URBAN LANDSCAPE DESIGN FOR IMPROVING THERMAL ENVIRONMENTS AND PROTECTING HUMAN HEALTH

A Dissertation

by

KANGHYUN LEE

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Chair of Committee,	Robert Brown
Committee Members,	Kirk Hamilton
	Galen Newman
	Donging Li
Head of Department,	Shannon Van Zandt

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ABSTRACT

Heat-related health problems, especially in urban areas, are becoming increasingly important due to global climate change (GCC) and urban heat island intensification (UHII). To address these problems, it is important to know how urban landscape design plays a role in urban thermal environments and human health. The comprehensive goal of this study is to understand the multiplicity of heat-related health associated with neighborhood environmental characteristics. This dissertation contains three independent studies, including one systematic review and two empirical studies at the macro-scale (neighborhood-level) and micro-scale (street-level).

The first study conducted a systematic review on the impacts of urban landscape characteristic (ULC) on heat-related health. According to the inclusion and exclusion criteria, 22 studies were selected. The results showed that ULC has positive or negative effects on heat-related health, and appropriate urban landscape design strategies for heat vulnerable areas can mitigate the negative effects of thermal environment on human health.

The second study analyzed the impact of urban landscape and sociodemographic characteristics on heat-related health using 27,807 heat-related emergency medical service (EMS) incidents data from 2016-2020, in Cincinnati (Ohio, US). The results showed that heat-related health incidents have been decreased in block groups with high green areas or a low percentage of impervious surfaces. The effect of these variables has increased with increasing temperature. Also, socially vulnerable groups were more vulnerable to heat-related health.

The third study developed the ground ratio factor (GRF) model to estimate the different terrestrial radiation according to different ground conditions. Three types of ground materials, including asphalt, concrete, and grass, were considered. Field measurements were conducted

during the hot season (July 13 to September 19, 2020). The model was validated by comparing the predicated terrestrial radiation (PTR) from the model with the actual terrestrial radiation (ATR). Through the GRF model, different terrestrial radiation was measured depending on different ground conditions, which can be utilized to improve existing energy budget models.

In conclusion, the findings of this dissertation provide new insights into the urban landscape design strategies and foundation of knowledge for local interventions for improving thermal environments and protecting human health. Therefore, efforts to address heat-related problems should be considered continuously by landscape designers, urban planners and policymakers, especially for vulnerable groups.

DEDICATION

I dedicate this dissertation to my family

for their endless support, encouragement, and love.

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I would like to thank my committee chair, Dr. Brown, for his endless support. He has always led me in a way that I can grow up to be the right researcher. It is the luckiest thing in my research life to have him as my mentor. I'm sure he is the best mentor in the world. I would also like to thank my committee members, Dr. Kirk Hamilton, Dr. Galen Newman, and Dr. Dongying Li, for their priceless support throughout the dissertation. It was a great honor to have them as my members.

NOMENCLATURE

A-C	Asphalt - Concrete
A-C-G	Asphalt - Concrete-Grass
A-G	Asphalt - Grass
ATR	Actual Terrestrial Radiation
C-G	Concrete - Grass
GR	Ground Ratio
GRF	Ground Ratio Factor
GRF-A	Air Temperature-based GRF
GRF-G	Ground Temperature-based GRF
PTR	Predicted Terrestrial Radiation
PTR-A	Predicted Terrestrial Radiation by GRF-A model
PTR-G	Predicted Terrestrial Radiation by GRF-G model
ULC	Urban Landscape Characteristic

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1. INTRODUCTION

1.1. Background

More than half of the world population now lives in cities (Brown & Gillespie, 1995; Graham, Vanos, Kenny, & Brown, 2016; Robinson et al., 2011), and in counties like the United States and Canada, more than 80% of the population lives in urban areas (Johnson & Shifferd, 2016). Urban population is expected to increase 72 percent from the current 3.6 billion to 6.3 billion by 2050 (UNDESA, 2011). In urban areas, two major trends are having negative effects on human health. Global Climate Change (GCC) is causing many areas of the world to experience an increase in the frequency and intensity of heatwaves, conditions that cause heat-related illnesses (Patz, Campbell-Lendrum, Holloway, & Foley, 2005). As cities grow to accommodate the increasing population, they are often inadvertently built in such a way as to create an urban climate that is warmer and drier than the prevailing conditions, a phenomenon known as the Urban Heat Island (UHI). Thermal environments caused by UHI dramatically increase human illness and death (Cao, Yu, Georgescu, Wu, & Wang, 2018; Harlan, Declet-Barreto, Stefanov, & Petitti, 2013; Kjellstrom et al., 2016; Limaye, Vargo, Harkey, Holloway, & Patz, 2018; Romeo Upperman et al., 2015; J. Tan et al., 2010).

High temperatures, especially during extreme heat events, were associated with a wide range of health effects from heat stress to heat-related death (Y. Xu et al., 2013). When people are exposed to extreme heat, they can suffer from deadly heat-related illnesses such as heat exhaustion, heat cramps, and heat stroke because they do not allow the body to cool sufficiently through perspiration. In addition, prolonged exposure to extreme heat can not only exacerbate existing chronic diseases such as the various respiratory, cerebral, and cardiovascular diseases, but also can lead to heat-related deaths (Melillo, Richmond, & Yohe, 2014). Heat-related health studies can be divided into two main categories, depending on which health outcomes were used: heat-related mortality and morbidity. According to Oudin Åström, Bertil, and Joacim (2011), morbidity studies typically used outcomes such as hospital admissions, emergency department visits, and ambulance calls. Most mortality studies used mortality data.

