy Cover: The distribution of tree canopy cover across the Dallas study area was mapped based on high resolution aerial imagery. Figure 3.1 presents the percent of total tree canopy cover for each grid cell throughout the city.

As illustrated in Figure 3.1, in most grid cells in the Downtown and airport/ industrial districts, tree canopy cover is less than 5%, with no grid cell exhibiting canopy cover greater than 15%. The most heavily forested zones of the city are found in the north and southeastern zones, although pockets of heavy canopy are found in residential and undeveloped areas across Dallas. In contrast to most other land cover types, tree canopy is found to range from a low level of zero coverage to 100% coverage in heavily forested areas. As discussed in Section 2.2.2, the Greening scenario is designed to strategically enhance tree canopy cover in the most sparsely canopied residential and commercial zones through the planting of trees along streets and within surface parking lots.

3.1.2 Grass Cover: Similar to tree canopy, areas of grass were mapped through the use of aerial imagery. The distribution of grass cover throughout the Dallas study area tends to be found outside of heavily forested zones and often along river and stream corridors (Figure 3.2). In addition to the extensive areas along the Trinity River, grass cover is most dense in the far northern and southern reaches of the city. Grass covers range from zero to 100%, are heaviest in areas of open space, and are most sparse in commercial and industrial zones. Grass land covers are not modified through our heat management scenario modeling.

3.1.3 Barren Land: A third class of undeveloped land that is incorporated through the climate scenario modeling is barren land. Consisting of active construction sites, poorly maintained lawn areas, and zones subject to extensive erosion or other vegetation-denuding conditions, the exposed soils of barren land can elevate local temperatures in a manner similar to impervious materials. Figure 3.3 presents the distribution of barren land throughout Dallas under current conditions. While few grid cells have extensive areas of exposed soil – as high as 40% of the grid cell area in some cases – barren land tends to account for a small percentage of all land covers throughout the study area. Similar to grass land covers, the distribution of barren land tends to follow the pattern of single-family residential development, suggesting that exposed soils are often associated with poorly maintained lawn areas.

3.1.4 Surface Impervious Cover: Several classes of impervious land cover are mapped for the Current Conditions scenario and then modified in the scenario modeling through increased street tree planting, parking lot tree planting, and the placement of canopy over other surface paving. Surface impervious cover consists

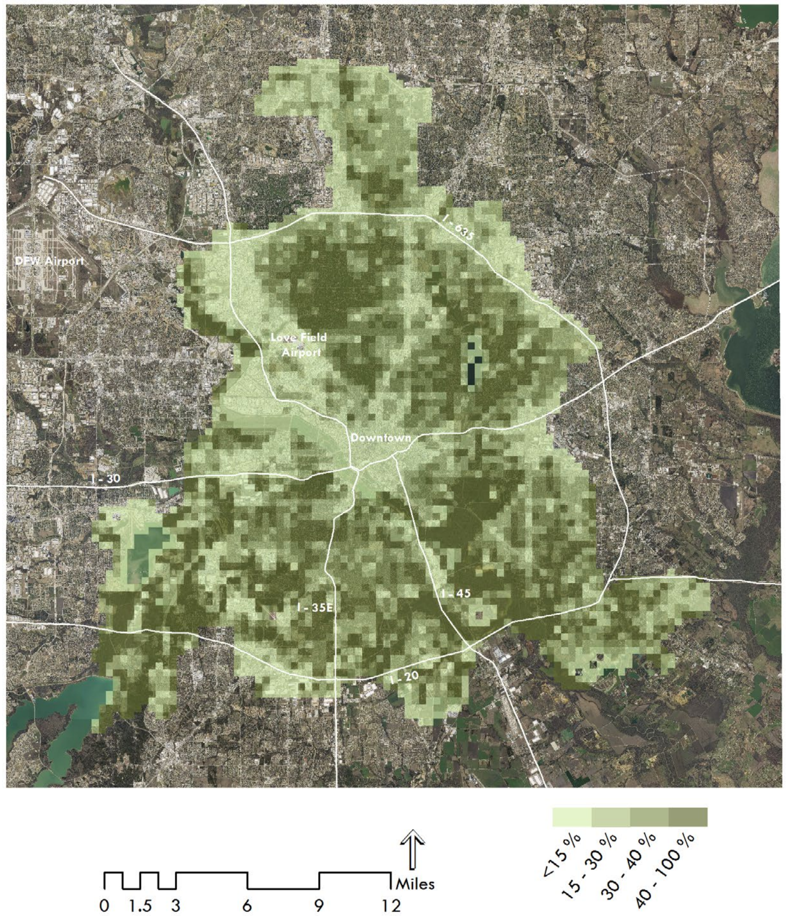


Figure 3.1 Tree canopy cover across Dallas as percentage of ½ km² grid cell

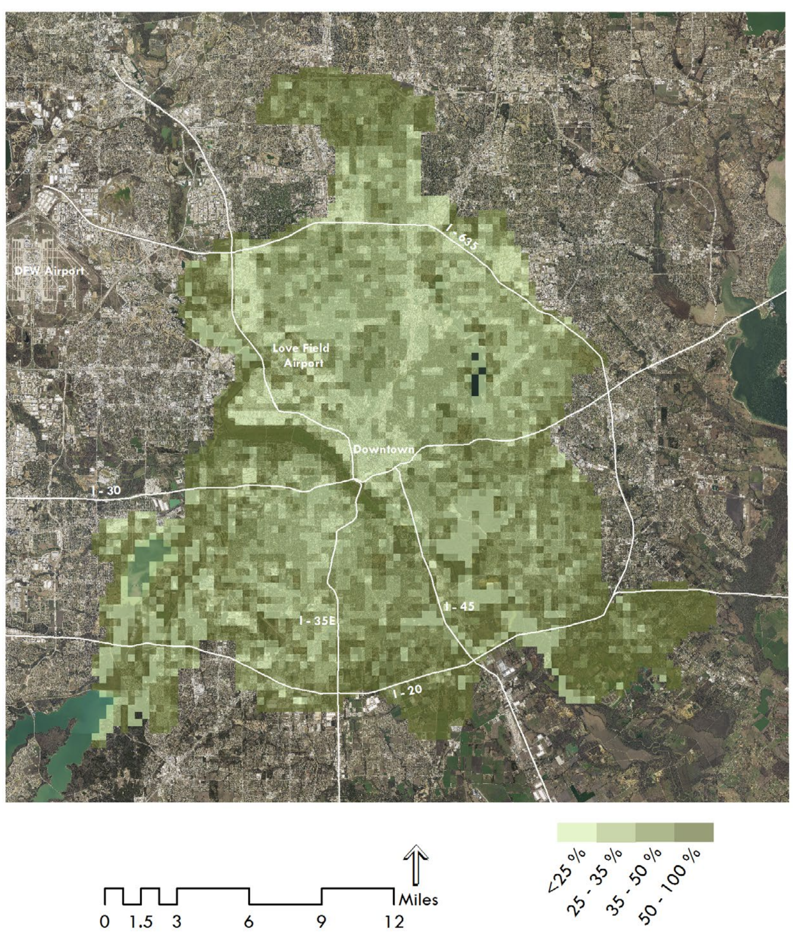


Figure 3.2 Grass cover across Dallas as percentage of ½ km² grid cell

of the impervious areas of roadways, parking lots, walkways, and driveways. Figure 3.4 presents the distribution of surface impervious cover throughout Dallas and clearly reveals the pattern of large roadways around the city. Also as expected, the Downtown district and large industrial zones are found to have high levels of imperviousness, with some zones approaching 100% impervious cover. Most grid cells in the city exhibit surface impervious areas of greater than 20%, directly contributing to heat island formation.

3.1.5 Building Impervious Cover: Building impervious covers consist of the roofing area of all buildings, including both residential and non-residential structures. Figure 3.5 maps the distribution of building roofing area under current conditions. The map reveals a clear pattern of more intense development to the north of Downtown than to the south, generally finding more than 15% of most grid cells to in the northern half of the city to be occupied by buildings and less than 15% in the southern half. While more than 50% of many grid cells Downtown and along the I-35 corridor are occupied by buildings, extensive tracts to the south, such as along the Trinity River and in proximity to Roosevelt Park, lack any significant development and thus are likely to play a key role in moderating regional temperatures. It should be noted that building footprint data was unavailable for the University Park area north of Downtown, and so this zone is omitted from the building impervious map.

3.1.6 Surface Water: A final class of land cover included in the climate modeling is surface water. The distribution of rivers, lakes, and other water bodies is presented in Figure 3.6.

3.2 Air Temperature Scenario Modeling

As outlined above in Section 2.2, the Weather Research and Forecasting regional climate model was used in this study to estimate the distribution of summer air temperatures throughout the Dallas area and to simulate how temperatures might change in response to the implementation of heat management strategies, as well as in response to further development. In this section of the report, we present the results of these climate model runs and assess the relative benefits associated with heat management strategies implemented alone and in concert. We first present a set of three maps illustrating the distribution of summer air temperatures across Dallas under current conditions, in which no heat management policies are assumed to be in place. In the remainder of this section, we present a series of maps illustrating how each land use change scenario influences maximum and minimum temperatures in the study area and the spatial extent of cooling or warming outcomes resulting from the simulated changes.

3.2.1 Current Conditions: Figure 3.9 illustrates the distribution of daily high air temperatures averaged over the period of May through September (2011) across the Dallas study area. Both high and low temperatures are averaged over the entire warm season to account for the variable effects of heat on human health during the course of the spring and summer. In the late spring, when the first hot temperatures of the year may be experienced and residents may not yet be fully acclimated to warm weather, vulnerability to heat illness may be elevated due to enhanced sensitivity. Later in the summer, when the population is better acclimated to heat, but extreme temperatures can persist for many days, vulnerability may be elevated due to the duration and intensity of heat. For this reason, the heat effects model used in this

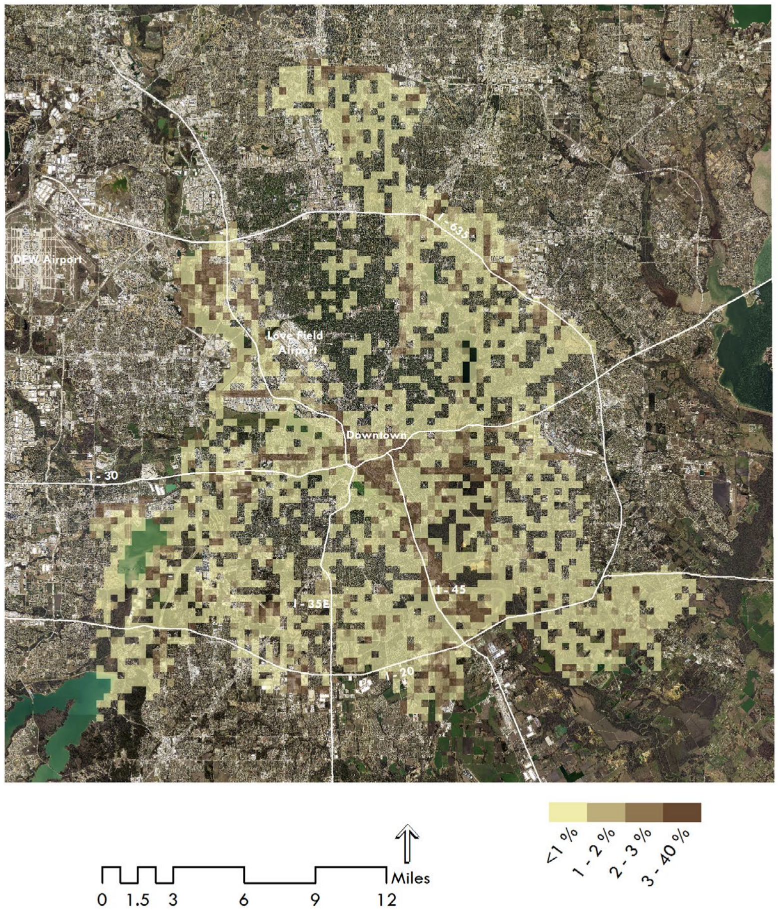


Figure 3.3 Barren land across Dallas as percentage of ½ km^2 grid cell

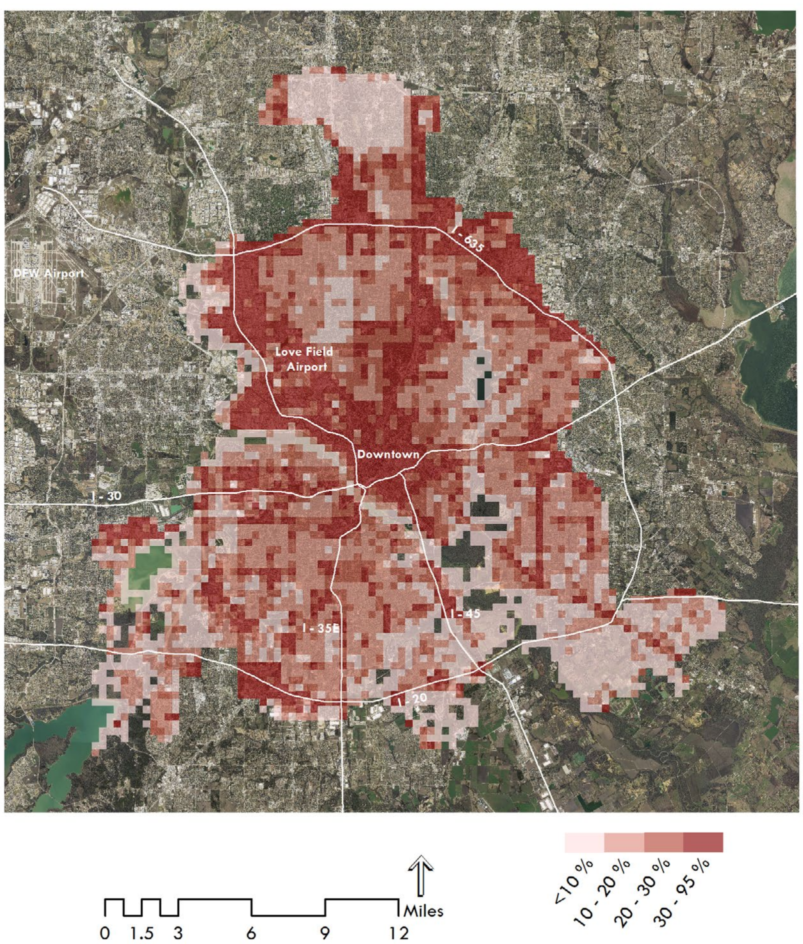


Figure 3.4 Surface paving area across Dallas as percentage of ½ km^2 grid cell

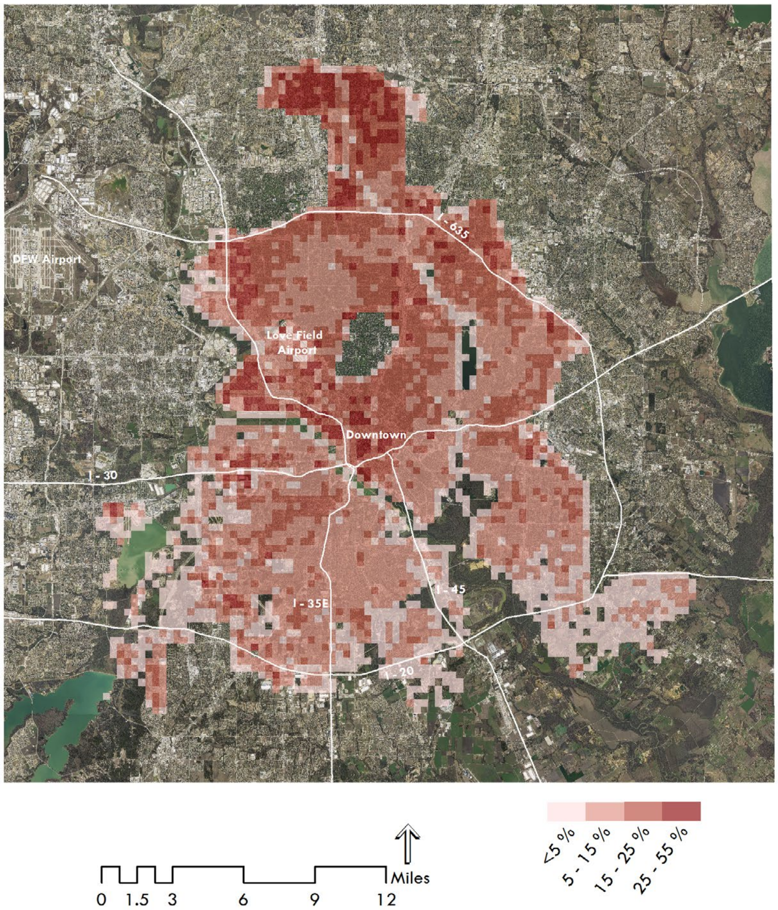


Figure 3.5 Building roof area across Dallas as percentage of ½ km² grid cell. Note: Incomplete data available for some areas.

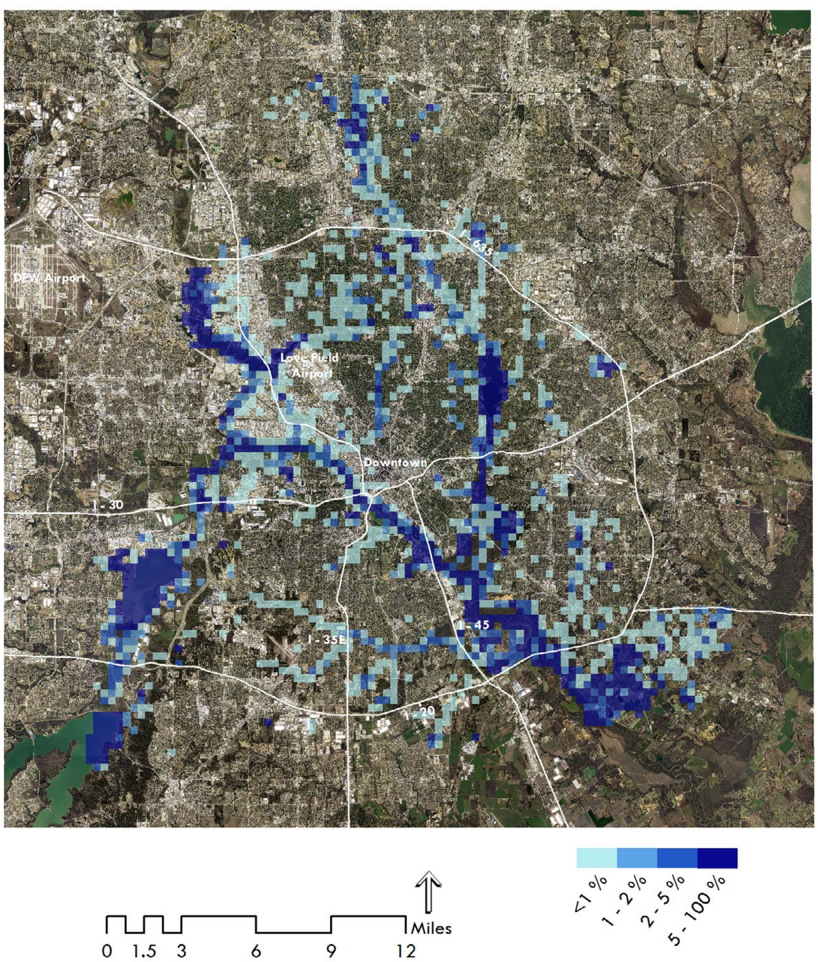


Figure 3.6 Water area across Dallas as percentage of ½ km² grid cell

study accounts for temperatures throughout the full warm season to capture potential health impacts of early, middle, and late summer heat exposure.

The daily high temperature map presents a classic urban heat island temperature pattern, with the highest temperatures found in the most intensely developed zones found in the Downtown district and with a gradual reduction in temperatures observed across less intensely developed and more heavily vegetated areas moving away from the downtown core. As consistent with the spatial pattern of warming, the most densely developed areas of Dallas tend to be found in the Downtown district and to the northwest, along the I-35 interstate corridor. The lowest late afternoon temperatures tend to be found along the periphery of the urban area, particularly to the northeast and southwest of Downtown.

The temperature maps presented in this section partition temperatures into five ranges, each with an approximately equal number of grid cells. Thus, the zone of highest average daily high temperatures (98.7 to 100.5°F) illustrated in Figure 3.7 is approximately equal in total area to the zone of lowest average daily high temperatures (89.9 to 97.8°F). The distribution of daily high temperatures during the warm season reveals a maximum urban island intensity, as measured within the city itself, of about 9°F, which is consistent with a large number of studies across numerous cities reporting a range of seasonal heat island intensities between about 2 and 12°F.

It should be noted that the temperatures mapped in Figure 3.7 present an average of 153 daily high temperatures over the period of May through September, and thus the high temperature (or the heat island intensity) on any particular day could be much lower or higher than those presented here. On many days during the 2011 summer, for example, the difference between the hottest and coolest areas of Dallas was found to be about 9°F. Likewise, on many days throughout the summer of 2011, daily high temperatures well exceeded 100°F - indeed, some grid cells were found to experience an average daily high temperature in excess of 100°F over the entire warm season, suggesting very hot conditions in these areas.

While high air temperatures are found to largely follow patterns of intense land development, a few hot spots are revealed in areas of relatively low development, such as near the intersection of the I-20 and I-45 interstate highways. While this zone is occupied by the large McCommas Bluff landfill and is thus characterized by barren soils and a lack of vegetative cover, other warm zones, such as along the Trinity River near Downtown, exhibit high air temperatures due to their proximity to intense development. In contrast to surface temperatures maps, which are more commonly used to map the extent of urban heat islands, near surface air temperature accounts for the movement of warm air throughout a region, and thus does not always reveal a direct relationship between temperature and underlying land covers.