Heat stress, which is not largely classified in heat-related health studies, needs to be noted since heat stress is the most important factor that causes heat-related health. According to Epstein and Moran (2006), various age groups, including infants, children, and older adults over 65 were vulnerable to heat-related death because they are more sensitive to excessive heat stress. Heat stress reduced worker’s productivity and caused more serious health problems, which have worsened in vulnerable groups (Abdel-Ghany, Al-Helal, & Shady, 2013).

Global climate change is the responsibility at the government and national levels. However, urban climate change is a different story. Each of us, as individual designers, can have substantial impacts on urban climate conditions and heat-related health issues through urban landscape design. For example, the street direction can have a significant effect on the movement of the wind through the city. The materials used on street canyon geometry, such as building facades or pavements, can substantially affect the amount of solar and terrestrial radiation received by urban residents.

Meanwhile, in recent years, research on Microclimatic Urban Design (MUD) has been gaining attention to mitigate the thermal environment and improve human thermal comfort at a micro-sale. MUD is the process of determining the physical organization of buildings and open spaces in cities to have a positive effect on microclimate and thermal environment. Lenzholzer and Brown (2016) analyzed MUD strategies to improve urban thermal environment, including fine-scale subjects such as street, roof, and pavement patch and coarser-scale subjects such as neighborhood and urban blocks. In this regard, to improve thermal environments of urban outdoor spaces and to adapt to the negative effects of GCC and UHI, urban landscape design strategies has been proposed in many studies, including the use of urban vegetation (Chen et al., 2014; Gunawardena, Wells, & Kershaw, 2017; Susca, Gaffin, & Dell'osso, 2011), type of the surface materials (Liu, Li, & Peng, 2018; Mohammad, Goswami, & Bonafoni, 2019), water bodies (Jenerette, Harlan, Stefanov, & Martin, 2011; Nakayama & Hashimoto, 2011; Vahmani & Jones, 2017), and changes in urban structure (Clarke, 1972; Johansson & Emmanuel, 2006; Yang, Wong, & Li, 2015) alleviate the urban thermal environment. Others assessed the effect of urban landscape design on heat-related health, including acute and chronic health (Burkart et al., 2016; Chen et al., 2014; Graham et al., 2016; Gronlund, Berrocal, White-Newsome, Conlon, & O'Neill, 2015; Harlan et al., 2013; Madrigano, Ito, Johnson, Kinney, & Matte, 2015; Y. Xu et al., 2013).

1.2. Significance & Objectives

This study aims to identify the relationship between urban landscape and human health micro to micro-scale for improving thermal environment and protecting human health. This study includes a literature review and two empirical studies by answering the knowledge gaps as below. First, this study aims to conduct a comprehensive systematic review of the relationship between urban landscape characteristics and heat-related health. In the relationship, three main components were included: 1) urban landscape characteristics, 2) urban thermal environment, and 3) human health. Many studies have shown that urban landscape design contributes to the mitigation of urban thermal environment, and there are several review papers on their relationship (Jaganmohan, Knapp, Buchmann, & Schwarz, 2016; Oliveira, Andrade, & Vaz, 2011; Y. Tan, Zhang, & Yao, 2013; B. Zhang, Xie, Gao, & Yang, 2014). Other studies have shown that alleviated urban thermal environment has a positive impact on human health (Hayhoe, Sheridan, Kalkstein, & Greene, 2010; Hoshiko, English, Smith, & Trent, 2010), and there are a lot of systematic reviews for the relationship (Cheng et al., 2014; Oudin Åström et al., 2011; Z. Xu et al., 2012). However, while several empirical studies have shown a clear connection between urban landscape design and heat-related health, there is no review paper on the relationship.

Second, several studies have identified the impact of the urban landscape characteristics on heat-related health. However, there is a lack of empirical research considering various health-related variables and conditions. In particular, most related studies have analyzed the relationship between urban landscape characteristics and health using data on deaths during hot days, requiring further analysis of acute heat-related health, which can analyze the direct effects of heat on health. Furthermore, in most related studies, limited urban landscape have been utilized in analysis, which requires additional studies to analyze the effects of various urban landscape factors together.

Third, at the micro-scale, among urban landscape design factors, such as green, surface, water, and urban structure, surface-related research has focused mainly on energy that depends on the albedo of ground materials and has rarely considered terrestrial radiation emissions. In addition, no studies have considered terrestrial radiation according to the surrounding ground condition at the point where the subject is standing. Thus, this study attempted to develop a Ground Ratio Factor (GRF) model that considers the surrounding pavement status and suggests a more accurate way to calculate the thermal energy budget.

1.3. Theoretical Background

To understand the impacts of urban landscape design on improving thermal environment and projecting human health, it is important to know the theoretical background about 1) thermal environment, including urban climate and human thermal comfort, 2) urban landscape design, and 3) heat-related health. Figure 1 shows the conceptual framework for the interactions from urban landscape characteristics to human health.