Figure 3.8 presents warm season average daily low temperatures across Dallas in 2011. Typically experienced in the early morning hours – between 3:00 and 6:00am – the daily low or minimum temperature has been found to be more closely associated with the occurrence of heat-related illness than the daily maximum temperature. High nighttime temperatures stress human respiratory and cardiovascular systems by prohibiting the body from fully recovering from high heat exposures during the day. Elevated nighttime temperatures, particularly during heat wave periods and for individuals lacking access to mechanical air conditioning, provide an important indicator of which areas of the Dallas area are most at risk to heat-related illness.

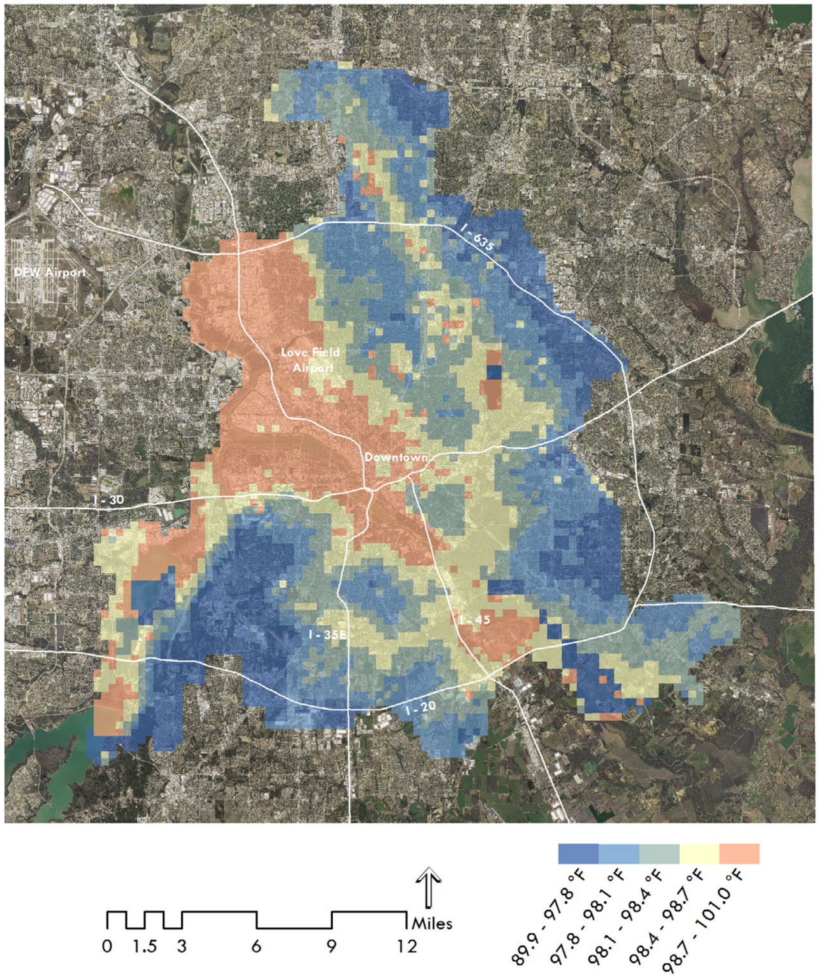


Figure 3.7 Warm season (May through September) average daily high temperature (°F) in Dallas

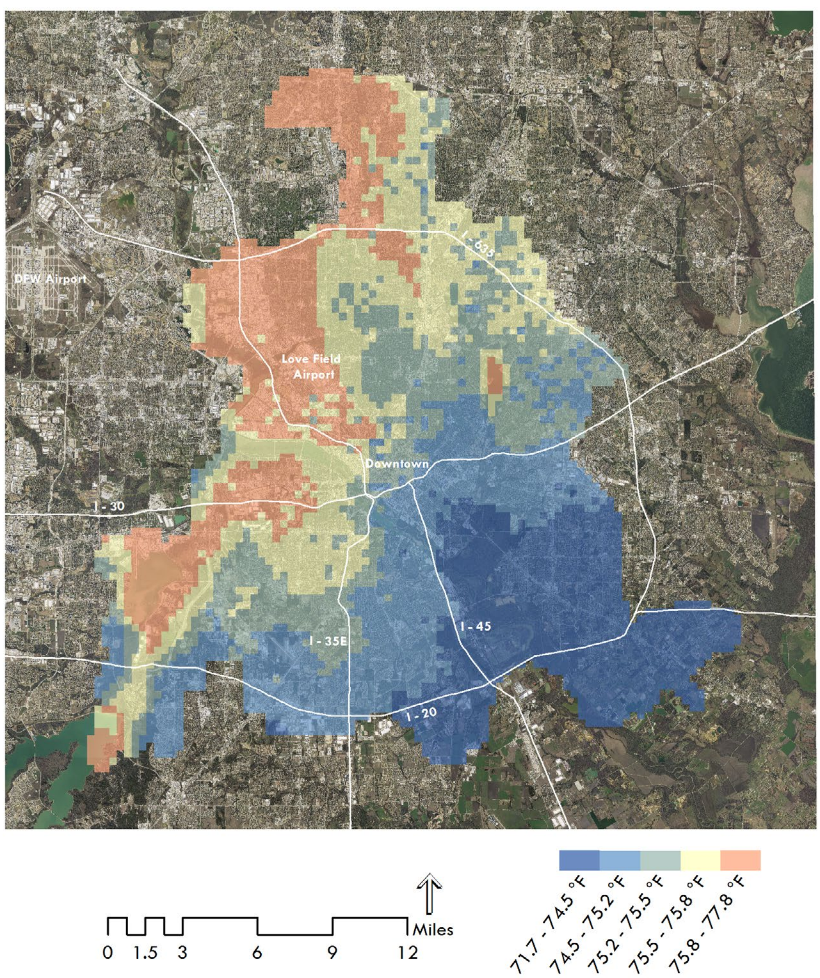


Figure 3.8 Warm season (May through September) average daily low temperature (°F) in Dallas

In contrast to the daily high temperature map, Figure 3.8 reveals a smoother or more uniform distribution of temperatures across the city. While the daily high temperature for one zone can occur at a different time than another, due to differential shading or cloud cover, daily low temperatures are more likely to be recorded during the same hour during the night, and thus the spatial distribution of temperatures is more uniform. Average low temperatures are found to range from approximately 72 to 78°F, depicting a less intense maximum nighttime heat island of about 6°F over the warm season.

The distribution of nighttime temperatures show a gradual decrease in temperatures moving from northwest to southeast, and are influenced by regional urbanization to the west of downtown. While hotspot zones tend to be characterized by extensive impervious cover, other factors, such as topography, may play a role in the elevation of daily low temperatures. The daily low temperature map reveals numerous residential zones characterized by elevated night temperatures and associated heat risk, with the coolest areas falling into less populated suburban and agricultural zones to the southeast.

3.2.2 Tree Loss Scenario: As discussed in Section 2.2.4, a recent study projects that the most rapid future development in Dallas, coupled with the most extensive loss of tree canopy, will occur in neighborhoods largely situated to the south of the Downtown district. Through the Tree Loss scenario, neighborhoods listed in Table 2.2 are assumed to lose 11% of present day tree canopy, while land cover in other regions of the city remain unchanged from the Current Conditions scenario. Figures 3.9 and 3.10 illustrate how tree canopy changes across Dallas in response to the Tree Loss and Greening scenarios.

The climate model results find that continued tree loss in Dallas influences both the range of warm season high temperatures and the spatial distribution. As shown in Figure 3.11, the range of average high temperatures increases modestly, to a maximum value of 101°F, 0.5°F higher than the Current Conditions scenario. The most pronounced change can be seen to the south east of the Downtown district, where the zone of highest temperatures continues into the far southern and eastern reaches of the city.

Also revealed by Figure 3.11, when compared to the Current Conditions map for high temperatures (Figure 3.7) is a new hotspot in the north eastern quadrant of the city, along I-635. The emergence of a hotspot in this zone is somewhat unexpected, as no additional tree loss was assumed to occur in this area under the Tree Loss scenario. While land cover changes are expected to most directly influence temperatures in the zone in which they occur, it is important to note that land cover changes in one region of the city can influence temperatures elsewhere due to the fluid dynamics of the local atmosphere. Remote effects of land cover change can be particularly pronounced during the hottest period of the day, when convective movements of heated air are maximized.

The Tree Loss scenario estimates the potential impacts of continued land development of temperature across Dallas, and, as such, serves as a business as usual scenario for our study. While no specific period of time is associated with an additional loss of 11% of the current tree canopy, this extent of tree loss could be realized over the next decade or two. As such, Figure 3.12 maps the potential changes in daily high temperatures that could be experienced around Dallas in response to tree loss in just 16 neighborhoods over the next 20 years or so.

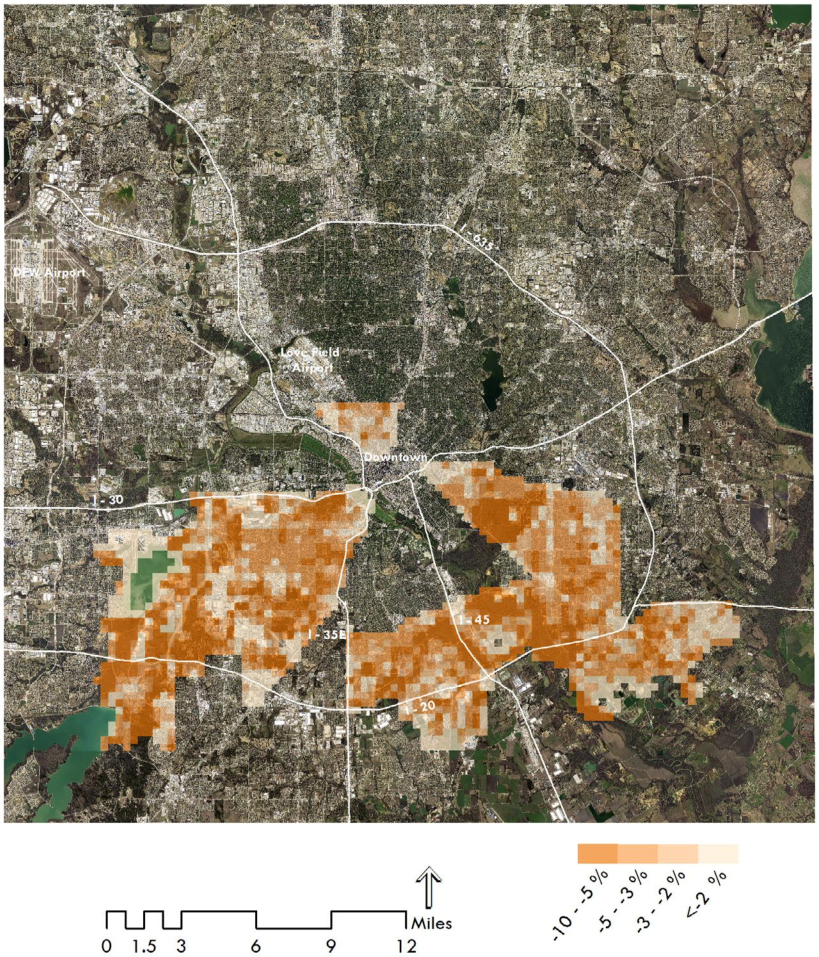


Figure 3.9 Lost tree canopy under Tree Loss Scenario as percentage of ½ km^2 grid cell

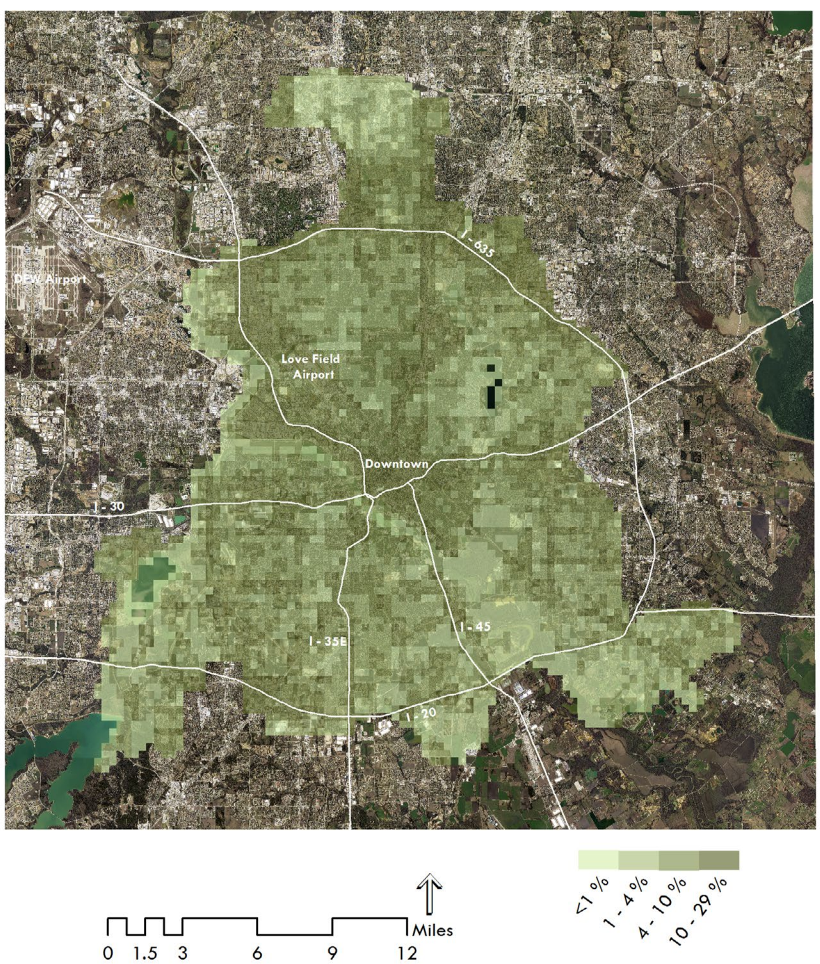


Figure 3.10 New tree canopy under Greening Scenario as percentage of ½ km^2 grid cell

What these results suggest is that the influence of tree loss on high temperatures is in many zones is mixed, with some areas experiencing a modest increase in temperatures in contrast with other areas experiencing a modest decrease in temperatures - an outcome that may result from an increase in surface reflectivity with the loss of dark, sunlight-absorbing tree canopy. On the whole, however, there are many more zones experiencing an increase in temperatures greater than 1°F than experiencing a decrease in temperatures of similar magnitude. And most of the zones of highest temperature gain are found to the south of the Downtown district, where tree loss is assumed to be occurring.

Figures 3.13 and 3.14 illustrate the distribution of average daily low temperatures in response to the Tree Loss scenario. The results suggest that, in contrast to daily high temperatures, low temperatures during the warm season are uniformly increased in response to continued tree loss over time. A trend towards warmer temperatures at night can present a greater human health threat than rising daily high temperatures, in that continued warm temperatures into the night can prolong periods of stress on the cardiovascular and respiratory systems as they work to maintain a narrow range of core body temperature.

As discussed in Section 2, the daily high and low temperatures associated with the Tree Loss scenario are used as a reference case for estimating temperature differences under the three heat mitigation scenarios next discussed. In short, our study considers two potential futures for Dallas over the next 10 to 20 years. A first in which tree canopy is lost through business as usual development, and a second in which tree canopy is either maintained at current levels or expanded through tree planting. Use of the Tree Loss scenario temperature maps as our baseline for computing temperature change resulting from the heat management scenarios accounts for a likely continuing rise in regional temperatures absent the development of a heat management plan for the city.

3.2.3 Greening Scenario: Through the Greening scenario, new tree canopy is added along roadways, within parking lots, and over other types of surface paving. In total, 249,234 over-story trees were added through the Greening scenario, equivalent to about 45 square kilometers of new canopy in total.

As illustrated in Figures 3.15 and 3.16, the Greening scenario was found to reduce temperatures relative to the Tree Loss scenario throughout much of the City of Dallas. Extensive zones to the north of Downtown, along the I-35 hotspot, to the southeast between the I-45 and 1-20 interstates, and to the north east along the I-635 interstates are found to experience a reduction in daily high temperatures of more than 1°F, and in many areas greater than 2°F. This reduction in high temperatures with tree planting was accompanied by a modest increase in temperatures, almost entirely less than 1°F in a smaller number of grid cells largely clustered to the immediate south and west of Downtown.

As noted above, because green plants tend to have a low albedo or reflectivity, due to the dark hue of leaf area, an increase in green cover can lead to an increase in solar absorption during daylight hours. Green plants are very effective in offsetting a reduced albedo through the process of evapotranspiration, through which the release of water vapor cools leaf surfaces and the surrounding air, but this process may slow during the hottest period of the day, as green plants work to conserve water. As a result, green strategies are often found to be less effective in reducing daily high temperatures than daily low temperatures.

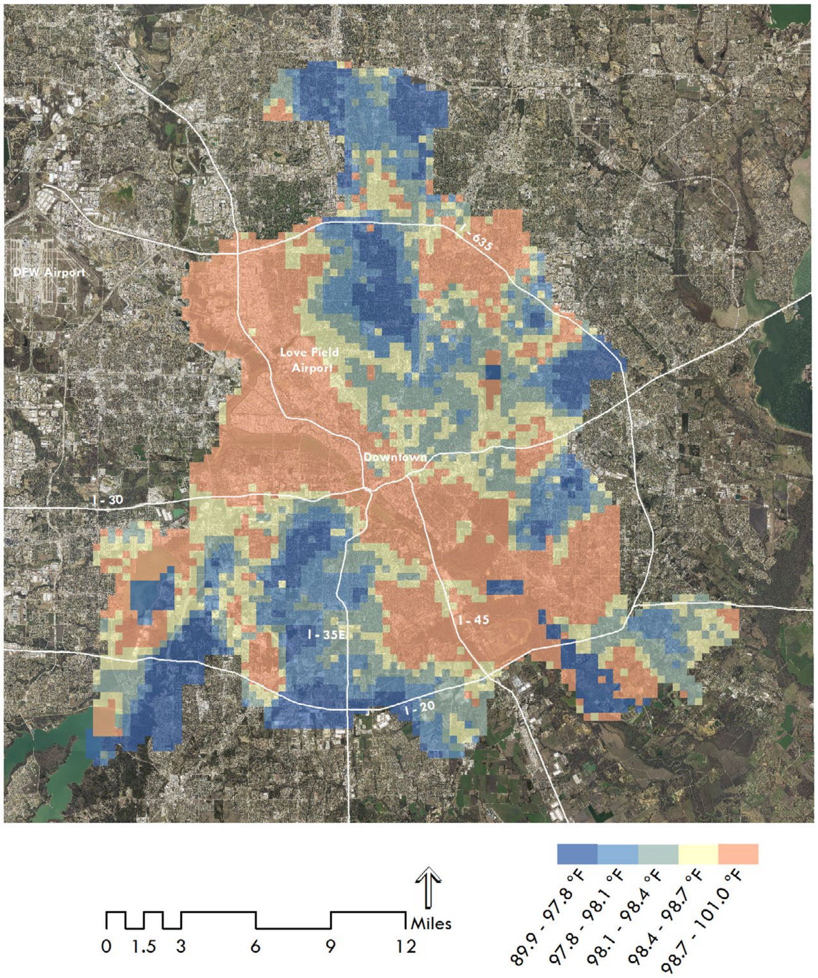


Figure 3.11 Warm season (May through September) average daily high temperature under the Tree Loss scenario

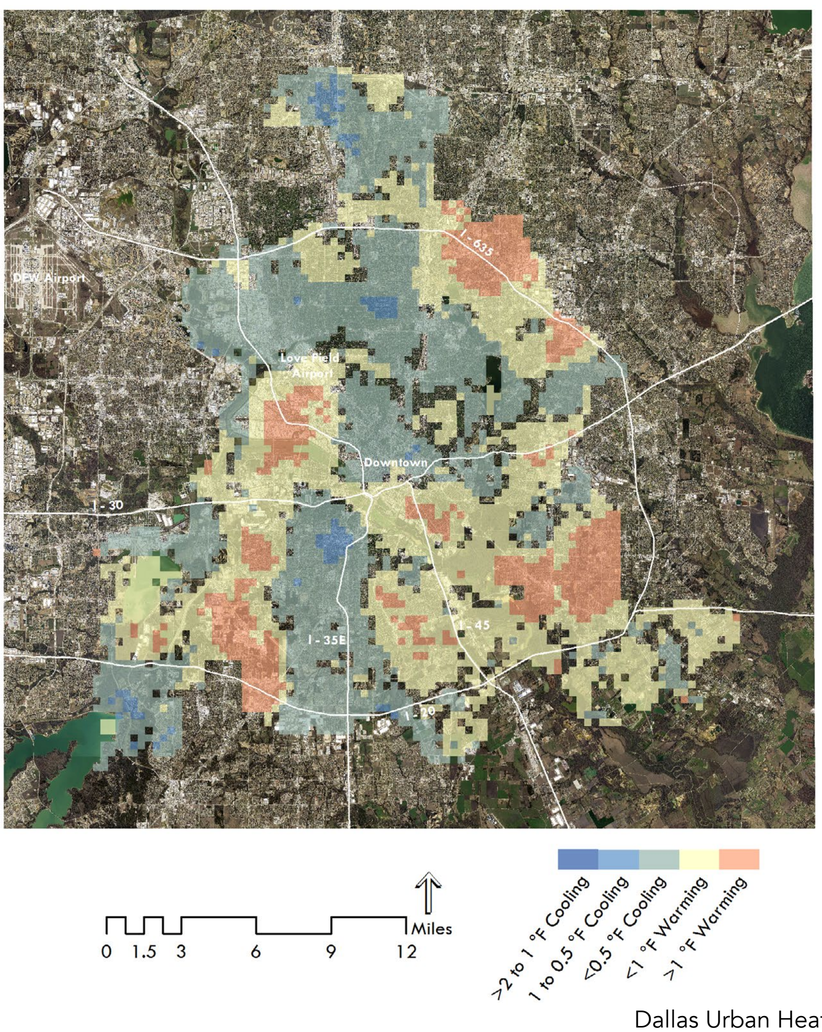


Figure 3.12 Warm season (May through September) average daily high temperature difference under the Tree Loss scenario relative to Current Conditions