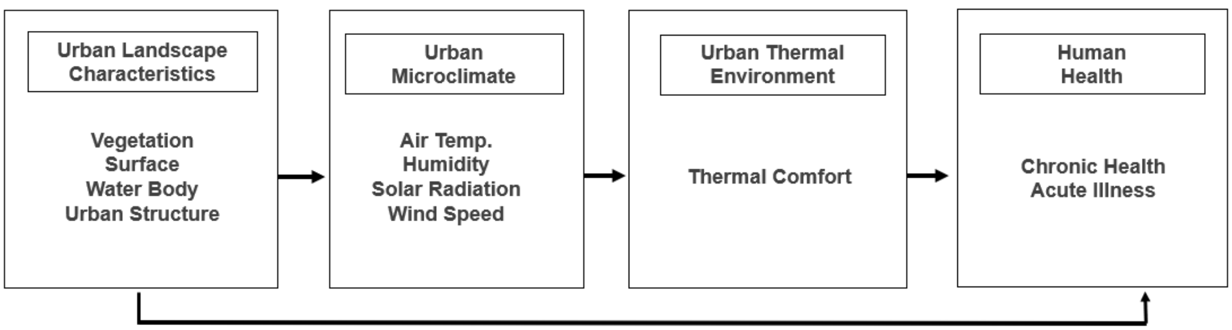

Figure 1. Conceptual Framework

1.3.1. Thermal Environment

1.3.1.1. Urban Thermal Environment

Urbanization has environmental impacts on urban heat island (UHI), which is attracting a wide range of attention, especially in urban areas with high population density and dense buildings. UHI effect means that the temperature in urban areas is higher than surrounding rural areas, mainly the result of rapid urbanization (Memon, Leung, & Chunho, 2008). Based on the UHI, urban thermal environment refers to heat-related physical environments that can affect human health and their living conditions (Yan, Wu, & Dong, 2018).

High temperatures in urban areas not only cause urban air pollution but also aggravate urban thermal environments, contributing to the UHI phenomenon (Kolokotroni, Zhang, & Watkins, 2007). There is growing interest in the impacts of the spatial patterns of urban landscape on urban thermal environment, and many studies have investigated the cooling or mitigation effects of urban landscape components. They indicated that the spatial pattern of the urban landscape plays an important role in mitigating the urban thermal environments (Estoque, Murayama, & Myint, 2017; Gunawardena et al., 2017; Liu et al., 2018; Mohammad et al., 2019).

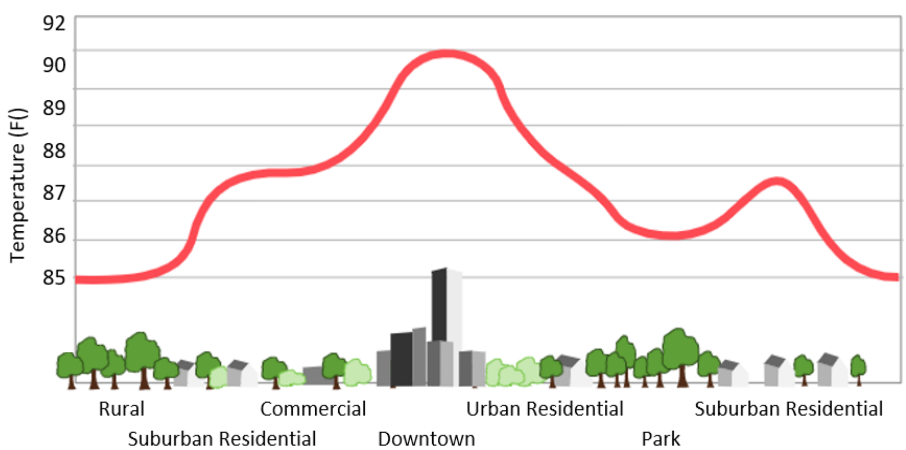

Figure 2. Urban Heat Island Profile (NOAA, 2011)

1.3.1.2. Urban Microclimate

Due to the rapid urbanization of the world population, a number of urban microclimate studies have recently been conducted (Toparlar, Blocken, Maiheu, & Van Heijst, 2017). Microclimate is the condition of solar and terrestrial radiation, wind, air temperature, humidity, and precipitation in a urban outdoor space (Brown & Gillespie, 1995). Urban microclimate can be defined as microclimate conditions in urban areas that are quite different from the surrounding rural areas (Toparlar, Blocken, Maiheu, & van Heijst, 2018).

Urban microclimates affect many aspects of city life, from human thermal comfort to the growth of plants and habitat of animals (Brown, 2018). Most urban microclimate-related studies have been conducted on how to measure and utilize urban microclimate data. For example, Priyadarsini, Hien, and David (2008) explained which urban microclimate components affect the urban heat island, and proposed mitigation strategies to address the heat-related problems. According to their results, the effect of façade material with various colors and wind speed was very significant and the temperature at the center of the narrow canyon rose to 2.5 °C with low albedo façade material. Toparlar et al. (2018) explored the relationship between urban microclimate and building cooling demand in the summertime in Belgium. They used simulation method to analyze the air temperature difference in various spatial areas. Their results showed that the average air temperature in urban areas close to the park was 3.3 °C and 2.4 °C higher, respectively, compared with the air temperature in rural areas. Bourbia and Boucheriba (2010) attempted to compare how urban microclimates differed depending on the different types of street canyons, and how they affect the neighborhood environments. The results showed that the difference in air temperature between the urban street and surrounding rural area was about 3–6 °C.

1.3.1.3. Human Thermal Comfort

Outdoor human thermal comfort is a crucial part of improving the urban microclimate that people usually perceive and leading a more holistic view of sustainable thermal environment development. Thermal comfort is defined as a state of mind that shows satisfaction with the thermal environment and is assessed by subjective evaluation (M. Xu, Hong, Mi, & Yan, 2018).

According to Brown and Gillespie (1995), the human body creates metabolic energy depending on its activity level and absorbs the radiation. Most of the terrestrial radiation to the human body has a high absorption rate, while solar radiation has a relatively low absorption rate. On the other hand, the human body loses evaporative energy through normal breathing and evaporation of perspiration of sweat in the skin. Also, when the wind carries heat from a person, the human body has convection heat loss, and the human body also emits terrestrial radiation outwards (Figure 3).