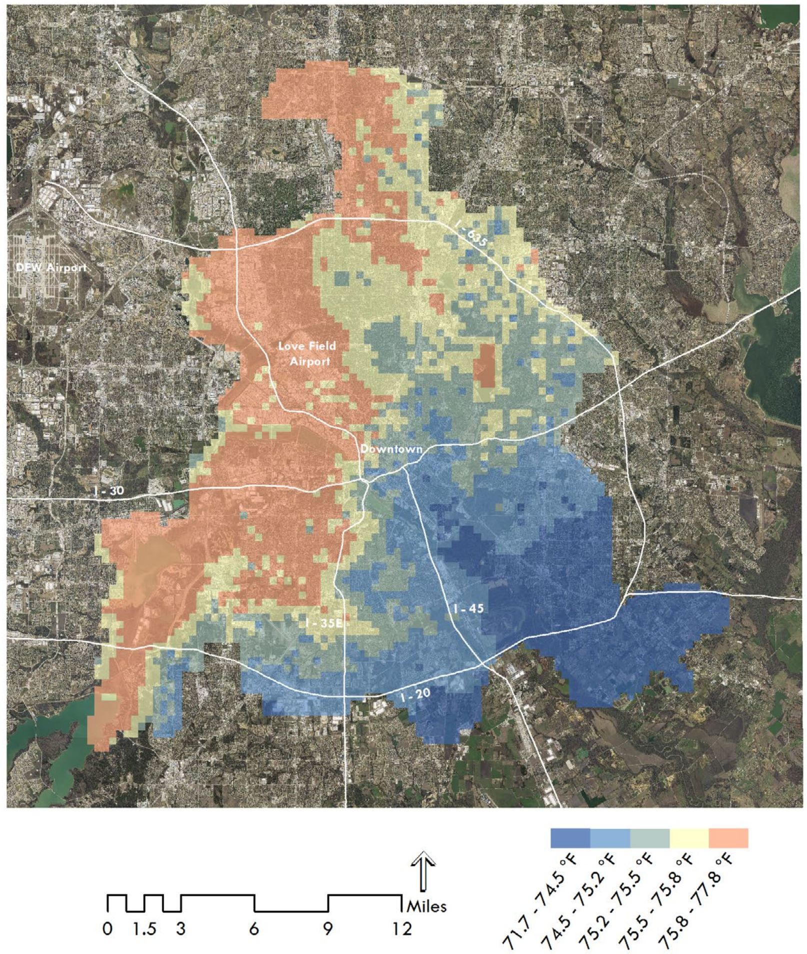


Figure 3.13 Warm season (May through September) average daily low temperature under the Tree Loss scenario

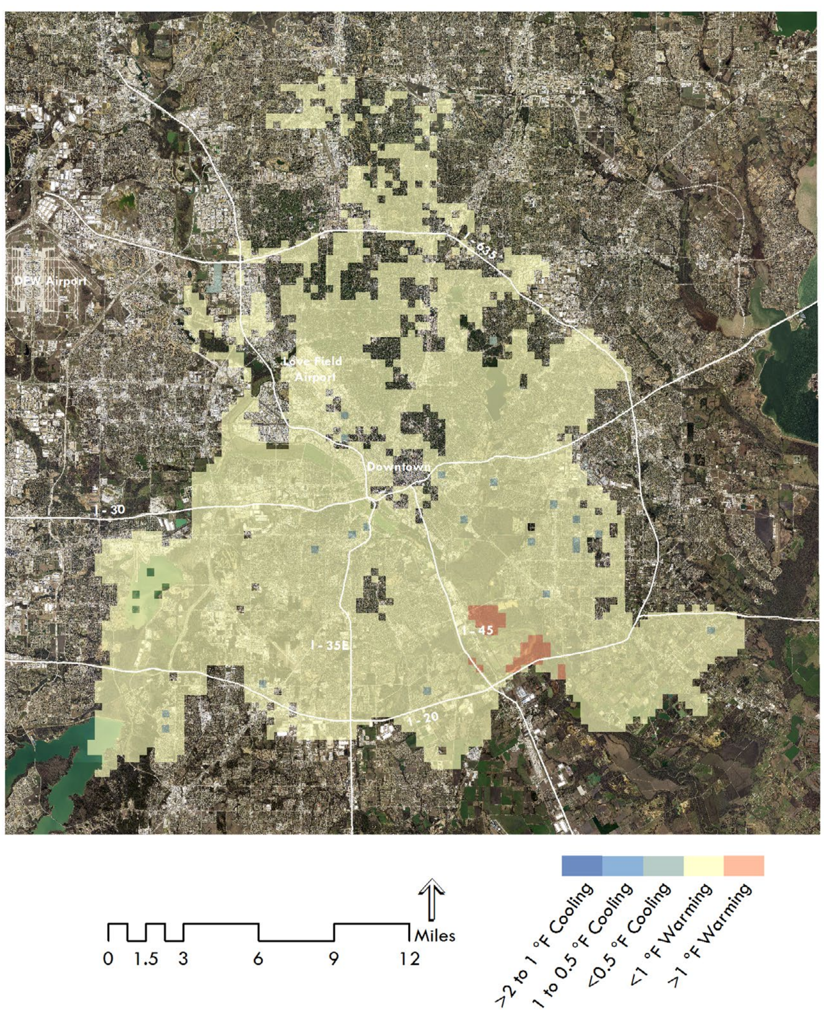


Figure 3.14 Warm season (May through September) average daily low temperature difference under the Tree Loss scenario relative to Current Conditions

But the overall trend revealed for daily high temperatures in response to tree planting is one of predominant cooling around Dallas - often in some of the hottest areas of the city.

Similar to the Tree Loss scenario, a more uniform effect of tree planting on temperatures is illustrated by Figures 3.17 and 3.18, which present the results for average daily low temperatures during the warm season. With continued evapotranspiration into the evening hours and diminished effects of low reflectivity, green plants play a key role in lowering nighttime temperatures in the urban core. These maps attest to the significant cooling effect of tree planting for nighttime temperatures around Dallas, an effect that in many instances exceeds 2°F. While a reduction in temperatures of only two degrees may seem modest on a hot day, it is important to emphasize that these maps illustrate the reduction in average temperatures over a period of more than 150 days during the spring and summer. Given that there is considerable variation in these temperature reductions from day to day, the daily reductions in both high and low temperatures can be much greater. On many days during the 2011 summer, for example, an expanded tree canopy was found to reduce daily high and low temperatures by more than 10 to 15°F in some locations.

Spatially, the cooling benefits of tree planting for nighttime temperatures is well distributed across Dallas, with much of the most pronounced cooling in areas projected to experience rapid development over time. Tree preservation and planting are found to be effective strategies for lower temperatures in and around the Downtown district and along the I-35 corridor to the north of Downtown, the city's most intense hotspot. Based on this pattern of cooling from tree planting, we expect to find benefits for public health also well distributed across the city.

3.2.4 Cool Materials Scenario: Conversion of building roof and street paving materials to highly reflective "cool" materials is found to have a significant impact on temperatures across the City of Dallas. As presented in Figures 3.19 and 3.20, average daily high temperatures throughout the study area, particularly in the downtown district and across west side neighborhoods, are significantly lower the current conditions in most areas of the city. Figure 3.20 shows that virtually every grid cell in the study area experiences a reduction in daily high temperatures in response to the coating of roadways and rooftops with sunlight-reflecting materials. Areas falling into the darkest blue zones experienced a cooling effect of at least 1°F and, in many cases, in excess of 3°F. Presented here as a warm season average, the reduction in high temperatures on single hot days was found to be in excess of 10 to 15°F in some locations. While significant cooling is observed in the Downtown districts and industrial hotspots, the most extensive cooling is found in residential zones outside of these hotspots. The lowest levels of cooling, or a few instances of a modest temperature increase, are generally observed in areas lacking impervious surfaces, such as water bodies or forested areas.

Similar to high temperatures, average daily low temperatures during the period of May through September of 2011 would have been lower under the Cool Materials scenario throughout virtually all of Dallas (Figures 3.21 and 3.22). The magnitude of reductions in daily low temperatures, however, is not as great as the reductions in daily high temperatures. Due to the fact that cool material coatings are engineered to reflect away incoming sunlight, and thus cool land surfaces through a reduction in the quantity of solar energy absorbed, this approach is less effective in reducing temperatures during the nighttime hours, although cooling benefits achieved during the day carry over into the evening. Figure

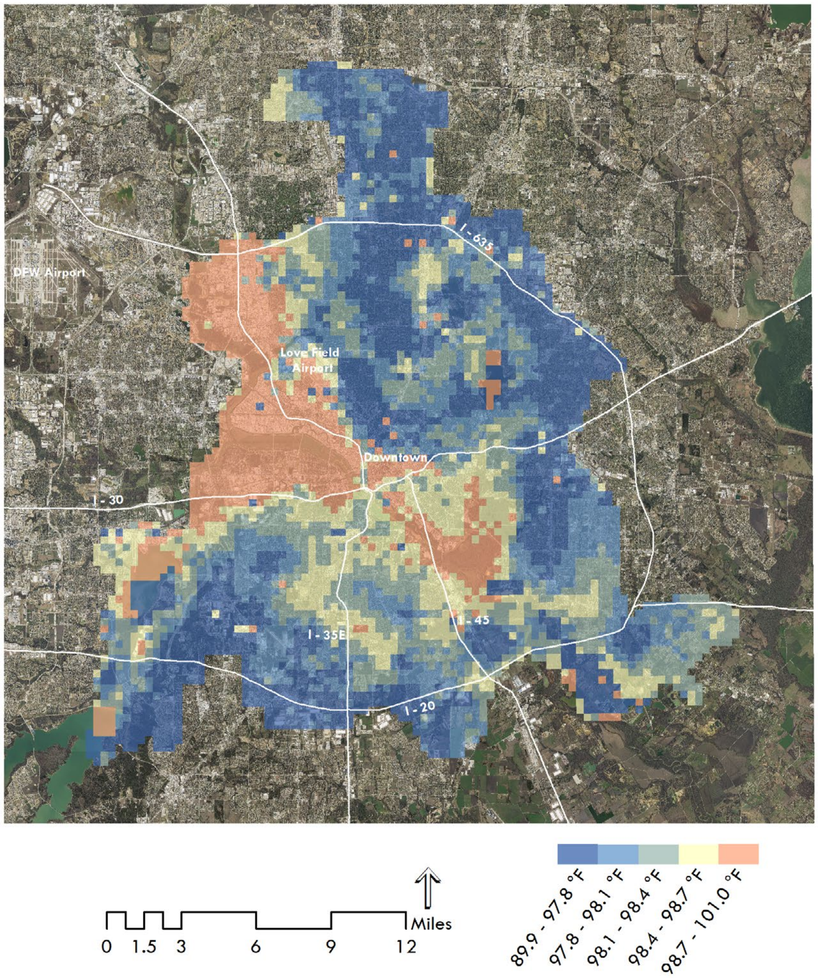


Figure 3.15 Warm season average daily high temperature under the Greening scenario

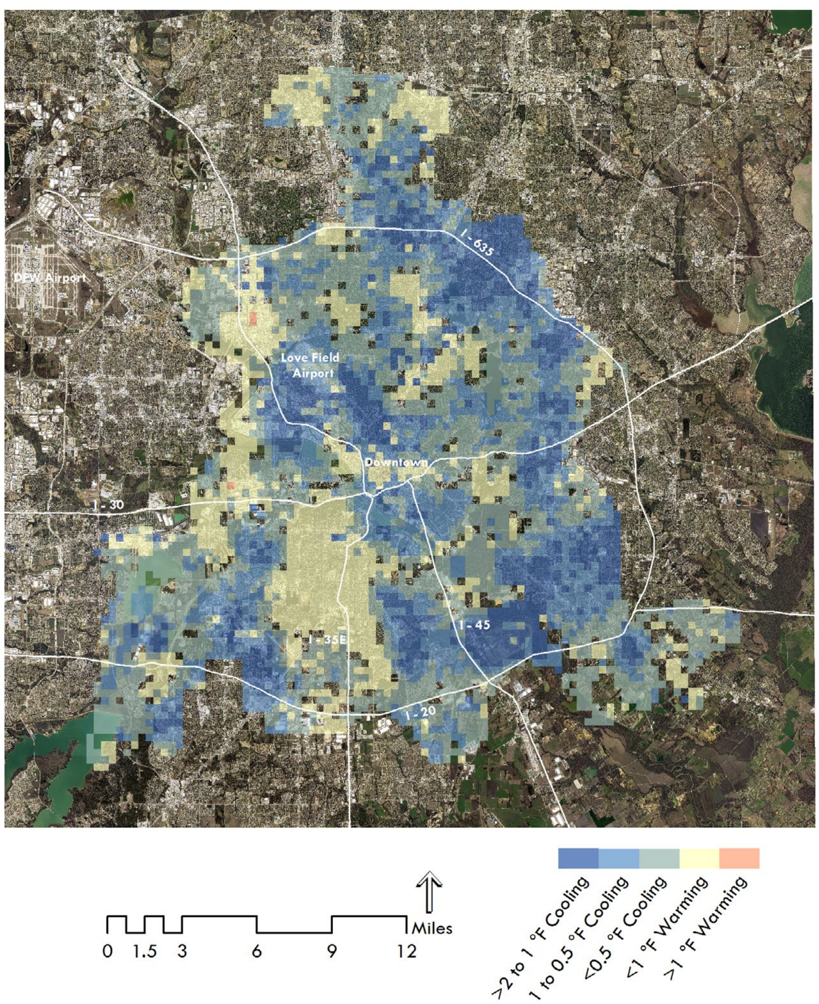


Figure 3.16 Warm season average daily high temperature difference under the Greening scenario relative to the Tree Loss scenario

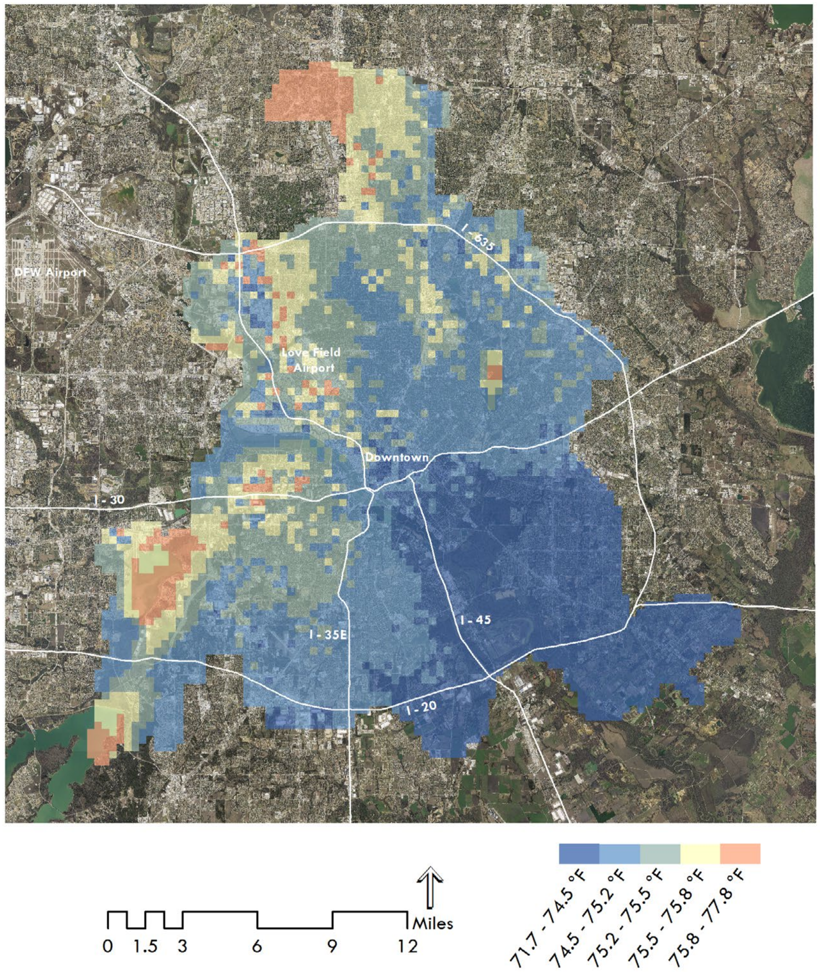


Figure 3.17 Warm season average daily low temperature under the Greening scenario

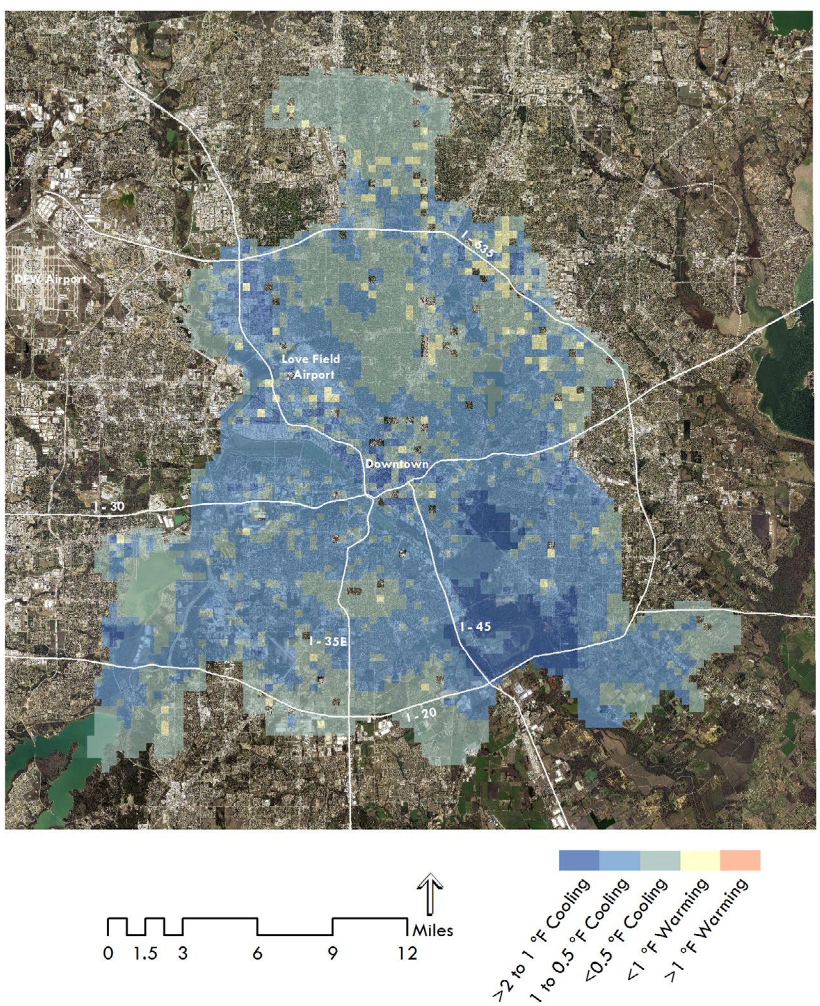


Figure 3.18 Warm season average daily low temperature difference under the Greening scenario relative to the Tree Loss scenario

3.22 finds reductions in warm season nighttime temperatures of 0.5 to 1°F in most of the Downtown I-35 corridor hotspots, with reductions in low temperatures for single hot nights to be in excess of 15°F in some areas.

Overall, the average reduction in daily high temperatures under the Cool Materials scenario is greater than under the Greening scenario, with the average city-wide reduction in median high and low temperatures found to be 130 and 12% greater than under the Greening scenario, respectively. As such, the results presented in Figures 3.15 through 3.22 raise an important question for heat management planning in Dallas: Are cool materials more effective in lowering urban temperatures than green cover? On average the Cool Materials scenario is indeed more effective in lowering both high and low temperatures region-wide than is the Greening strategy. The principal reason for this outcome, however, is simply due to the much greater land area impacted by the cool materials conversions than the addition of new tree cover, as driven by the study's assumptions.

Overall, the total area converted to cool materials is about 2.5 times as great as the total area converted to new tree canopy: 230 square kilometers of new cool surfaces vs. 92 square kilometers of new green cover. This outcome results from the assumption that all roadway and roofing areas can be converted to cool materials at the time of routine resurfacing at only modest additional expense. Converting all roofing and paving areas to green cover, by contrast, would be both infeasible and prohibitively expensive, and so only about a third of the city's total impervious cover is overlaid with new tree canopy.

Are cool materials more effective in lowering temperatures than green cover when comparing equivalent conversion areas? Our results find each new square meter of tree canopy to be 1.6 times as effective in reducing average summer temperatures as each new square meter of cool materials, and 3.3 times as effective in reducing nighttime temperatures, to which carry the greatest threat to human health. As such, new tree canopy is much more effective in reducing air temperatures than cool materials for project sites of equal area. The challenge for green strategies is in increasing the total area subject to green conversions at a cost that is comparable to cool materials conversions.

3.2.5 Combined Strategies Scenario: The final scenario simulated for the 2011 warm season entailed a combination of the Greening and Cool Materials scenarios. As each of these classes of strategies can be largely implemented independent of one another, the combined effects of each land cover strategy can be modeled simultaneously. In doing so, tree planting strategies are assumed to be implemented first, with all remaining unshaded surface paving and non-vegetated rooftop areas then converted to cool materials. The results of this final combined strategies scenario are presented in Figures 3.23 through 3.26.

As expected, the Combined Strategies scenario was found to have a more significant effect on citywide temperatures than either stand-alone heat management strategy. Similar to the effects of cool materials on daily high temperatures (Figure 3.19), the Combined Strategies scenario almost entirely offsets the expansive daytime hotspots over the Downtown district and I-35 industrial corridor to the northwest. Figure 3.23 finds moderately more daytime cooling in the Downtown district and to the southeast of Downtown than under the Cool Materials scenario. Relative to business as usual development under the Tree Loss scenario, the Combined Strategies scenario yields cooling in almost every zone of the Dallas

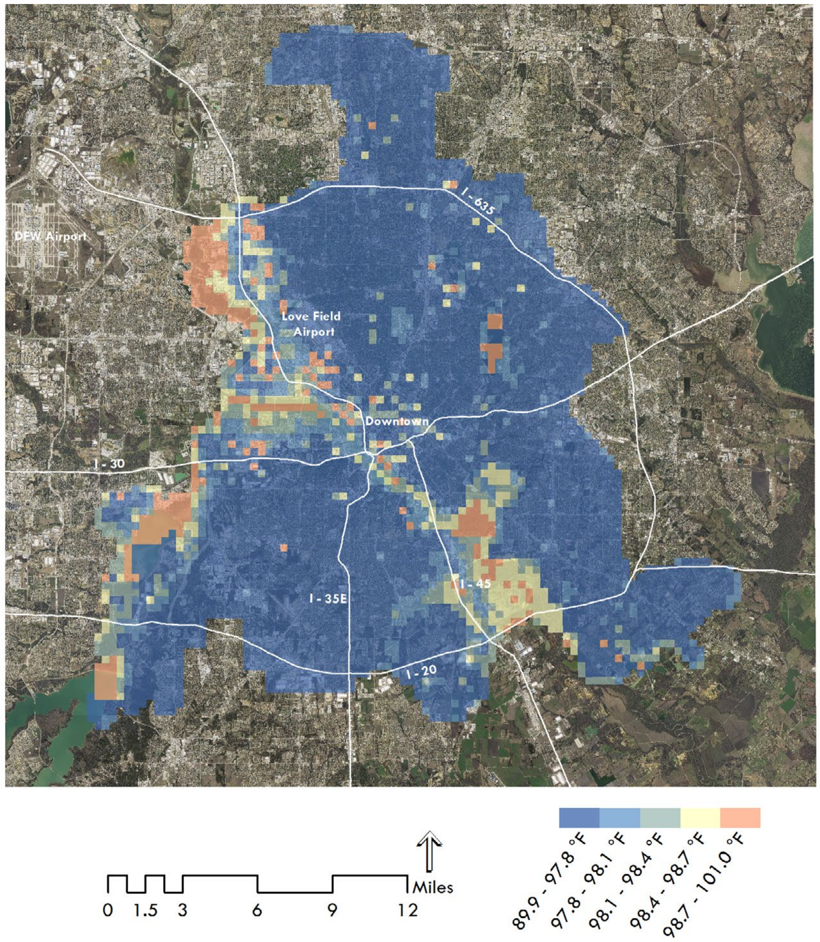


Figure 3.19 Warm season average daily high temperature under the Cool Materials scenario

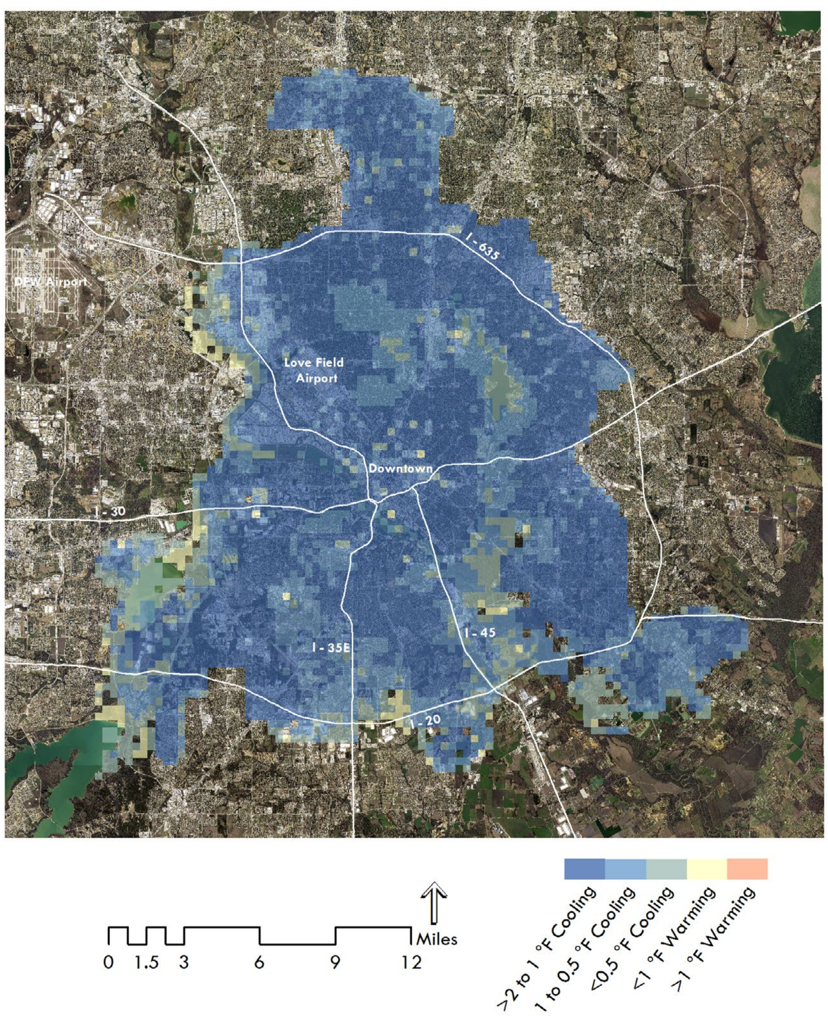


Figure 3.20 Warm season average daily high temperature difference under the Cool Materials scenario relative to the Tree Loss scenario

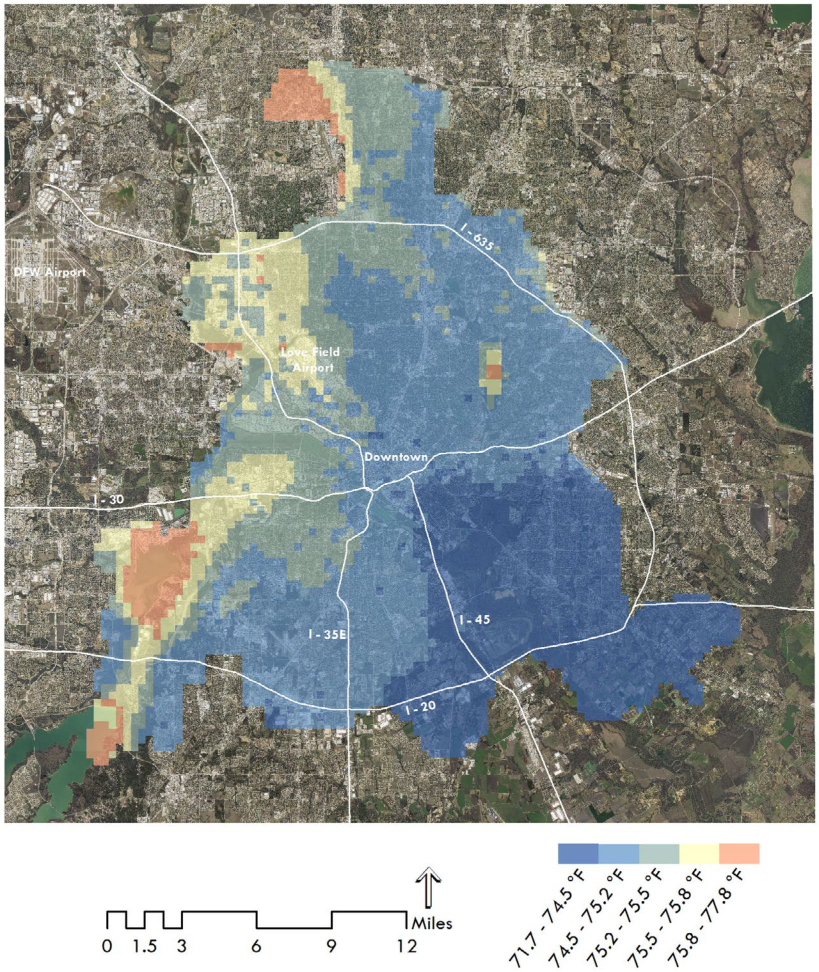


Figure 3.21 Warm season average daily low temperature under the Cool Materials scenario

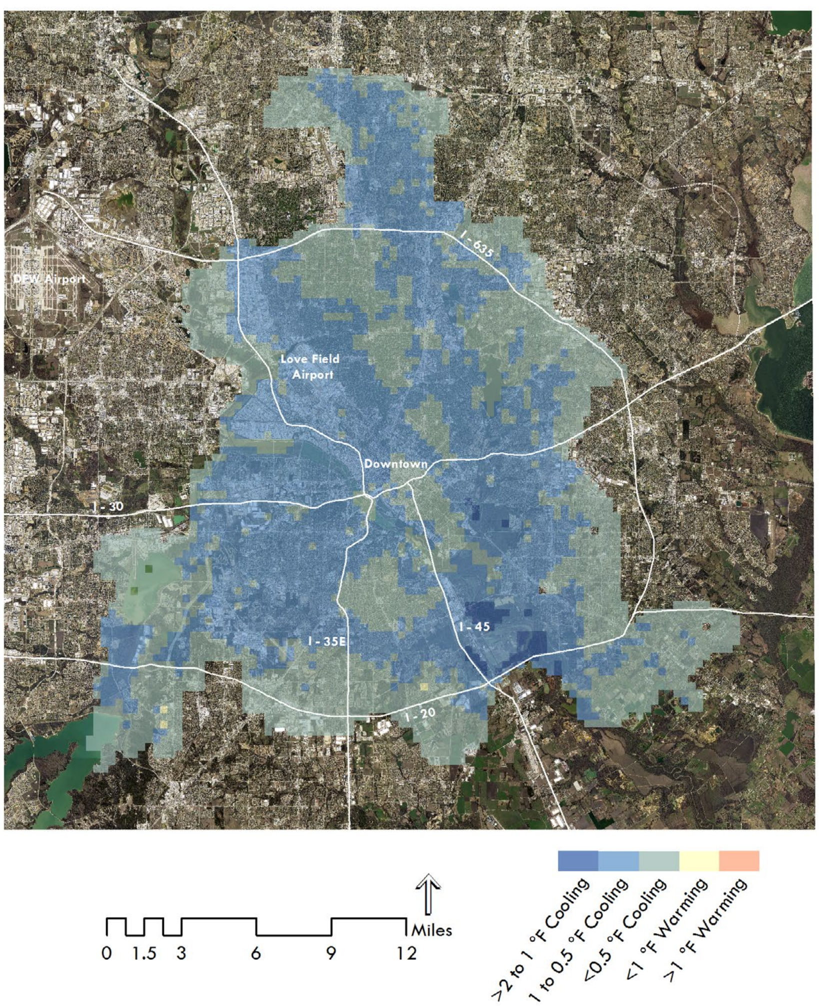


Figure 3.22 Warm season average daily low temperature difference under the Cool Materials scenario relative to the Tree Loss scenario

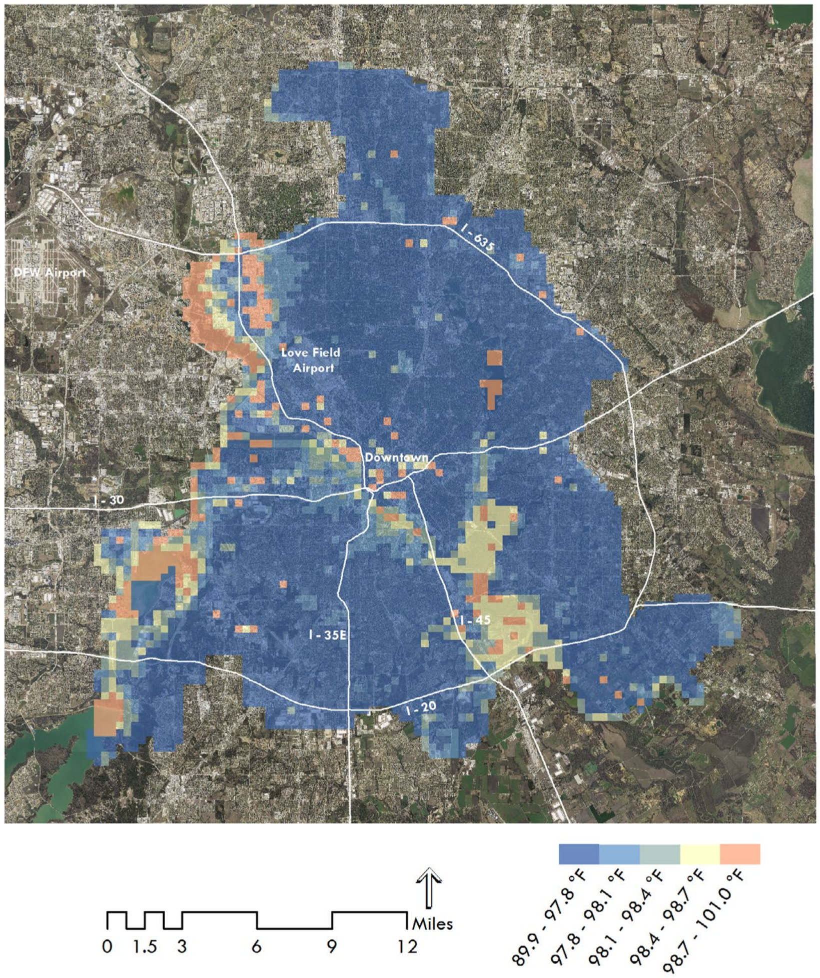


Figure 3.23 Warm season daily high temperature under the Combined Strategies scenario

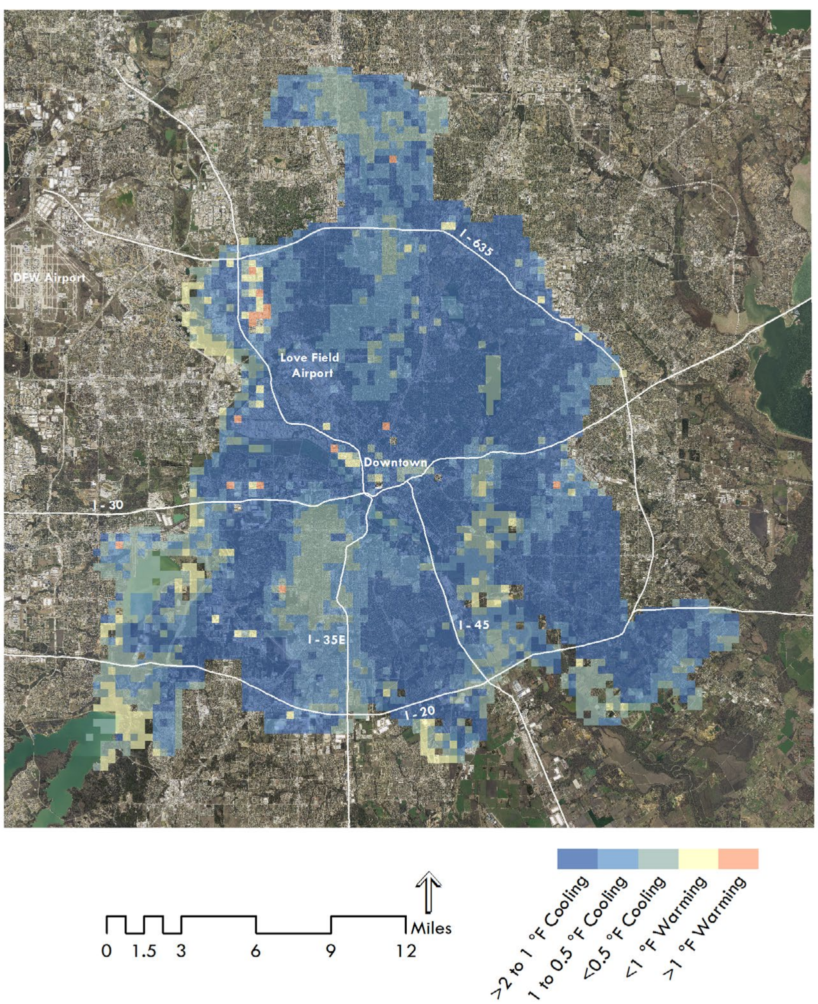


Figure 3.24 Warm season daily high temperature difference under the Combined Strategies cenario relative to the Tree Loss scenario

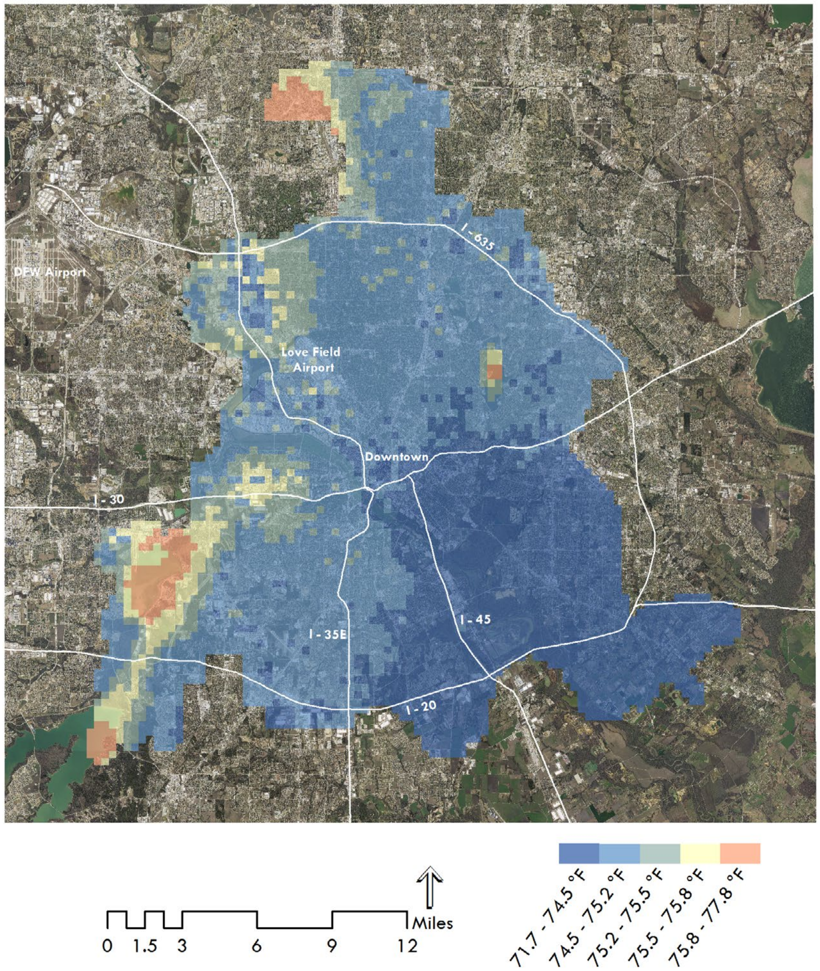


Figure 3.25 Warm season daily low temperature under the Combined Strategies scenario

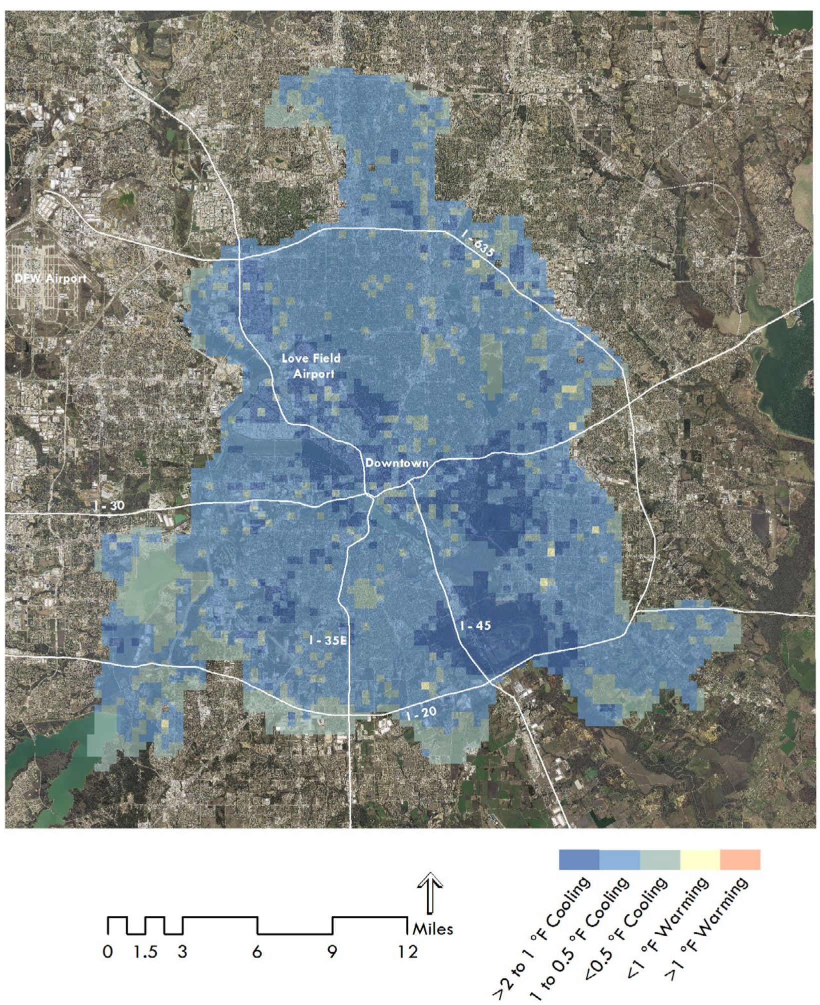


Figure 3.26 Warm season daily low temperature difference under the Combined Strategies scenario relative to the Tree Loss scenario

study area - with the reduction in average warm season high temperatures exceeding 10°F in some areas.