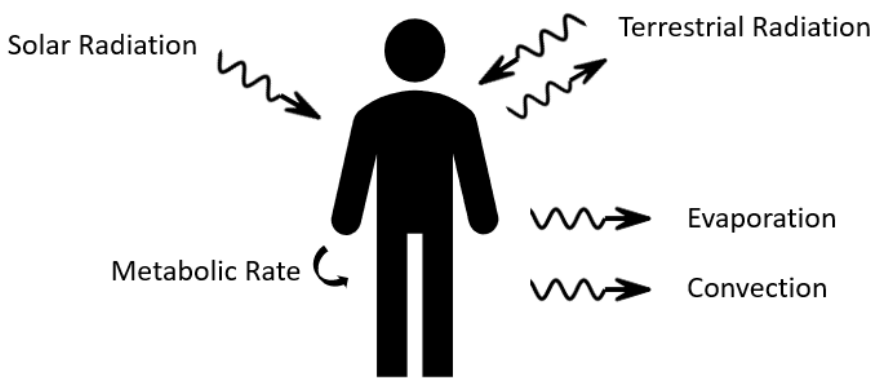

Figure 3. Heat Exchanges for Human Thermal Comfort

* Energy Budget = Metabolic Energy + Solar Radiation gained + Terrestrial Radiation gained – Evaporative Heat Loss – Convective Heat Loss – Terrestrial Radiation emitted

To measure the heat exchanges between a human body and its surroundings, we need to know human characteristics such as their activity level and clothing insulation as well as physical parameters including air temperature, wind speed, relative humidity, and radiation. Various thermal index models have been developed to measure the energy budget balance, which quantitatively indicates human thermal comfort, including Temperature-Humidity Index (THI), Vinje's Comfort Index (PE), the Thermal Sensation Index (TS), Predicted Mean Vote (PMV), COMFA model, Physiological Equivalent Temperature (PET), Universal Thermal Climate Index (UTCI), etc. (Lai, Liu, Gan, Liu, & Chen, 2019).

1.3.2. Urban Landscape Design

Urban design is the process of determining the physical environment of cities and it has influence over most of the urban space. According to Memlük (2012), a landscape is created by natural and cultural dynamism that affects the human lifestyle. Thus, urban landscape includes green spaces as well as a composition of various outdoor spaces including streets, squares, parks, playgrounds, waterfronts, paths, and urban structures. Since urban landscape is a key part of urban elements, urban landscape design should be considered as an essential part of urban design. Urban landscape design not only contributes to the identity of urban areas by creating high-quality places, but also creates healthy urban thermal environments (Gunawardena et al., 2017; J. Li et al., 2011; Yang et al., 2015).

According to previous studies, urban landscape design elements can be divided into approximately four categories: vegetation, surface, water, and urban structure. Some studies recommended the urban vegetation, such as tree canopy, vegetation cover, urban park, street tree, etc. (Burkart et al., 2016; Graham et al., 2016; Gronlund et al., 2015; Gunawardena et al., 2017; Son, Lane, Lee, & Bell, 2016; Susca et al., 2011; X. Zhang, Wu, & Chen, 2010). While others suggest surface elements, such as pavement, albedo, etc. (Estoque et al., 2017; Fintikakis et al., 2011; Liu et al., 2018; Mohammad et al., 2019; Salata et al., 2017), water bodies, such as water body coverage, proximity to water body, lakeside, etc. (Jenerette et al., 2011; Nakayama & Hashimoto, 2011; Nishimura, Nomura, Iyota, & Kimoto, 1998; Sun, Chen, Chen, & Lü, 2012; Sun & Chen, 2012; Vahmani & Jones, 2017), and urban structure, such as high & width radio, sky view factor (SVF), orientation of street, etc. (Clarke, 1972; Johansson & Emmanuel, 2006; J. Li et al., 2011; X. Li, Zhou, Ouyang, Xu, & Zheng, 2012; Yang et al., 2015; Zhou, Huang, & Cadenasso, 2011). Also, several relevant review papers in the urban landscape design elements also have the same direction for these categories (Lai et al., 2019; Santos Nouri, Costa, Santamouris, & Matzarakis, 2018).

1.3.3. Heat-related Health

Most heat-related health studies have been conducted on macro-scale, such as city and metropolitan levels. Because of the urban heat island (UHI) phenomenon, urban areas have higher temperatures than their surroundings. These thermal environments cause heat-related health problems (Heisler & Brazel, 2010). High temperatures, especially extreme heat, are associated with a wide range of health effects (Y. Xu et al., 2013). When people are exposed to extreme heat, they can suffer from deadly heat-related illnesses such as heat exhaustion, heat cramps, and heat stroke because they do not allow the body to cool sufficiently through perspiration. In addition, prolonged exposure to extreme heat can not only exacerbate existing chronic diseases such as the various respiratory, cerebral, and cardiovascular diseases, but also can lead to heat-related deaths (Melillo et al., 2014). Thus, according to previous studies, heat-related health can be divided into two main categories: heat-related mortality and heat-related morbidity. In the heat-related morbidity studies, typically hospital admission, emergency department visit, and ambulance call can be used as a proxy of heat-related illnesses, and most of the heat-related mortality studies used all-cause mortality or heat-related mortality (Oudin Åström et al., 2011).