Under the Combined Strategies scenario, significant reductions in daily low temperatures occur across a more spatially expansive zone than in response to any other scenario. In particular, as illustrated in Figure 3.25, pronounced nighttime hotspots in the Downtown and I-35 corridor zones are almost entirely offset, yielding substantial reductions in heat exposure during the night, when heat risk is elevated.

Presented in Figures 3.24 and 3.26, the area around the Downtown district experiences an average reduction in daily high and low temperatures of more than 1°F and in excess of 15°F in some areas on hot summer days. While less spatially expansive hotspots persist in a few zones, such as over lager water bodies at night, virtually all populated zones of the Dallas area are found to benefit from urban tree canopy and cool materials strategies when combined.

The results for the Combined Strategies scenario clearly demonstrate that the simultaneous implementation of urban tree canopy and cool materials strategies more effectively manages urban heat exposure than any single approach to mitigation. This outcome likely can be attributed to the complementarity of the Cool Materials and Greening scenarios, through which the increased reflectivity of impervious surfaces in proximity to tree canopy offsets the low albedo of the darkly hued vegetation, while green plant materials in proximity to cool paving and roofing enables evaporative cooling in these zones. Furthermore, the two approaches tend to achieve maximum benefits at different times during the day, with cool materials yielding maximum benefits during the daylight hours, when the receipt of solar energy is greatest, and with tree canopy providing more extensive cooling benefits during the night.

The complementarity of these strategies is strongly supportive of an integrated approach to heat management in Dallas. Overall, the heat management scenario modeling finds the most densely populated zones of the Dallas area to experience temperatures as much as 10°F greater than nearby rural areas during the day, and as much as 6°F warmer during the night. This magnitude of warming in the urban core is higher than observed in most large US cities and constitutes a growing threat to public health as the city and region continue to develop and warm.

To assess the spatial pattern of heat risk, we present in Section 4 of this report the results of a heat health effects assessment for the 2011 warm season in response to the Current Conditions and three heat management scenarios.

4 Population Vulnerability Assessment

The air temperature analysis presented in Section 3 of this report finds the enhancement of reflective surfaces and vegetative cover to significantly reduce warm season temperatures, with the most concentrated benefits resulting in the urban and industrial cores. In this section of the report, we present the results of a population heat vulnerability assessment, through which the distribution of warm season heat-related deaths during the summer of 2011, in response to the different heat management scenarios, is modeled and mapped.

As discussed in Section 1, hospital records on the number of individuals succumbing to heat-related illnesses each year provide an incomplete record of heat deaths, as extreme temperatures tend to exacerbate underlying health conditions, such as cardiovascular or respiratory illness. For this reason, we make use of a published statistical association between temperature and excess mortality developed for the Dallas region to assess how different climate scenarios may influence heat-related mortality [45].

In this section, we first present the modeled distribution of heat-related mortality across the Dallas area under the Current Conditions scenario. We then present a set of maps detailing the distribution of heat deaths across the city in response to each heat management scenario.

4.1 Health Impacts under the Current Conditions Scenario

Heat-related deaths in Dallas are estimated through the application of a heat risk factor derived from a study of temperature and mortality rates from all causes over time. By determining how many additional deaths result in the region for every one-degree increase in temperature, it is possible to estimate the number of heat-related deaths likely to occur on each day in the May through September warm season. Applying this approach, 112 residents of the City of Dallas are estimated to have died from a heat-related cause during the 2011 warm season.

It is important to note that some percentage of the heat-related deaths found to occur in Dallas are not attributable to the region's heat island. As rural areas of the region were also found to experience very hot temperatures, although less frequently than the urbanized area, some fraction of the region's heat mortality is simply a product of regional hot weather. To determine what number of heat-related deaths are attributable to the region's heat island, and thus may be potentially avoidable through heat management strategies, we estimate the number of heat-related deaths that would have resulted over the summer of 2011 had Dallas exhibited temperatures experienced in rural areas outside of the city. Over the 2011 warm season, we find 53 deaths, or just under 50% of the total number of heat-related deaths, to be a product of the region's heat island.

Figure 4.1 presents the distribution of these heat deaths across Dallas under current conditions, classifying each grid cell as having a low, medium, or high number of heat-related deaths. The map shows the highest zones of heat mortality to be clustered mostly in residential zones to the northeast and southwest of the Downtown district. Due to the fact that the number of heat-related deaths occurring in any grid cell will be a product not only of the temperature of the grid cell, but of the total population and demographic composition of each cell as well, the distribution of heat mortality is not expected to overlap directly with the distribution of high temperatures. Zones in which the highest levels of heat mortality tend to be characterized by high temperatures, large population sizes, and a higher than average number of elderly residents.

For reference, Figures 4.2 and 4.3 present the distribution of total population and the population of residents over the age of 65 by grid cell across Dallas. These maps find the distribution of heat mortality presented in Figure 4.1 to closely follow the distribution of population, with lower rates of mortality in the Northwest Dallas and Southeast Dallas areas where fewer residents live relative to other neighborhoods. By contrast, mortality levels are high in North Dallas and the Far North zone, where population and, in particular, a greater proportion of senior residents live.

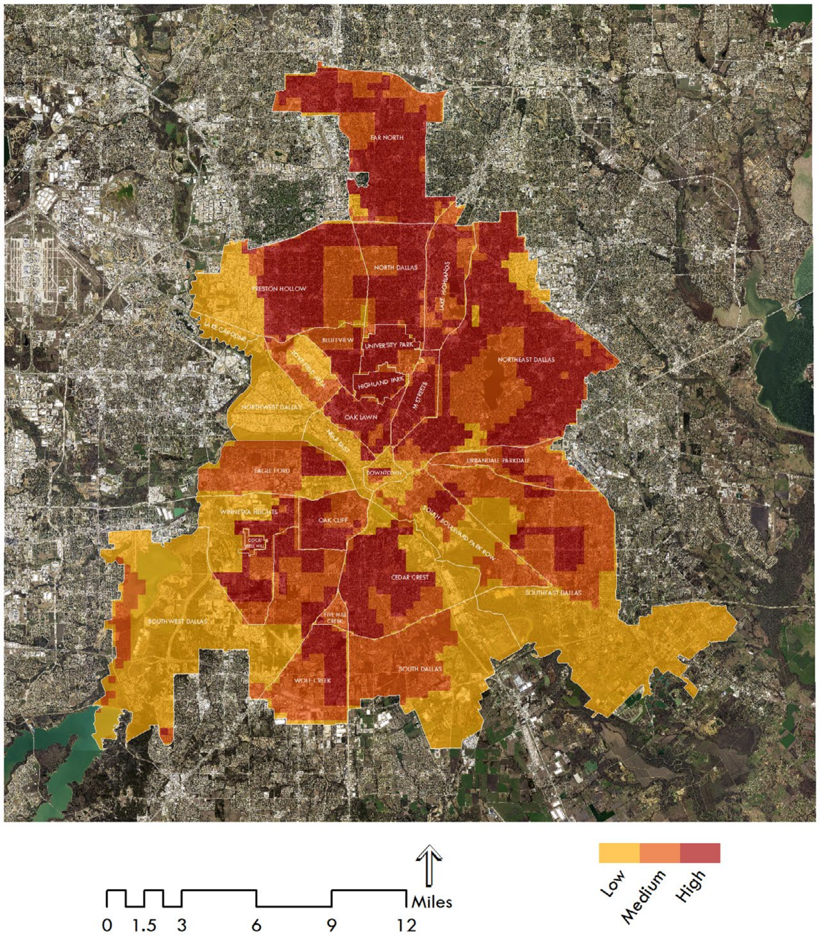


Figure 4.1
Distribution of heat deaths during May to September 2011 by ½ km^2 grid cell in Dallas

To illustrate how the number and spatial distribution of heat mortality changes under each heat management scenario relative to the Tree Loss scenario, Figures 4.4 through 4.6 present the number of avoided heat deaths per grid cell in response to the various individual and combined heat management strategies. All grid cells are classified as No Benefit, indicating that no reduction in heat-related deaths occurred in response to a heat management strategy, Low Benefit, indicating modest reductions in heat mortality, and High Benefit, indicating significant reductions in heat-related mortality following the implementation of a strategy or combination of strategies.

The benefits of increased tree canopy for heat mortality are presented in Figure 4.4. Consistent with the spatial pattern of heat mortality, increased tree canopy is found to offset mortality most significantly to the north and northeast of the Downtown district, with a more modest impact on health in Southeast Dallas, where the population is more sparse. Tree planing and preservation strategies immediately north of Downtown, in the Oak Lawn, Highland Park, and University Park districts, where residential densities are relatively high, were found to be effective in offsetting heat-related mortality.

Overall, the Greening scenario was found to reduce heat-related mortality relative to the Tree Loss scenario by 12% across the City. The health benefits of tree planting and preservation strategies are well distributed across residential areas, with limited benefits found in areas dominated by industrial and commercial land uses or extensive parklands.

Under the Cool Materials scenario (Figure 4.5), through which the reflectively of all

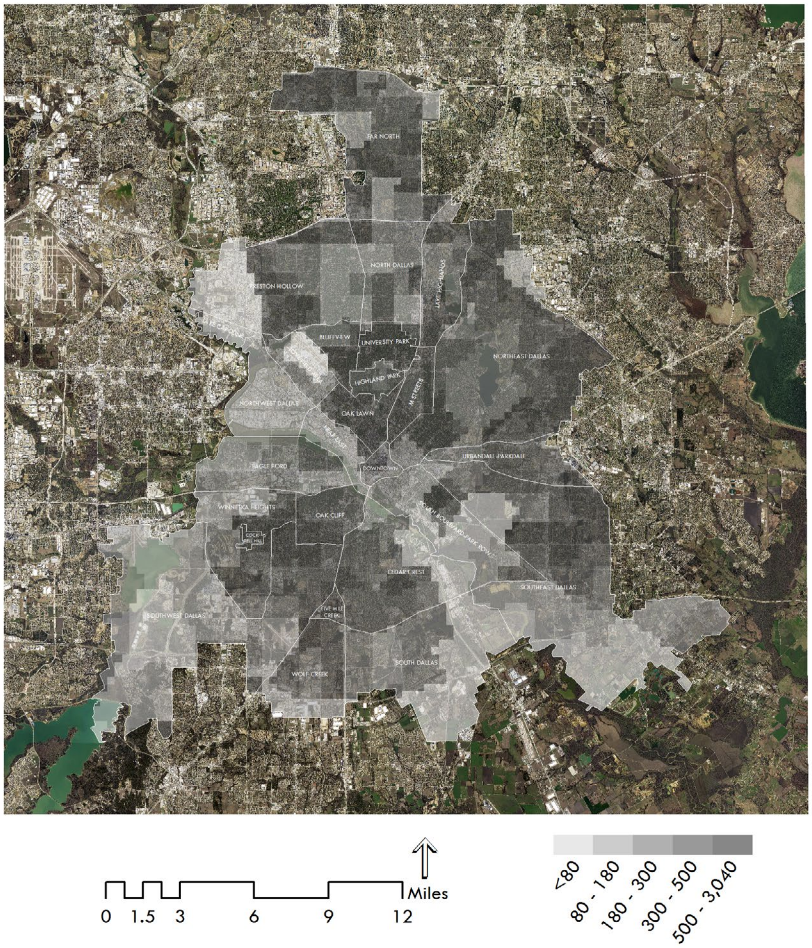


Figure 4.2
Distribution of total population by ½ km² grid cell in Dallas

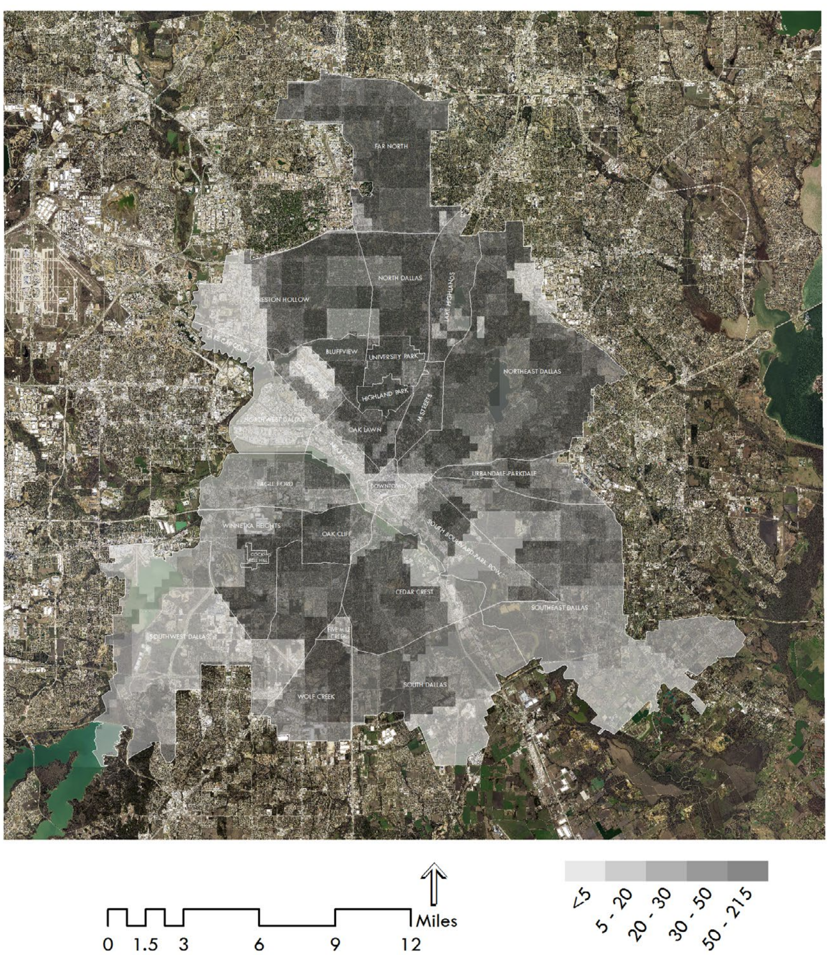


Figure 4.3
Distribution of population over 65 by ½ km² grid cell in Dallas

rooftops, streets, parking lots, and other paved surfaces is increased, most residential zones of the urban core are found to experience a modest to large reduction in heat mortality. Overall, heat deaths are reduced by 16% across Dallas under the Cool Materials scenario relative to the Tree Loss scenario. Similar to the Greening scenario, the benefits of cool materials for offsetting heat mortality are found to the north and northeast of the Downtown district, with more extensive health benefits observed to the southeast in, for example, the Oak Cliff, Winnetka Heights, and Cedar Crest districts.

As expected, less populated industrial zones, parklands, and agricultural zones do not exhibit measurable reductions in heat mortality due to the small number of residences found in these zones.

The combination of tree planting and preservation with the installation of cool roofing and paving materials across Dallas was found to yield greater health benefits for the City than either individual heat management strategy. Overall, the combination of heat management strategies was found to reduce heat mortality relative to the Tree Loss scenario by 22%. This represents a significant reduction in heat-related mortality that would measurably increase the population's resilience to heat wave conditions in future years.

As presented in Figure 4.6, areas within almost every neighborhood district fall within the High Benefit category, with the zone of health benefits reaching more extensively into the Southeast Dallas than either the Greening or Cool Materials scenarios. Some reduction in mortality was found to occur across all residential zones. When averaged across Dallas as a whole, the Combined Strategies scenario was found to reduce the UHI-attributable heat mortality in 2011 from 51 deaths to 40.

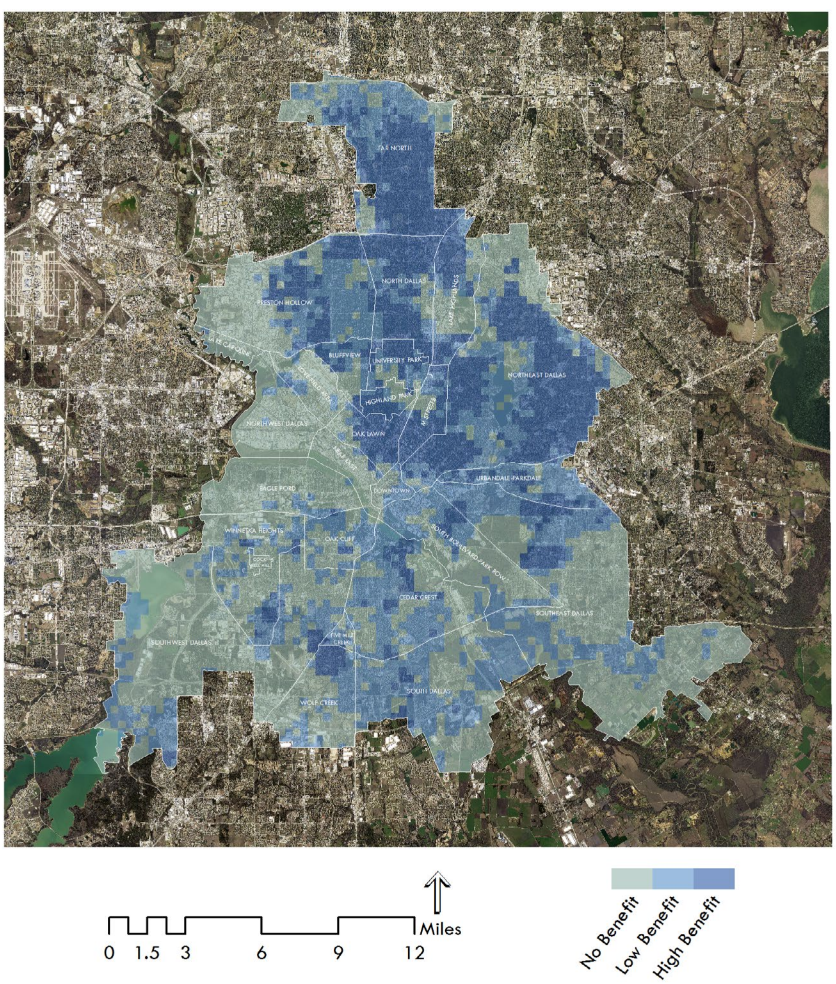


Figure 4.4
Distribution of avoided heat deaths under the Greening scenario relative to the Tree Loss scenario during May to September 2011 by ½ km² grid cell in Dallas

A more than 20% reduction in heat mortality across the City of Dallas suggests that urban heat management should be a component part of the region's heat wave preparedness planning. While most major cities in the US have provisions in place to respond to the occurrence of extreme heat events, no major US city has developed and adopted an urban heat management or mitigation plan designed to lessen the intensity of heat during such events. As extreme heat events have grown more frequent, more intense, and of a longer duration over recent decades – trends that are projected to continue into the future – it is imperative that county emergency management officials and city planners broaden heat wave response plans to include long term heat mitigation measures, in addition to short term heat wave early warning systems and the provision of neighborhood cooling centers, among other response strategies deployed immediately in advance of or during an extreme heat event [46]. The results of this analysis highlight the zones wherein such interventions should be targeted, as well as the areas wherein the most significant health benefits may be realized.

As a final component of this study a series of district level recommendations for tree planting, tree preservation, and cool materials installation will be developed. We believe the comprehensive and spatially resolved information on heat management and public health developed by this study will provide Dallas with a strong scientific foundation to become a national leader in urban resilience and heat adaptation planning.

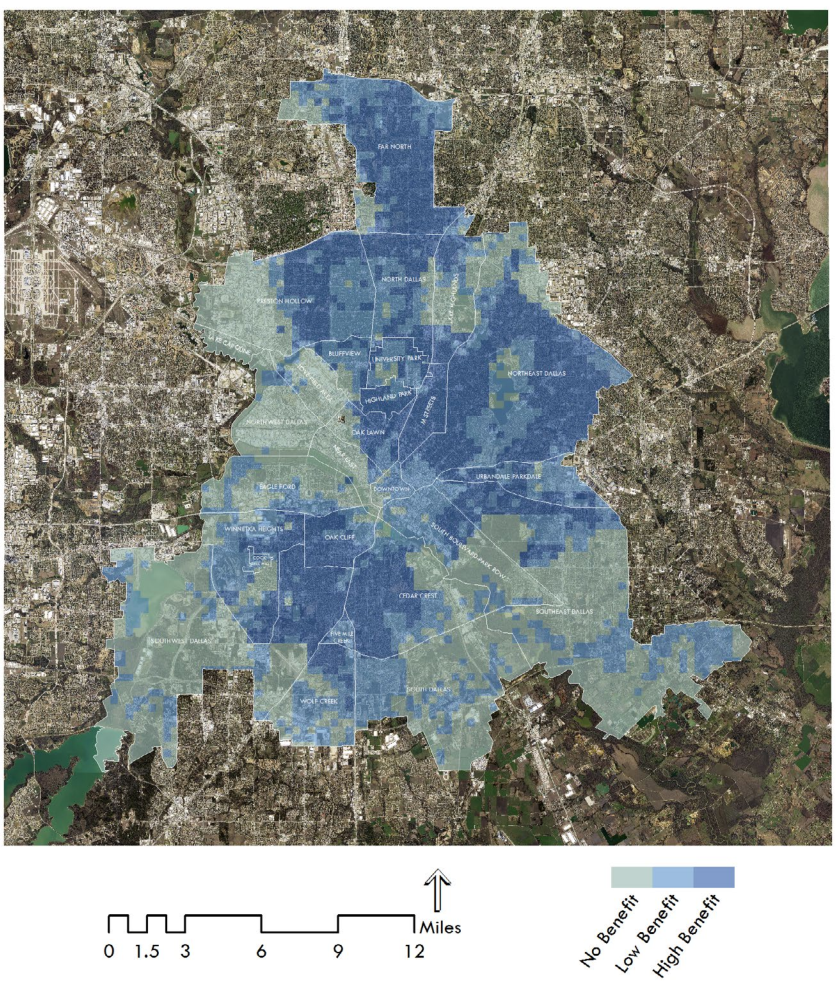


Figure 4.5
Distribution of avoided heat deaths under the Cool Materials scenario relative to the Tree Loss scenario during May to September 2011 by ½ km^2 grid cell in Dallas

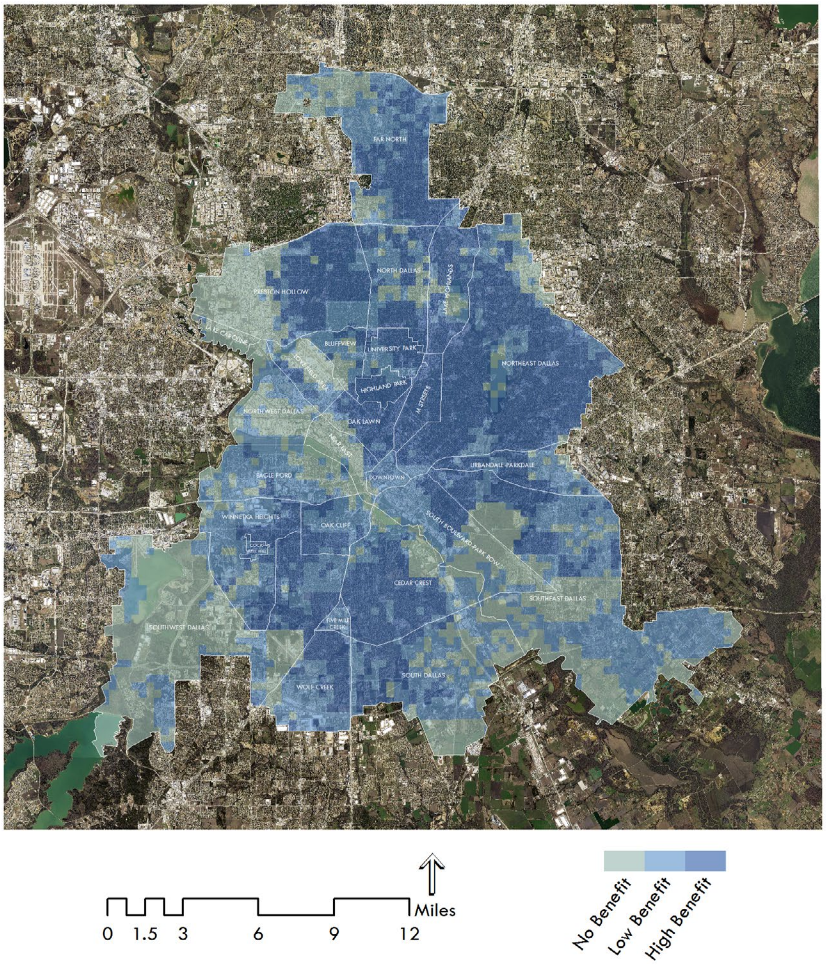


Figure 4.6
Distribution of avoided heat deaths under the Combined Strategies scenario relative to the Tree Loss scenario during May to September 2011 by ½ km^2 grid cell in Dallas

5

Heat Management Recommendations

The urban scale climate modeling carried out for this study yields a number of key policy-relevant findings to inform heat adaptation planning. In this section of the report, four general policy recommendations are first highlighted, followed by the presentation of specific neighborhood-based planting and cool materials recommendations associated with the heat management scenarios developed for the analysis. These neighborhood-based recommendations provide the basis for developing a comprehensive heat management plan for Dallas.

5.1 Study Recommendations for Heat Management

Recommendation 1: The principal recommendation of the report is that the City of Dallas undertake comprehensive urban heat management planning in the near term to adapt to a rising incidence of extreme heat. The results of this study, in concert with previous work focused on Atlanta, Louisville, Philadelphia, and Phoenix, conclusively show that physical changes to the built environment and landscape of large cities can measurably reduce population exposure to ambient heat over time, and consequently reduce heat-related mortality during the warm season. While Dallas County and the City of Dallas have in place emergency response plans to manage extreme heat events, these plans emphasize short-term actions to reduce heat injury through the provision of public services, such as emergency cooling centers, rather than through lessening the intensity of heat exposure through physical changes to the built environment designed to moderate ambient temperatures. We find the preservation and expansion of the urban forest, combined with the use of highly reflective roofing and paving materials, to reduce summer afternoon temperatures by as much as 15°F and to reduce warm season heat mortality by more than 20%. To attain these environmental and health benefits, the City of Dallas and community partners such as the Texas Trees Foundation should develop an urban heat management plan to target heat-adaptive measures to neighborhoods most at risk to extreme temperatures and heat illness.

Recommendation 2: Tree planting and preservation throughout the City of Dallas and Dallas County should serve as the principal adaptive strategy to lessen heat exposure and moderate rising temperatures over time. Policies promoting enhanced vegetative cover, particularly in residential and retail zones, are likely to yield a higher cooling benefit per unit of area installed than cool materials, and are more likely to provide greater secondary benefits, such as improved stormwater management and enhanced property values. Through this study we find every square meter of added tree canopy to provide average cooling benefits 3.5 times greater than for each added square meter of reflective roofing or paving, and 7.5 times the cooling benefits of reflective materials at night (when heat risk is maximized), suggesting that expanded tree canopy is the most effective strategy available for heat management in Dallas. Potential policy tools to enhance green cover across Dallas include public incentives for tree planting and preservation, the establishment of minimum green cover standards by zoning class, and a public and privately-funded tree planting campaign, as recently undertaken by Denver, Houston, Los Angeles, and New York.

Recommendation 3: Policies promoting the resurfacing of roofing and surface paving to cool, high-albedo coatings and materials should be adopted or expanded to lessen solar absorption and heat in highly impervious zones where the opportunities for tree planting are limited or cost-prohibitive. While cool roofing and paving strategies were found to be less effective at moderating temperatures when implemented across equivalent conversion areas, our analysis found the total land area in Dallas available for cool materials conversions to be greater than the land area available for tree planting in proximity to impervious cover, such as along streets and within parking lots, by a ratio of more than six-to-one. Because such approaches are well suited to areas with limited planting opportunities, cool materials strategies should be prioritized in industrial, shipping/transport, and commercial zones. We recommend that the City of Dallas adopt policies incentivizing or requiring minimum albedo levels at the time of routine roof, street, and parking lot resurfacing and for all new development and resurfacing projects.

Recommendation 4: Greening and cool materials strategies should be implemented in concert to yield the greatest heat management and health benefits for Dallas. While each of these heat management strategies was found to yield measurable cooling and health benefits when implemented independent of the other, the combination of strategies was found to outperform any single management approach, yielding significant temperature reductions in all districts across the City. This finding demonstrates that the greening and cool materials strategies are reinforcing of one another, as opposed to being redundant in their effects.

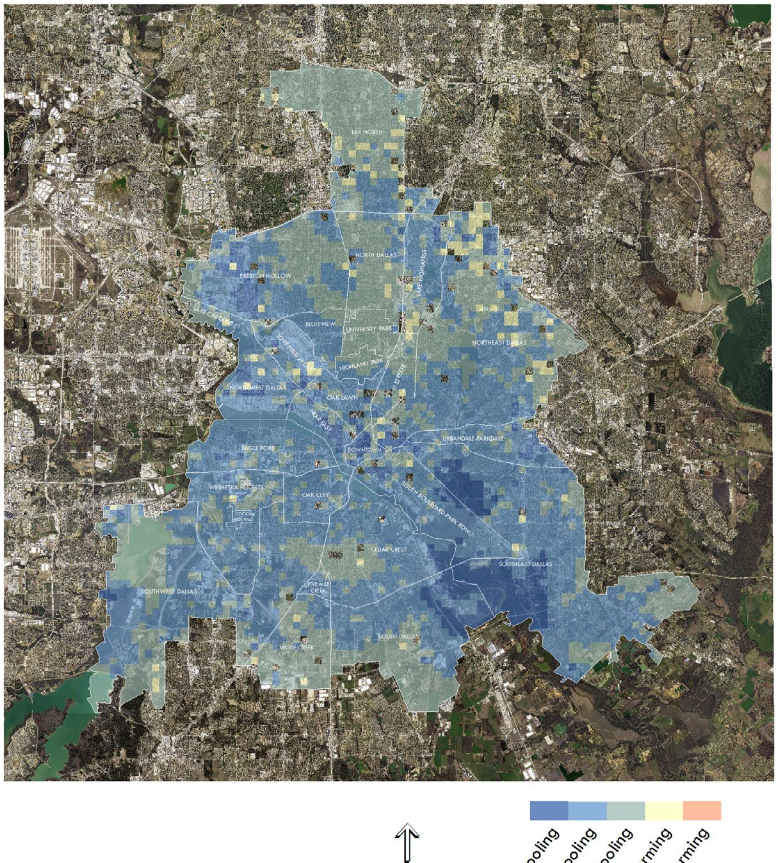
Importantly, the benefits of the combined approaches were found to be equal to or greater than the sum of the independent effects. As illustrated in Figure 5.1, the area of the city subject to average, warm season cooling benefits of 0.5°F or greater is far more expansive than the comparable zone for the greening or cool materials strategies when implemented independently, and covers almost the entirety of Dallas. Likewise, the zone of maximum cooling benefits in proximity to the Downtown district is also far greater in area than under either independent strategy. In response to this key finding, we recommend that greening and cool materials strategies be implemented in concert at the neighborhood level, with specific canopy and cool materials goals being set at neighborhood level through an urban heat management plan. The remainder of this concluding component of the report recommends such specific goals by neighborhood.

5.2 Neighborhood-Based Strategies

To assist in the achievement of Recommendation 4, that both vegetative and cool materials strategies be implemented, we present quantitative tree planting, cool roofing, and cool paving targets for each Dallas neighborhood. Sections 5.2.1 through 5.2.3 of this report quantify the area of land conversions associated with each heat management strategy developed for the climate modeling scenarios. For each strategy, land conversion targets are presented for each neighborhood as a whole, as well as for the zones of low and high heat mortality benefits within each neighborhood, as illustrated in Figures 4.4-4.6. We recommend that the land conversion targets associated with high benefit zones for heat mortality be adopted as a short term goal (1 to 5 years) and the land conversion targets reported for each neighborhood as a whole be adopted as a long term goal (6 to 10 years).

The results of our study find a combination of tree planing and cool materials use to reduce temperatures relative to the tree loss, or business as usual scenario, in every neighborhood in Dallas. Table 5.1 presents the neighborhood temperature changes for the full warm season (May to September) of 2011 in response to each scenario. On average, mean daily temperatures were found to be reduced by almost 1°F at the neighborhood level, with temperature differences on single hot days exceeding 10°F in some areas. The recommended tree planting and cool material enhancements that follow are consistent with the modeled neighborhood changes reported in table 5.1.

5.2.1 Tree Planting: For the Greening scenario, tree canopy was added along roadways and in parking lots. Table 5.3 reports the approximate number of trees added to each neighborhood, assuming an average canopy size consistent with a fully mature deciduous tree (50 foot crown diameter). Across the Dallas area as a whole, a tree canopy area equivalent to about



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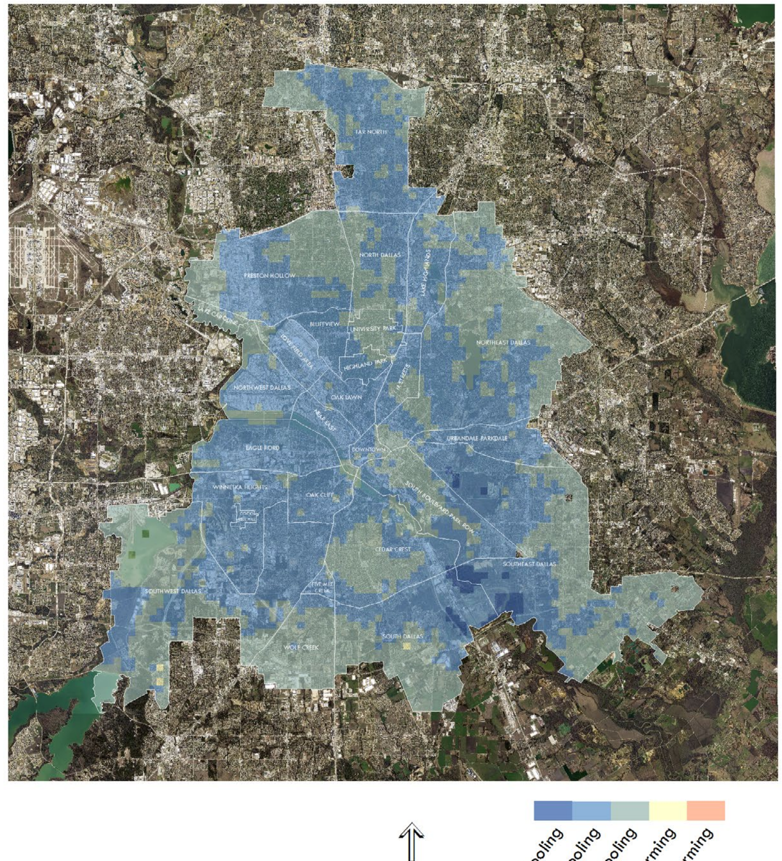

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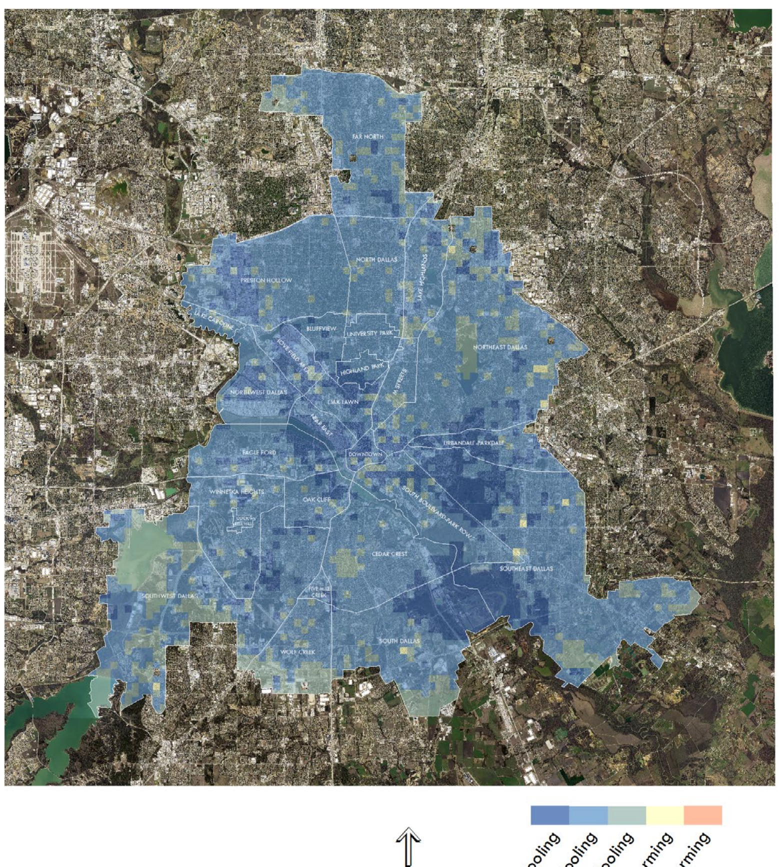

C

Figure 5.1: Enhanced nighttime cooling benefits resulting from heat management strategies. Scenario in each panel as follows: A) Greening; B) Cool Materials; C) Combined Strategies

249,234 mature trees was added to existing tree canopy cover through the Greening scenario. An average of about 9,200 trees was added to each neighborhood, with the greatest number of new trees – 32,300 – added to Northeast Dallas. About 3,700 trees were added through the Greening scenario to the Downtown district, where average tree canopy cover is low relative to other large US cities.

A total of about 56,000 new trees was added to neighborhood areas where the health benefits of heat management strategies were found to be highest, highlighting this number as a minimum tree planting goal to maximize health benefits in the most vulnerable areas of Dallas. On average, the city, neighborhood groups, and individual homeowners would need to plant about 2,000 trees per neighborhood to minimize health risks in highly vulnerable areas only.

The tree planting goals for Dallas highlighted by this study are significantly lower than goals set by several other large US cities – cities including Houston, Los Angeles, and New York – where campaigns to add 1,000,000 new trees are underway of have been completed. While a more ambitious tree planting goal than 250,000 new trees may be expected to yield greater cooling and other environmental benefits than suggested by this study, this number would be a central component of a city-wide initiative to lower temperatures and reduce heat mortality.

5.2.2 Cool Roofing: Through the Cool Materials scenario, all building roofing areas were converted to highly reflective surfaces. Table 5.2 estimates the number of large cool roofs installed per Dallas neighborhood by assuming a roof area of 1,000 m^2 (approximately 10,000 ft^2) per cool roof installation.

Across Dallas as a whole, the equivalent of more than 95,000 cool roofs of 1,000 m^2 in area are assumed to be in place under the Cool Materials scenario. An average of 3,500 cool roofs was assumed to be in place in each neighborhood, with the greatest potential for cool roof development found to be in Northeast Dallas, due to extensive industrial development in this region.

Of the 95,000 cool roofs assumed to be in place city-wide, about 44,000 of these were located in zones found to exhibit high benefits for heat mortality under the Combined Strategies scenario. The targeting of new cool roof installations to these zones is likely to yield the greatest near-term benefits for public health.

Model policies for increasing the use of cool roofing materials in US cities include a cool roofing ordinance in Los Angeles, California, and a requirement that all new commercial buildings in Houston install reflective roofing materials.

5.2.3 Cool Paving: Table 5.4 presents the area of cool paving assumed to be in place by neighborhood under the Cool Materials scenario. As discussed in Section 2.2.3, all roadway paving, parking lots, and other surface paving are assumed to exhibit a moderately reflective albedo but less reflective than the roof areas converted to cool materials. Across Dallas area as a whole, about 13,500 hectares or 135 square kilometers of surface paving is converted to cool materials. An average of 500 hectares of paving is converted to cool materials per whole, about 13,500 hectares or 135 square kilometers of surface paving is converted to cool materials. An average of 500 hectares of paving is converted to cool materials per neighborhood, an area equivalent to the parking lot area of about 120 supermarkets

Neighborhood	Tree Loss	Current Conditions	Cool Materials	Greening	Combined
Bluffview	86.71	0.26	-1.01	-0.72	-0.91
Cedar Crest	86.48	0.14	-0.70	-0.24	-0.77
Cockrell Hill	86.58	0.68	-1.12	-0.49	-1.21
Downtown	86.70	0.03	-0.79	-0.34	-1.13
Eagle Ford	87.14	0.29	-0.86	-0.13	-1.01
Far North	86.18	-0.07	-0.60	-0.27	-0.43
Five Mile Creek	86.15	-0.12	-0.59	0.04	-0.43
Highland Park	86.58	0.16	-0.90	-0.72	-1.07
Lake Caroline	87.14	-0.18	-0.28	0.03	-0.30
Lake Highlands	86.75	0.42	-1.04	-0.67	-1.50
Love Field Area	87.16	0.37	-1.01	-0.61	-1.37
M Streets	86.37	0.07	-0.92	-0.41	-1.27
Near East	87.35	0.45	-1.07	-0.51	-1.37
North Dallas	86.12	-0.13	-0.64	-0.48	-0.59
Northeast Dallas	86.45	0.30	-0.88	-0.56	-1.27
Northwest Dallas	87.34	0.37	-0.82	-0.37	-1.33
Oak Cliff	86.34	-0.17	-0.61	0.20	-0.38
Oak Lawn	86.85	0.18	-0.98	-0.87	-1.36
Preston Hollow	86.65	-0.15	-0.58	-0.16	-0.59
South Boulevard Park Row	86.61	0.40	-0.82	-0.50	-0.96
South Dallas	86.14	0.15	-0.51	-0.48	-0.70
Southeast Dallas	85.90	0.31	-0.65	-0.44	-0.81
Southwest Dallas	86.17	0.12	-0.55	-0.19	-0.49
University Park	86.41	0.14	-0.75	-0.59	-1.04
Urbandale Parkdale	86.20	0.15	-0.80	-0.40	-0.72
Winnetka Heights	86.44	0.32	-0.83	-0.22	-0.79
Wolf Creek	85.84	0.02	-0.55	-0.14	-0.66

Table 5.1 Average mean warm season temperature (°F) by neighborhood under Tree Loss scenario and temperature change by Current Conditions and heat mitigation scenarios.