Meanwhile, we need to pay attention to heat stress, which is not being classified significantly in heat-related health studies. Heat stress is the most important factor that causes heat-related health. According to Epstein and Moran (2006), various age groups, including infants, children, and older adults over 65 were vulnerable to heat-related mortality because they are more sensitive to excessive heat stress. Heat stress reduced worker's productivity and causes more serious health problems, and these problems get worse in vulnerable groups (Abdel-Ghany et al., 2013). High temperature causes people to be thermally uncomfortable and causes heat stress. Many studies use human thermal comfort, which is defined as a state of mind that shows satisfaction with the thermal environment (M. Xu et al., 2018), as an indicator of how heat stress can be assessed (Abdel-Ghany et al., 2013; Epstein & Moran, 2006; Kovacs, Kezer, Ruff, Szenci, & Jurkovich, 2018) and most of these studies have conducted at the micro-scale.

1.4. Scope of Study

Research on the effects of the urban landscape characteristics on heat-related health is underway on different scales, depending on the type of health outcome. Depending on the spatial scale, the analysis methodology of the relevant studies and the urban landscape characteristics are different. Most heat-related mortality and morbidity studies are conducted on the macro-scale, while studies on thermal stress and thermal comfort are mainly conducted at the micro-scale.

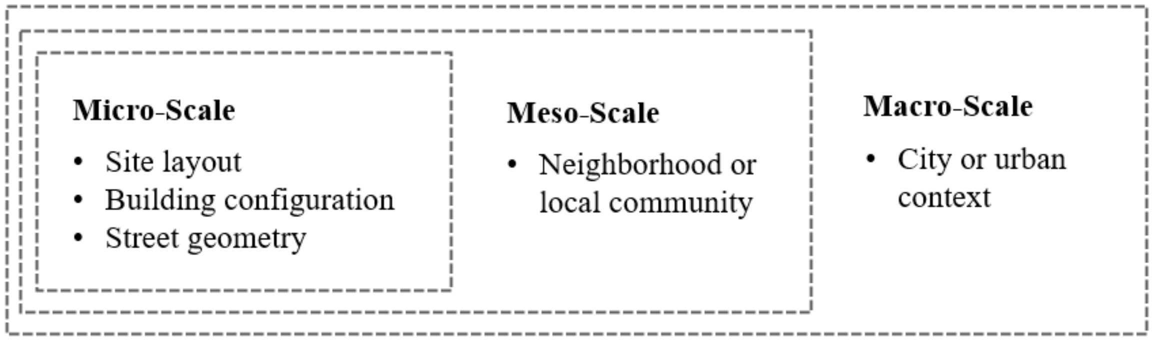

Figure 4. Micro and Macro spatial scales

According to Sharifi and Yamagata (2018), the macro-scale spatial spaces can be classified as city size, regional connectivity, and urban context, meso-scale spaces can be classified as neighborhood or local community size, and micro-scale spaces can be classified as site and building size (Figure 4). In this dissertation, due to the characteristics of the relevant research, we classify the spatial scale into two large groups, small and medium, combined. The spatial scale was classified as micro and macro-scale, and the macro-scale includes the meso-scale.

1.5. Structure of the Dissertation

The structure of this study is shown in Figure 5. In Study One, a systematic review of the relationship between urban landscape characteristics and heat-related health was conducted. In Study Two, an empirical study was conducted to identify the health effects of urban landscape and sociodemographic characteristics at the macro-scale (city-level). This study compares urban land use data & heat vulnerability index with Emergency Medical Service (EMS) call data, which is the proxy of heat-related health. In Study Three, a model for estimating terrestrial radiation for different surrounding ground conditions based on the Ground Ratio Factor (GRF) model at the micro-scale.