Neighborhood	Total Trees Planted	Trees Planted Low Benefit Zones	Trees Planted High Benefit Zones
Bluffview	2,091	527	624
Cedar Crest	11,064	5,151	1,367
Cockrell Hill	466	42	0
Downtown	3,690	1,651	57
Eagle Ford	9,930	1,120	47
Far North	15,063	2,329	9,228
Five Mile Creek	1,096	550	153
Highland Park	1,260	189	580
Lake Caroline	1,428	16	0
Lake Highlands	9,748	2,028	3,907
Love Field Area	7,799	991	136
M Streets	4,486	963	3,077
Near East	5,437	351	221
North Dallas	9,423	2,152	6,240
Northeast Dallas	32,353	6,166	15,783
Northwest Dallas	11,111	433	36
Oak Cliff	3,810	1,834	263
Oak Lawn	5,511	628	3,340
Preston Hollow	20,760	4,207	3,100
South Boulevard Park Row	9,987	4,998	521
South Dallas	10,216	5,987	558
Southeast Dallas	20,929	7,239	1,904
Southwest Dallas	23,684	4,282	505
University Park	3,659	1,296	1,658
Urbandale Parkdale	6,685	4,462	1,617
Winnetka Heights	9,856	2,528	630
Wolf Creek	7,691	1,976	503

Table 5.2 Neighborhood tree planting under Greening scenario.

or home improvement stores. Northeast Dallas was found to have the largest area of surface paving available for conversion to cool materials under this scenario.

For zones in which heat management strategies were found to have a high benefit for reducing heat-related mortality, about 5,700 hectares of cool paving were assumed to be in place, or an average of about 200 hectares (about 48 large parking lots) of paving per neighborhood. If the area of cool paving assumed to be in place in high benefit zones only was set as a short-term goal for each neighborhood, the Downtown district would require the 165 hectares or the equivalent of about 40 large parking lots to be resurfaced with cool coatings or materials. Northeast Dallas, the district found to have the most paving available for resurfacing ,would require the equivalent of about 475 large parking lots to be converted.

5.3 Key Findings

This urban heat management study carried out for the City of Dallas is among the first heat adaptation assessments performed for any major city in the United States and positions the city to proactively address the rising threat of heat for its residents and for critical infrastructure. As only the second major US city to conduct such an assessment, Dallas serves as an important national and international model for heat management planning. Through the performance of near-surface temperature and humidity climate modeling throughout Dallas, this study provides regional, urban, and neighborhood-scale data on the spatial pattern of extreme heat, as well as the spatial pattern of population heat risk. The following key findings result from this work:

- Tree planting and preservation should be prioritized in residential zones, where population exposures to heat are greatest and lower-cost planting opportunities are found (Tables 5.1 and 5.2). We recommend that, over time, 250,000 trees be added to the city's urban forest in strategic locations.

- Cool materials strategies should be prioritized in industrial and commercial zones exhibiting extensive impervious cover with limited opportunities for cost-effective vegetation enhancement. (Tables 5.3 and 5.4).

- Some combination of heat management strategies should be undertaken in every zone targeted for heat adaptation planning. As highlighted in Figure 5.1, the benefits of tree planting and preservation are greatly enhanced when combined with cool materials strategies, just as the benefits of cool materials are greatly enhanced when combined with greening strategies.

- A combination of new regulatory and economic incentive programs will be needed to bring about the land cover changes and energy efficiency outcomes modeled through this study.

Neighborhood	Total Cool Roofs (1,000m²/roof)	Cool Roofs Low Benefit Zones (1,000m²/roof)	Cool Roofs High Benefit Zones (1,000m²/roof)
Bluffview	1,280	589	250
Cedar Crest	3,815	707	2,862
Cockrell Hill	67	22	44
Downtown	981	829	84
Eagle Ford	2,965	1,633	287
Far North	12,471	4,348	4,786
Five Mile Creek	309	232	78
Highland Park	101	1	101
Lake Caroline	255	0	0
Lake Highlands	3,364	686	2,316
Love Field Area	1,685	635	280
M Streets	1,903	0	1,903
Near East	1,799	112	126
North Dallas	4,971	1,448	2,498
Northeast Dallas	15,852	2,108	12,420
Northwest Dallas	3,419	936	19
Oak Cliff	1,881	925	895
Oak Lawn	2,451	326	1,925
Preston Hollow	9,294	1,395	3,828
South Boulevard Park Row	2,551	1,403	718
South Dallas	2,138	1,040	820
Southeast Dallas	7,110	3,430	2,000
Southwest Dallas	6,635	2,316	1,894
University Park	138	13	125
Urbandale Parkdale	2,150	930	989
Winnetka Heights	3,237	1,555	1,361
Wolf Creek	2,524	1,132	1,179

Table 5.3 Recommended cool roofing by neighborhood.

Neighborhood	Total Cool Paving Area (Hectares)	Cool Paving Low Benefit Zones (Hectares)	Cool Paving High Benefit Zones (Hectares)
Bluffview	149	64	33
Cedar Crest	634	143	405
Cockrell Hill	24	6	18
Downtown	165	134	15
Eagle Ford	468	274	38
Far North	999	312	434
Five Mile Creek	56	36	20
Highland Park	125	19	106
Lake Caroline	65	1	0
Lake Highlands	523	98	371
Love Field Area	353	90	46
M Streets	268	0	268
Near East	260	29	29
North Dallas	534	142	288
Northeast Dallas	1,975	299	1,482
Northwest Dallas	496	163	4
Oak Cliff	271	139	119
Oak Lawn	333	43	261
Preston Hollow	1,095	181	347
South Boulevard Park Row	474	256	118
South Dallas	493	264	124
Southeast Dallas	1,075	492	291
Southwest Dallas	1,201	359	239
University Park	245	74	166
Urbandale Parkdale	324	148	138
Winnetka Heights	488	231	191
Wolf Creek	405	231	128

Table 5.4 Recommended cool paving by neighborhood.

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Appendix

Neighborhood	Total Trees
Bluffview	21,074
Cedar Crest	83,880
Cockrell Hill	2,873
Downtown	1,120
Eagle Ford	31,091
Far North	72,396
Five Mile Creek	4,563
Highland Park	12,541
Lake Caroline	9,224
Lake Highlands	28,280
Love Field Area	5,875
M Streets	14,374
Near East	4,027
North Dallas	48,083
Northeast Dallas	178,053
Northwest Dallas	13,302
Oak Cliff	25,962
Oak Lawn	14,686
Preston Hollow	90,493
South Boulevard Park Row	68,193
South Dallas	116,209
Southeast Dallas	251,639
Southwest Dallas	225,579
University Park	17,254
Urbandale Parkdale	18,836
Winnetka Heights	58,392
Wolf Creek	41,122

Table A.1 Total trees under Current Conditions scenario by neighborhood.

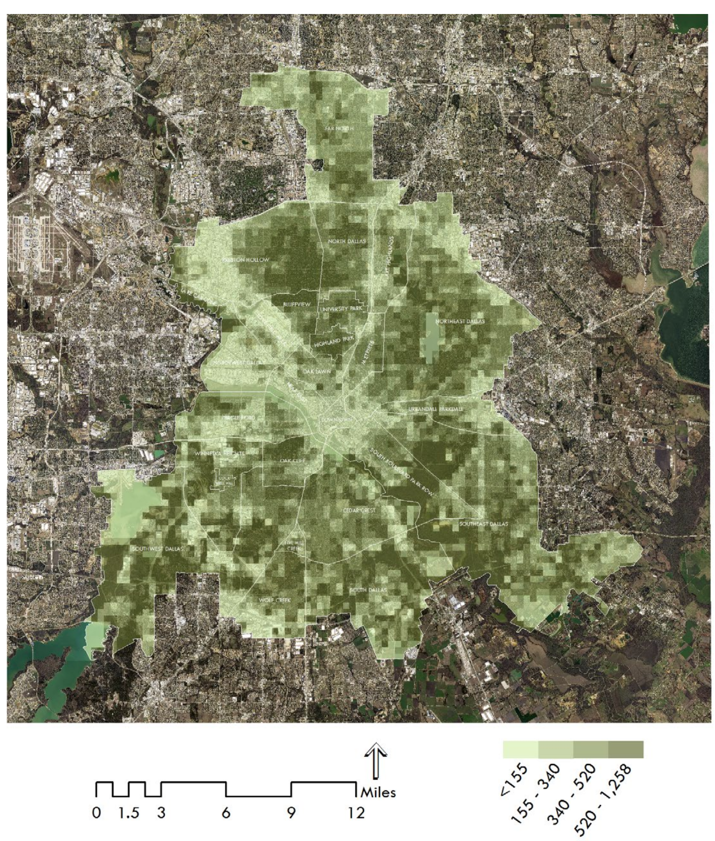

Figure A.1
Trees under Current Conditions scenario by neighborhood.

Neighborhood	Total Trees Planted	Trees Planted Low Benefit Zones	Trees Planted High Benefit Zones
Bluffview	2,091	527	624
Cedar Crest	11,064	5,151	1,367
Cockrell Hill	466	42	0
Downtown	3,690	1,651	57
Eagle Ford	9,930	1,120	47
Far North	15,063	2,329	9,228
Five Mile Creek	1,096	550	153
Highland Park	1,260	189	580
Lake Caroline	1,428	16	0
Lake Highlands	9,748	2,028	3,907
Love Field Area	7,799	991	136
M Streets	4,486	963	3,077
Near East	5,437	351	221
North Dallas	9,423	2,152	6,240
Northeast Dallas	32,353	6,166	15,783
Northwest Dallas	11,111	433	36
Oak Cliff	3,810	1,834	263
Oak Lawn	5,511	628	3,340
Preston Hollow	20,760	4,207	3,100
South Boulevard Park Row	9,987	4,998	521
South Dallas	10,216	5,987	558
Southeast Dallas	20,929	7,239	1,904
Southwest Dallas	23,684	4,282	505
University Park	3,659	1,296	1,658
Urbandale Parkdale	6,685	4,462	1,617
Winnetka Heights	9,856	2,528	630
Wolf Creek	7,691	1,976	503

Table A.2 Neighborhood tree planting under Greening scenario.

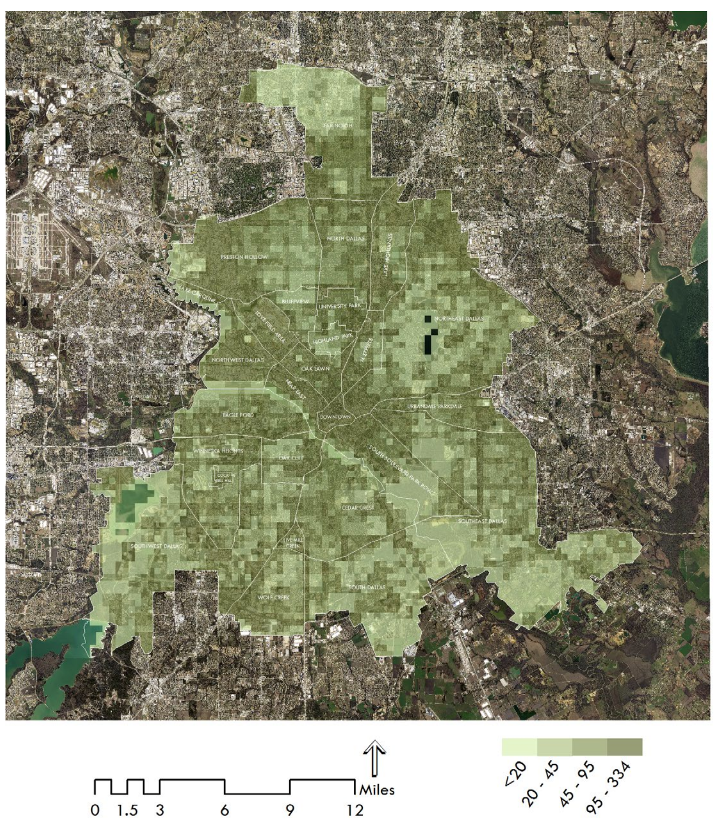

Figure A.2 Neighborhood tree planting under Greening scenario.

Neighborhood	Total Cool Roofs (1,000m²/roof)	Cool Roofs Low Benefit Zones (1,000m²/roof)	Cool Roofs High Benefit Zones (1,000m²/roof)
Bluffview	1,280	589	250
Cedar Crest	3,815	707	2,862
Cockrell Hill	67	22	44
Downtown	981	829	84
Eagle Ford	2,965	1,633	287
Far North	12,471	4,348	4,786
Five Mile Creek	309	232	78
Highland Park	101	1	101
Lake Caroline	255	0	0
Lake Highlands	3,364	686	2,316
Love Field Area	1,685	635	280
M Streets	1,903	0	1,903
Near East	1,799	112	126
North Dallas	4,971	1,448	2,498
Northeast Dallas	15,852	2,108	12,420
Northwest Dallas	3,419	936	19
Oak Cliff	1,881	925	895
Oak Lawn	2,451	326	1,925
Preston Hollow	9,294	1,395	3,828
South Boulevard Park Row	2,551	1,403	718
South Dallas	2,138	1,040	820
Southeast Dallas	7,110	3,430	2,000
Southwest Dallas	6,635	2,316	1,894
University Park	138	13	125
Urbandale Parkdale	2,150	930	989
Winnetka Heights	3,237	1,555	1,361
Wolf Creek	2,524	1,132	1,179

Table A.3 Recommended cool roofing by neighborhood.

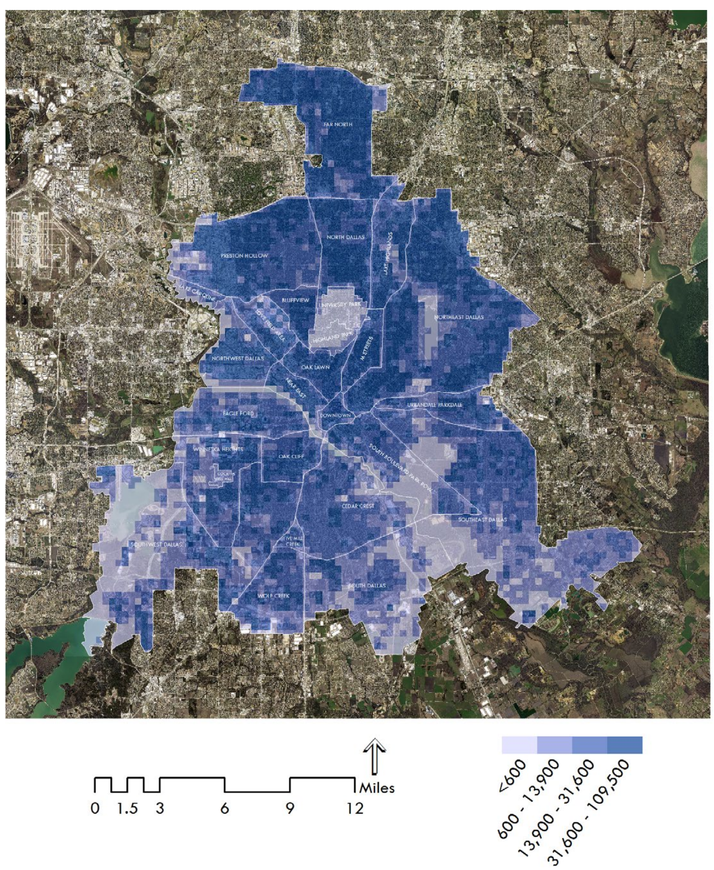

Figure A.3 Recommended cool roofing by neighborhood.

Neighborhood	Total Cool Paving Area (Hectares)	Cool Paving Low Benefit Zones (Hectares)	Cool Paving High Benefit Zones (Hectares)
Bluffview	149	64	33
Cedar Crest	634	143	405
Cockrell Hill	24	6	18
Downtown	165	134	15
Eagle Ford	468	274	38
Far North	999	312	434
Five Mile Creek	56	36	20
Highland Park	125	19	106
Lake Caroline	65	1	0
Lake Highlands	523	98	371
Love Field Area	353	90	46
M Streets	268	0	268
Near East	260	29	29
North Dallas	534	142	288
Northeast Dallas	1,975	299	1,482
Northwest Dallas	496	163	4
Oak Cliff	271	139	119
Oak Lawn	333	43	261
Preston Hollow	1,095	181	347
South Boulevard Park Row	474	256	118
South Dallas	493	264	124
Southeast Dallas	1,075	492	291
Southwest Dallas	1,201	359	239
University Park	245	74	166
Urbandale Parkdale	324	148	138
Winnetka Heights	488	231	191
Wolf Creek	405	231	128

Table A.4 Recommended cool paving by neighborhood.

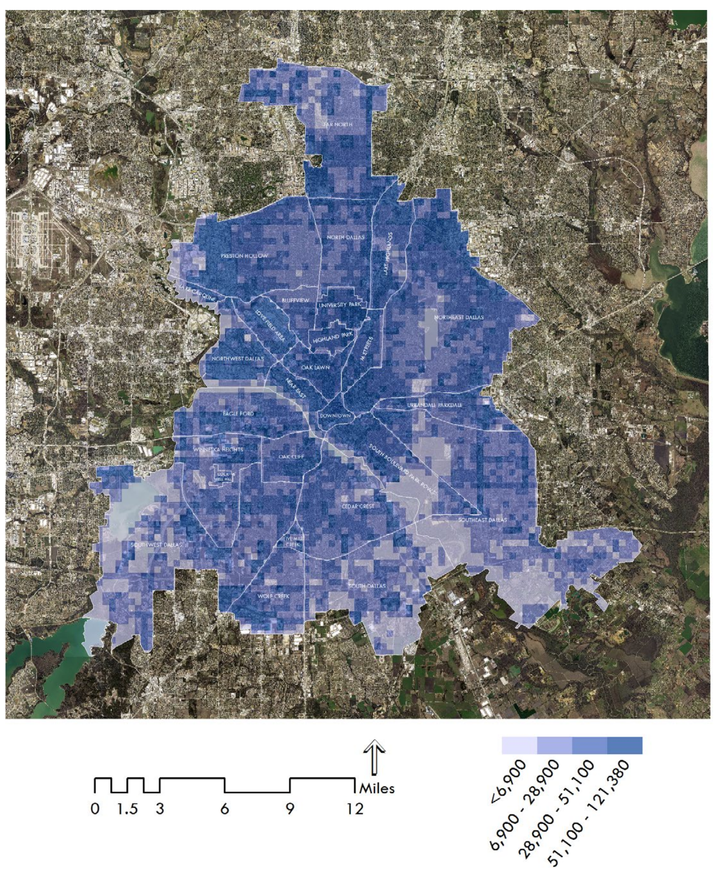

Figure A.4 Recommended cool paving by neighborhood.

Neighborhood	Tree Loss	Current Conditions	Cool Materials	Greening	Combined
Bluffview	86.71	86.45	85.70	85.99	85.80
Cedar Crest	86.48	86.33	85.78	86.23	85.70
Cockrell Hill	86.58	85.90	85.46	86.09	85.37
Downtown	86.70	86.67	85.91	86.36	85.57
Eagle Ford	87.14	86.85	86.28	87.01	86.13
Far North	86.18	86.25	85.57	85.91	85.75
Five Mile Creek	86.15	86.28	85.57	86.19	85.72
Highland Park	86.58	86.43	85.68	85.86	85.52
Lake Caroline	87.13	87.27	86.81	87.14	86.80
Lake Highlands	86.75	86.33	85.71	86.08	85.25
Love Field Area	87.16	86.79	86.15	86.55	85.79
M Streets	86.37	86.29	85.45	85.96	85.10
Near East	87.35	86.90	86.28	86.84	85.97
North Dallas	86.12	86.25	85.48	85.64	85.53
Northeast Dallas	86.45	86.15	85.57	85.89	85.18
Northwest Dallas	87.33	86.96	86.51	86.96	86.00
Oak Cliff	86.34	86.51	85.73	86.54	85.96
Oak Lawn	86.85	86.68	85.87	85.98	85.49
Preston Hollow	86.65	86.80	86.07	86.49	86.06
South Boulevard Park Row	86.61	86.21	85.80	86.12	85.65
South Dallas	86.14	85.99	85.63	85.67	85.44
Southeast Dallas	85.90	85.60	85.26	85.46	85.09
Southwest Dallas	86.17	86.05	85.62	85.99	85.68
University Park	86.41	86.26	85.66	85.81	85.36
Urbandale Parkdale	86.20	86.04	85.40	85.80	85.47
Winnetka Heights	86.44	86.12	85.61	86.22	85.65
Wolf Creek	85.84	85.83	85.29	85.70	85.19

Table A.5 Average mean temperature (°F) by neighborhood and scenario.

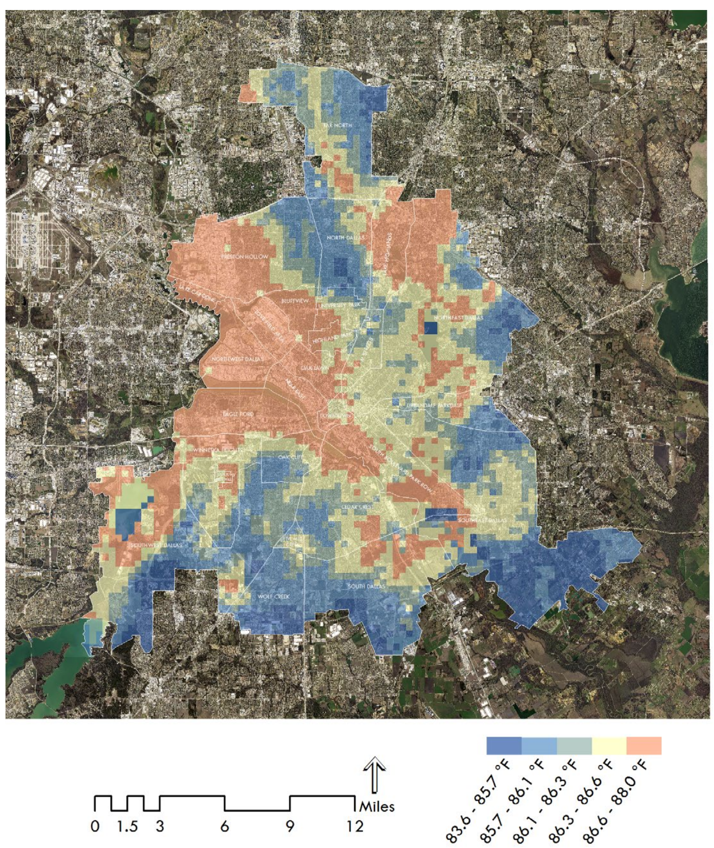

Figure A.5a
Average mean temperature by neighborhood: Tree Loss scenario

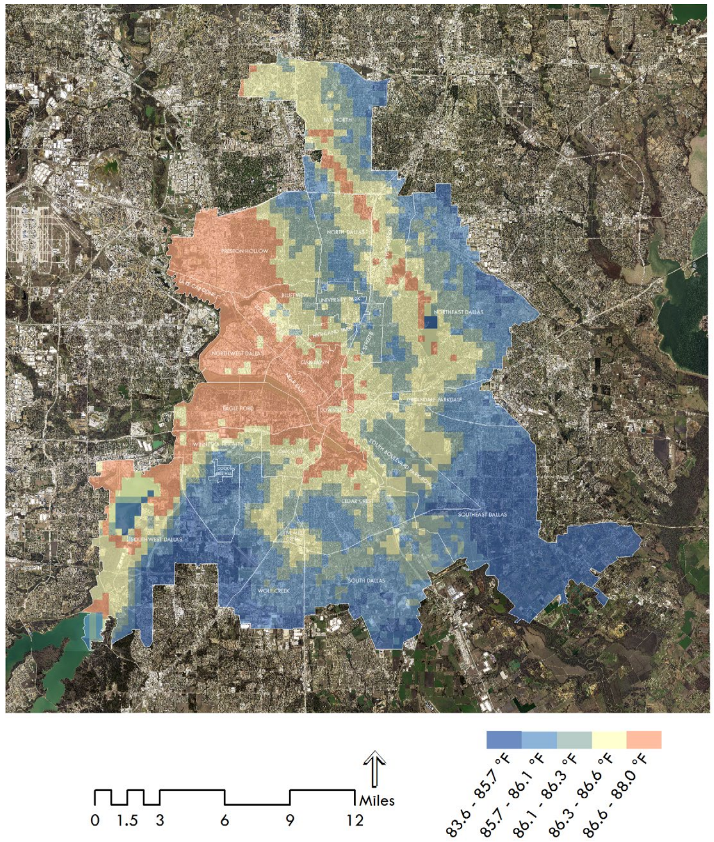

Figure A.5b
Average mean temperature by neighborhood: Current Conditions

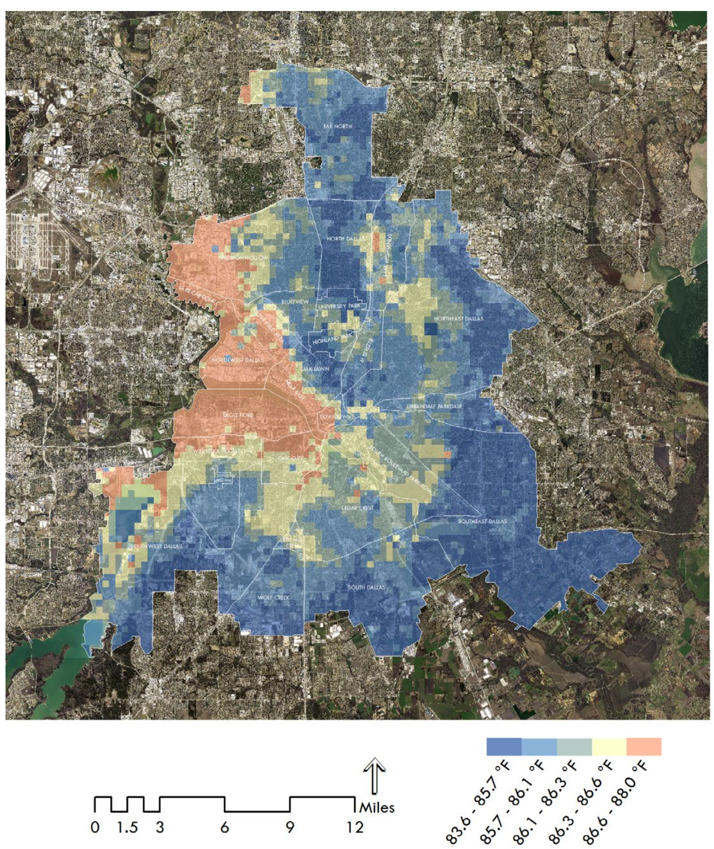

Figure A.5c
Average mean temperature by neighborhood: Greening scenario

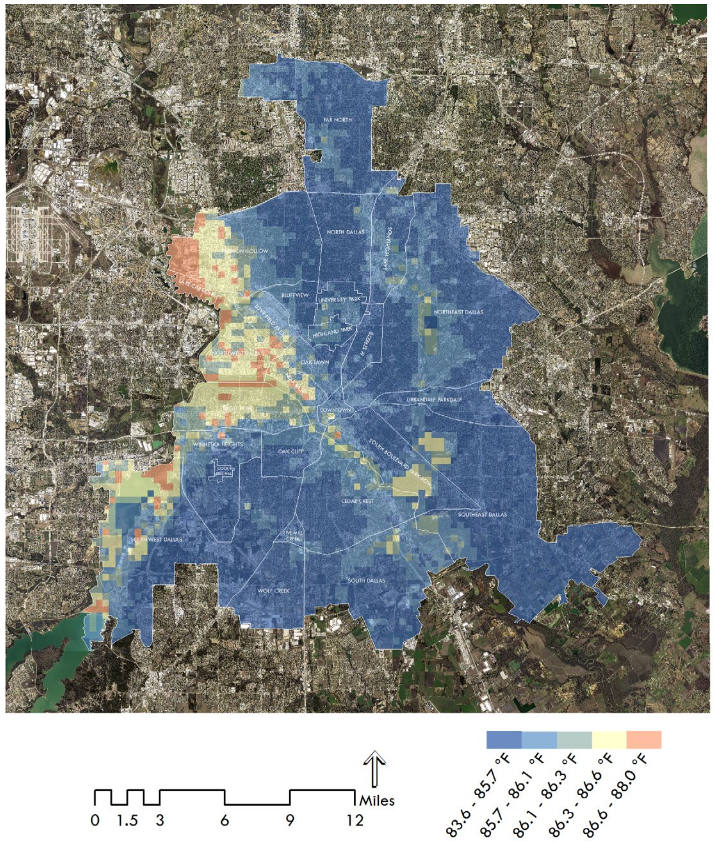

Figure A.5d
Average mean temperature by neighborhood: Cool Materials scenario

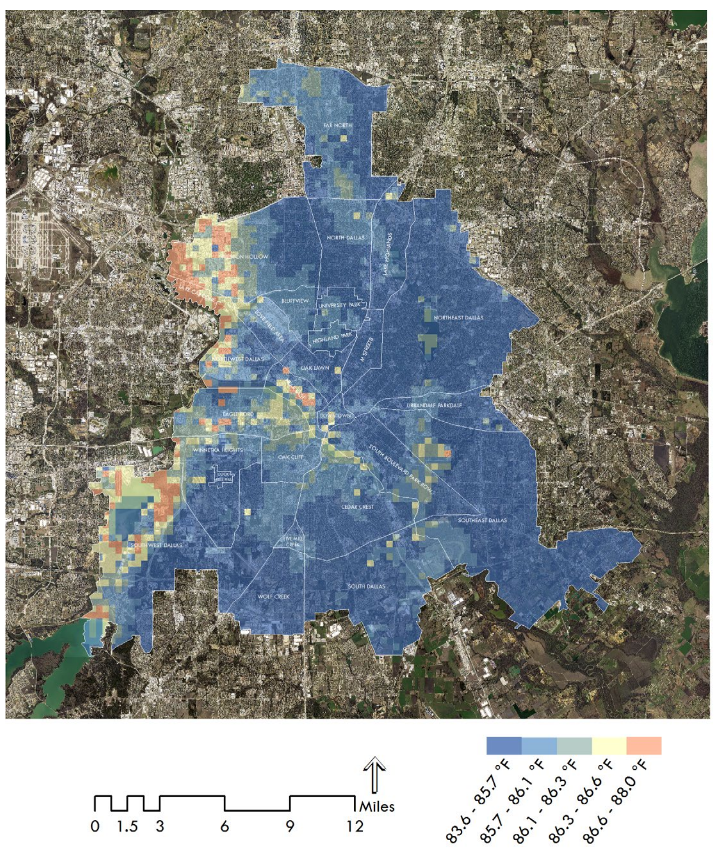

Figure A.5e
Average mean temperature by neighborhood: Combined Strategies scenario

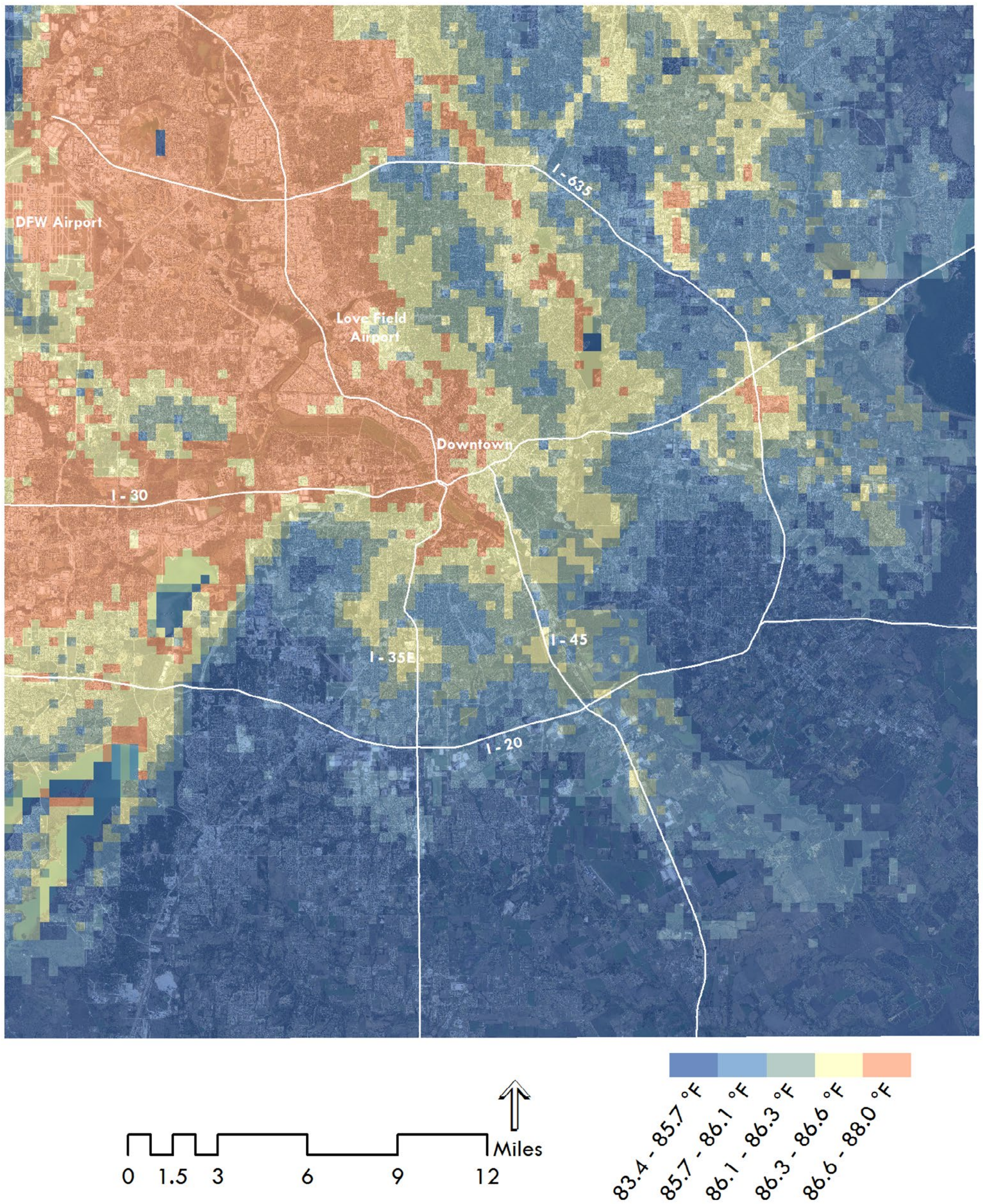

Figure A.5f
Average mean daily temperature for Dallas County: Current Conditions

Neighborhood	Tree Loss	Cool Materials	Greening	Combined
Bluffview	1.47	1.42	1.43	1.43
Cedar Crest	6.12	5.58	5.92	5.50
Cockrell Hill	0.28	0.27	0.30	0.26
Downtown	0.29	0.27	0.28	0.26
Eagle Ford	2.13	2.15	2.29	2.02
Far North	11.97	11.09	11.02	11.29
Five Mile Creek	0.38	0.34	0.37	0.35
Highland Park	1.25	1.15	1.17	1.10
Lake Caroline	0.04	0.04	0.04	0.04
Lake Highlands	4.37	4.20	4.16	3.77
Love Field Area	0.65	0.67	0.66	0.60
M Streets	2.51	2.18	2.29	2.06
Near East	0.40	0.40	0.41	0.37
North Dallas	7.76	7.28	6.84	7.23
Northeast Dallas	19.61	17.59	17.86	16.27
Northwest Dallas	0.43	0.44	0.44	0.39
Oak Cliff	2.43	2.22	2.40	2.27
Oak Lawn	3.06	2.91	2.75	2.73
Preston Hollow	8.54	7.97	8.20	7.90
South Boulevard Park Row	2.40	2.23	2.29	2.15
South Dallas	2.78	2.68	2.60	2.45
Southeast Dallas	6.75	6.47	6.54	6.09
Southwest Dallas	6.10	5.62	6.00	5.66
University Park	1.93	1.83	1.74	1.66
Urbandale Parkdale	2.04	1.85	1.87	1.82
Winnetka Heights	3.50	3.27	3.52	3.19
Wolf Creek	3.10	2.95	3.06	2.80

Table A.6 Total heat deaths by neighborhood and scenario.

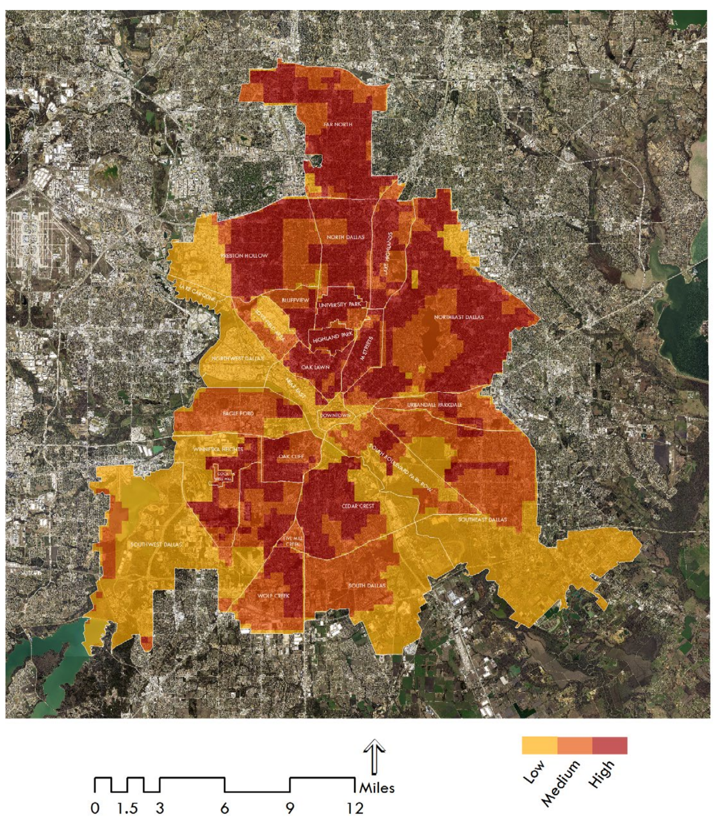

Figure A.6a
Total heat deaths by neighborhood: Tree Loss scenario

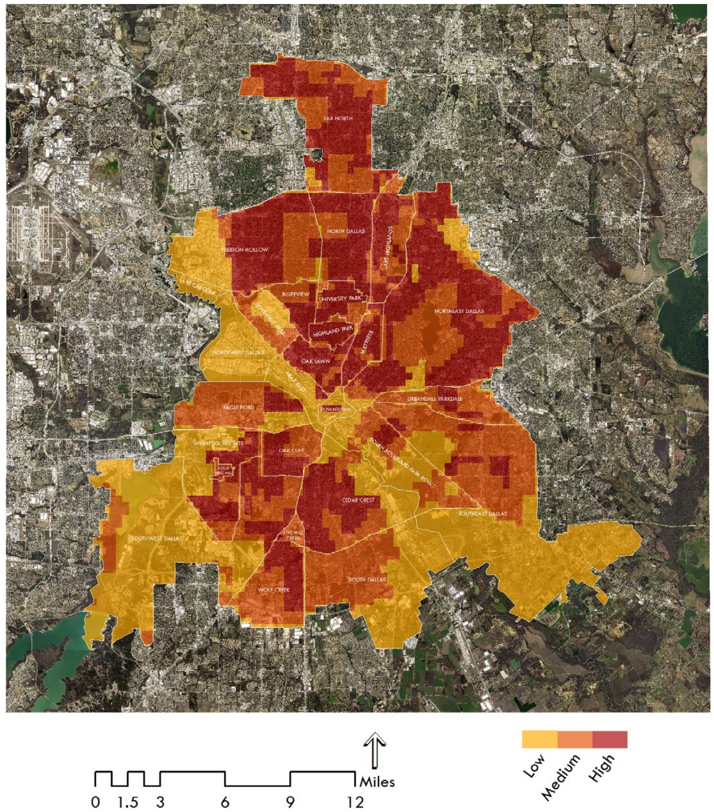

Figure A.6b
Total heat deaths by neighborhood: Greening scenario

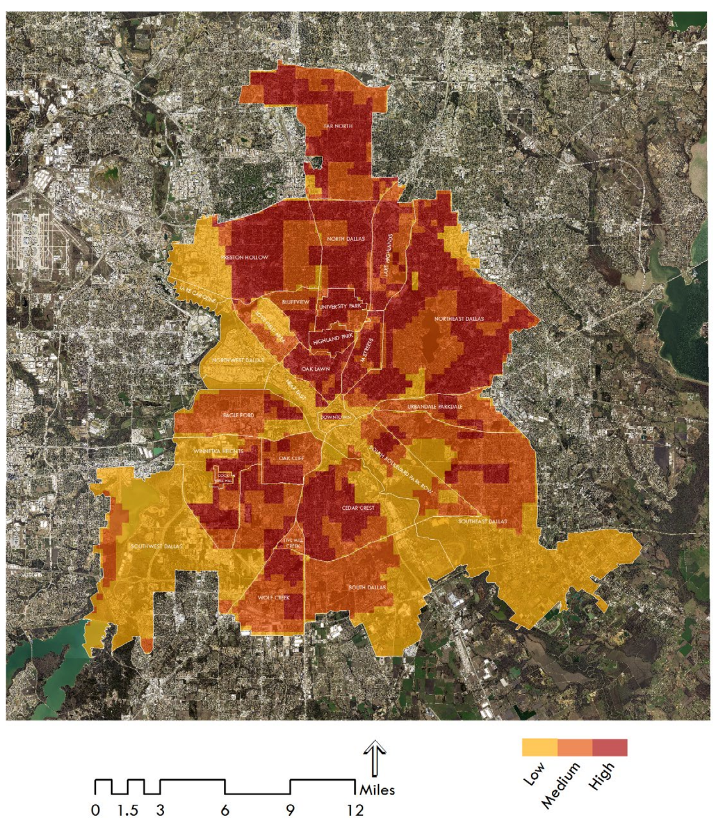

Figure A.6c
Total heat deaths by neighborhood: Cool Materials scenario

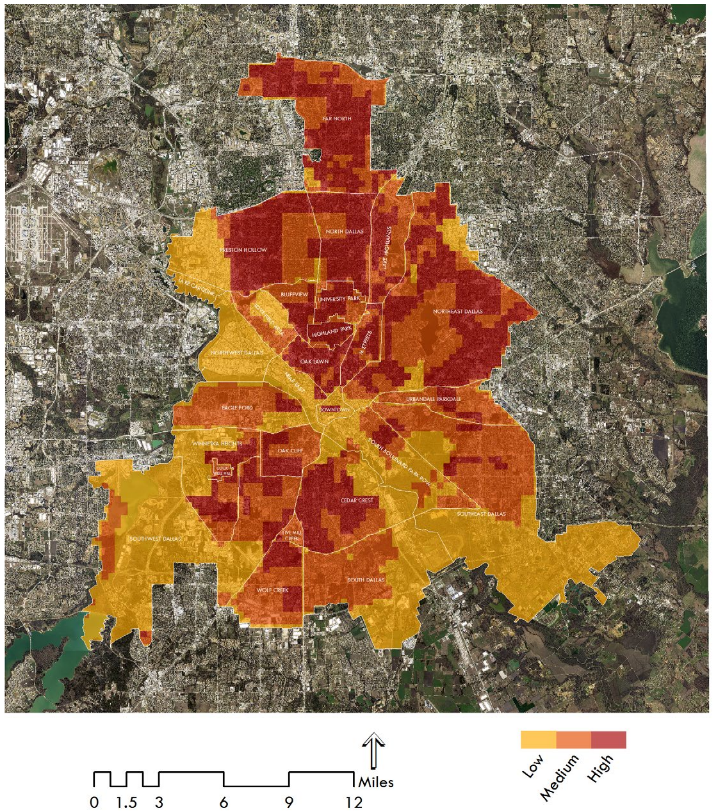

Figure A.6d
Total heat deaths by neighborhood: Combined Strategies scenario