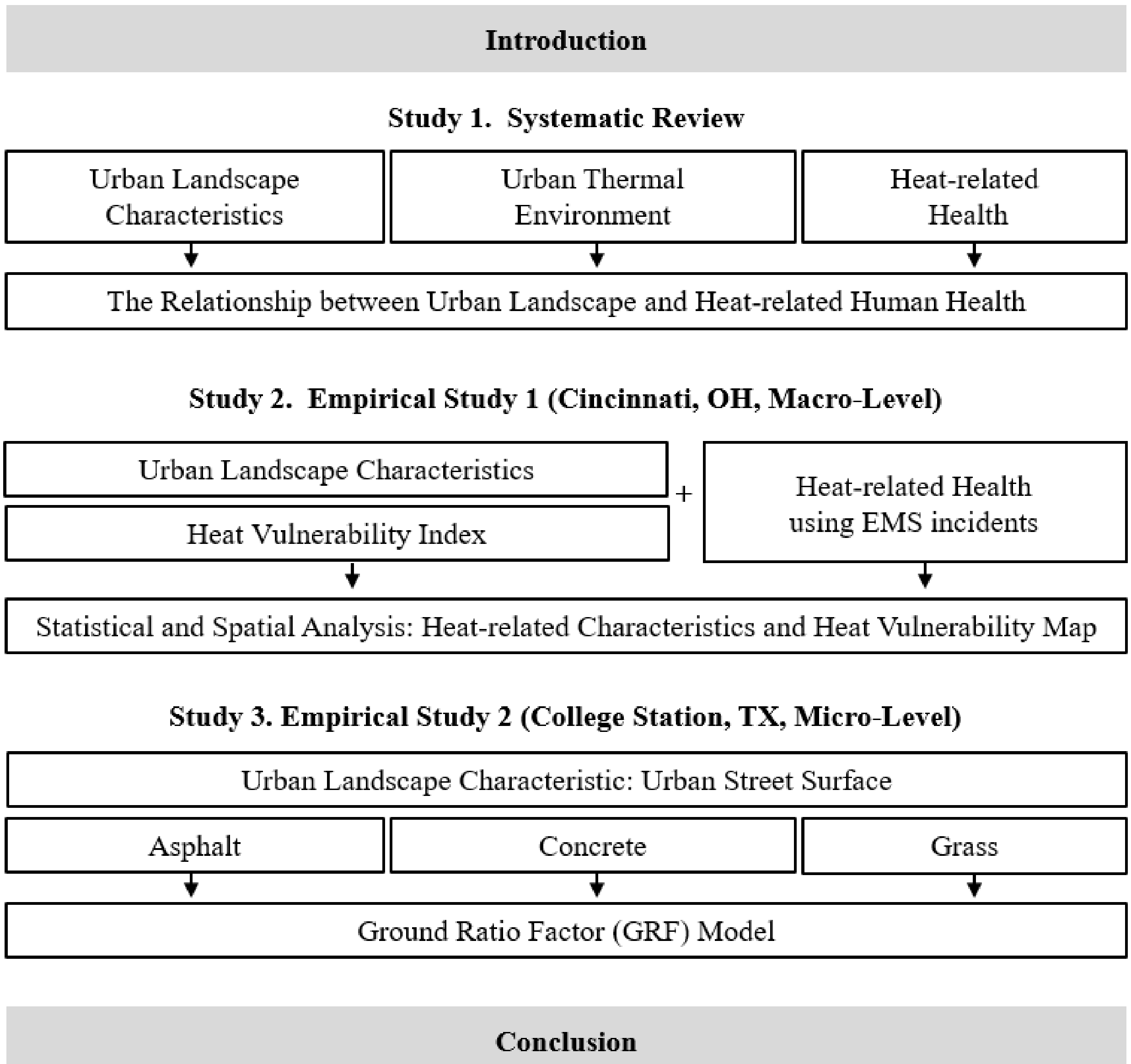

Figure 5. Structure of the Dissertation

2. STUDY ONE: URBAN LANDSCAPE CHARACTERISTICS AND HEAT-RELATED HEALTH: A SYSTEMATIC REVIEW

2.1. Summary

Cities are becoming hotter through urban heat island (UHI) intensification leading to a growing interest in the study of urban climate mitigation. As climate change progresses, one of the main problems is the effect on human health. While much research is being done on the potential health risks associated with urban climate change, there are still many gaps to address the future health need of urban residents. The goal of this study was to understand the multiplicity of heat-related health associated with neighborhood environmental features to propose future research directions. This study conducted a systematic review on the impact of urban landscape characteristics (ULC) on heat-related human. Empirical studies on the relationship between ULC and heat-related mortality & morbidity were included. Twenty-two studies were considered in detail. Most existing studies have shown that ULC can be classified into four categories: water, vegetation, surface, and urban structure and that ULC for each category has positive or negative effects on heat-related health. The results indicate that appropriate urban landscape design strategies for heat vulnerable areas can mitigate the effects of thermal environments on human health. More research should focus on vulnerable groups such as older adults and children because are more vulnerable to heat-related health, but there is not enough research involved. Also, more research needs to be done on more diverse climate zones to build more accurate relationships. Lastly, further empirical research is needed to create accurate information for more diverse environments to address heat-related health issues.

2.2. Introduction

Global Climate Change (GCC) is causing many areas of the world to experience an increase in the frequency and intensity of heatwaves, conditions that cause heat-related illnesses Patz, Campbell-Lendrum, Holloway, and Foley (2005). At the same time, people all over the world are moving to cities and more than half of the world's population now lives in cities (Robinson et al., 2011). Urban population is expected to increase 72 percent from the current 3.6 billion to 6.3 billion by 2050 (UNDESA, 2011). As cities grow to accommodate the increasing population, unintentionally, warmer and drier climates were formed in urban areas than in surrounding areas, called Urban Heat Island (UHI) (Memon, Leung, & Chunho, 2008). GCC exacerbated by UHI produces extreme heat that can dramatically increase human illness and death (S. L. Harlan, Declet-Barreto, Stefanov, & Petitti, 2013; Hayhoe, Sheridan, Kalkstein, & Greene, 2010; Hoshiko, English, Smith, & Trent, 2010; Jones et al., 1982; D. W. Kim, Deo, Chung, & Lee, 2016; J. Madrigano, Ito, Johnson, Kinney, & Matte, 2015).

At the individual level, we have little control over the negative health effects of CCG and UHI. However, many studies have provided a lot of evidence that urban landscape design has significant impacts on improving urban microclimate to address the heat-related health problems (Jaganmohan, Knapp, Buchmann, & Schwarz, 2016; Oliveira, Andrade, & Vaz, 2011; Y. Tan, Zhang, & Yao, 2013; Zhang, Xie, Gao, & Yang, 2014; Zhao, Liu, & Liu, 2016). At the micro-scale, urban landscape design can be used to mitigate urban microclimate through modification of solar radiation, terrestrial radiation, and wind speed, but some microclimate components such as air temperature and humidity are not easy to control by design because they are spatially conservative (Brown, 2018). On the contrary, these components can be controlled through urban landscape design at the macro-scale (Lenzholzer & Brown, 2013). Unlike global climate change issues that need to be addressed at the national or international level, urban microclimate issues to address heat-related health problems can be controlled through urban landscape design at individual and neighborhood levels. Many studies have focused on the following strategies as major components of urban landscapes: green areas (Gunawardena, Wells, & Kershaw, 2017; Susca, Gaffin, & Dell'osso, 2011), surface of building and pavement (Estoque, Murayama, & Myint, 2017; Liu, Li, & Peng, 2018), water bodies (Jenerette, Harlan, Stefanov, & Martin, 2011; Nakayama & Hashimoto, 2011; Vahmani & Jones, 2017), and structure of streets and buildings (Johansson & Emmanuel, 2006; Yang, Wong, & Li, 2015) at the micro and macro-scale.

In recent years, there has been growing interest in investigating the impact of urban landscape on heat-related health. There is a clear relationship between the way a city is designed and the resulting urban climate (Jaganmohan et al., 2016; Oliveira et al., 2011; Y. Tan et al., 2013; Zhang et al., 2014; Zhao et al., 2016), and there is a well-established connection between the urban climate and the health of residents (Hayhoe et al., 2010; Hoshiko et al., 2010; Jones et al., 1982; D. W. Kim et al., 2016; Jaime Madrigano et al., 2013). Several studies have also shown that there is a link connection urban landscape and resident heat-related health. However, to date, no review studies have paid particular attention to the relationship between urban landscape characteristics (ULC) and heat-related health.

Therefore, the main goal of this study is to understand the heterogeneity of heat-related health in relation to neighborhood environmental features and conduct a comprehensive review to provide robust evidence on the impact of ULC on heat-related health through a systematic review. The detailed objectives of this study are to 1) investigate what ULC are associated with heat-related human health at various scales, 2) provide a summary of the directions and magnitudes of these environmental impacts, 3) discuss the extent to which the consistencies in these findings are related to how the environmental characteristics are measured, and 4) suggest some recommendations for the future research.

2.3. Methods

2.3.1. Data sources and search strategy

This study conducted a search on empirical studies of the effects of ULC on heat-related health published by May 2021. Journal databases, such as PubMed, Web of Science, ScienceDirect, and EBSCO, were used. Titles and abstracts were preferentially considered to investigate relevant research. The references of selected studies were also reviewed after collection of the full article, and additional search was conducted to include relevant research not screened in the main search. Only peer-reviewed journal articles with English were considered by using the following MeSH (Medical Subject Headings) terms and keywords: for urban landscape, vegetation, green, tree, canopy, shade, green roof, water, and wind were used; for thermal environments, extreme heat and heat waves were used; for human health, mortality, morbidity, heat stroke, emergency medical service, hospital admission, and ambulance call were used. Also, all sub-keywords were included.

2.3.2. Inclusion and exclusion criteria

Studies on the relationship between urban landscape and heat-related health mainly can be divided into two categories such as micro and macro-scale studies depending on information such as the methodology and health outcomes. While micro-scale studies mainly focus on thermal comfort and thermal stress, which cause heat-related mortality and morbidity (Sharon L.

Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006), most heat-related mortality and morbidity studies have been conducted at the macro-scale. It is well known that urban landscape affects human health through mitigating urban microclimate (Gronlund, 2014; S. L. Harlan et al., 2013). Thus, we conducted a review of studies that are considering all factors such as physical neighborhood environmental characteristics, urban microclimate, and human health together. According to Santos Nouri, Costa, Santamouris, and Matzarakis (2018) and Lai, Liu, Gan, Liu, and Chen (2019), review studies on the impact of urban landscaping on heat-related human health at the micro-scale are well established. However, there are no review studies specifically addressing the relationship between ULC and heat-related health. Therefore, we mainly focused on a systematic analysis of macro-scale studies, and conducted a briefly comprehensive review of micro-scale studies. The target population of this review is of all ages and There were no regional restrictions.

To clarify the relationship between urban landscape and health, we used the following eligibility criteria. First, studies were included if the following criteria were met: 1) urban landscape characteristic was a main exposure of interest and heat-related health issues were also analyzed, 2) studies have results of appropriate quantitative effect estimates using original data, and 3) studies discussed comparable outcomes of heat-related health. Meanwhile, studies related to thermal stress and thermal comfort on micro-scale have been excluded from the systematic analysis of this study only by conducting a brief comprehensive review. Also, studies were excluded if they were 1) not assessed the urban landscape effect on heat-related issues, 2) only focused on the temperature effect on health, 3) not used the original heat-related health data sources, 4) not considered all the factors such as urban landscape, urban microclimate, and human health together. Lastly, reference list, study area, unit of analysis, time period, target population, study design, ULC elements, health outcomes, and key findings were recorded by two reviewers.

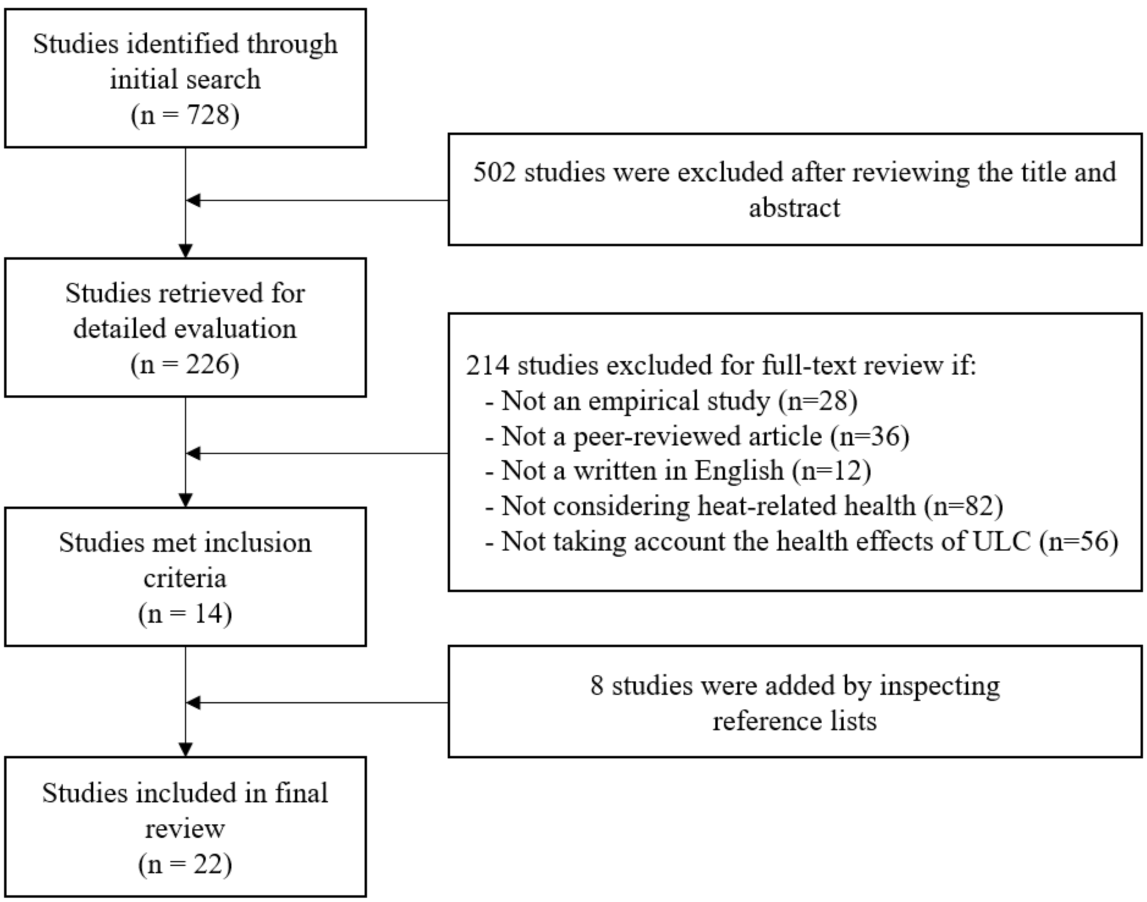

Figure 6. Article Selection Process

2.4.Results

A total of 728 articles were identified in the initial search. 502 studies were excluded after reviewing the title and abstract. 226 Studies were retrieved for detailed evaluation. According to the inclusion criteria and exclusion criteria, 14 studies were included. Then, to include relevant research not screened through the eligibility criteria, the references of selected studies were also reviewed. Finally, 22 studies were selected in the review (Figure 6). Among them, 16 studies identified the relationship between ULC and mortality, and 6 studies analyzed the impact of ULC on morbidity such as heat stroke, emergency medical service, hospital admission, and ambulance call.

2.4.1. Impact of urban landscape characteristics on heat-related health

It is well known that urban landscape is highly related to urban thermal environment. Previous studies have shown the relationship between ULC and thermal environment by referring to how urban landscape contributes to the reduction of urban temperature (Jaganmohan et al., 2016; Oliveira et al., 2011; Y. Tan et al., 2013; Zhang et al., 2014; Zhao et al., 2016). Also, a lot of other studies have demonstrated that thermal environment such as extreme heat and heatwaves caused heat-related health issues (S. L. Harlan et al., 2013; Hayhoe et al., 2010; Hoshiko et al., 2010; Jones et al., 1982; D. W. Kim et al., 2016; Jaime Madrigano et al., 2013).

The findings of this review indicate four main types of urban landscape characteristics: vegetation, urban structure, surface, and water body. Elements used slightly different words such as urban vegetation cover, tree cover, grass cover, vegetation area, urban green space, rooftop green space, urban forest cover, canopy cover, and so on, but they all meant green areas. For the comprehensive concept of green area, most studies have focused on the percentage of green space rather than on the consideration of detailed information about various types of vegetation elements. It means that the main urban landscape characteristic may be a percentage of green space at the macro-scale studies. The studies used in the analysis have shown that urban green space contributes to lower heat-related health. According to Burkart et al. (2016), the relationship between 1°C increase in universal thermal climate index (UTCI) and heat-related mortality in the 99th percentile of extreme heat days was increased in regions where the Normalized Difference Vegetation Index (NDVI) quartile (14.7% higher; 95% CI: 1.9, 17.5%) is lowest than in regions where NDVI is highest quartile (3.0%; 95% CI: 2.0, 4.0%). Chen et al. (2014) found that creating public parks in cities and doubling the green area of cities could reduce heat-related health problems by about 33 percent to 99 percent. Also, the result of Son et al. (2016) showed that, at the 90th percentile (25.1°C) or above, the association between temperature 1°C increase and heat-related mortality was highest in areas with low vegetation level. One study suggested that low amounts of rooftop greening worsens heat-related human health (E. J. Kim & Kim, 2017). According to them, mortality during heat wave increased in areas with low rooftop green space (OR=1.207; 95% CI: 1.042–1.399). Other studies showed that ULC such as shade, grass, and shrubs contribute to addressing heat-related morbidity. According to Kilbourne et al. (1982), residential areas with trees and shrubs have an effect on reducing heat stroke.

Other studies have noted urban structure, surfaces, and water bodies rather than green space. Water infrastructure as well as green space ensure pleasant living outdoors and prevent heat-related health (Mazhar, Brown, Kenny, & Lenzholzer, 2015). Burkart et al. (2016) considered proximity to water by using remote sensing data such as NASA Shuttle Radar Topographic Mission (SRTM). In their spatial program, the distance to water was calculated for each pixel and they used the mean distance for the entire parish area. They found that the short distance from water bodies can alleviate health problems along with the fact that a 1C increase in thermal comfort model (UTCI) in areas with a distance of more than 4 kilometers from water was related to 7.1 percent increase in heat-related mortality (95% CI: 6.2, 8.1%). In contrast, heat-related mortality estimates increased only 2.1 percent in areas with less than 4 kilometers of water (95% CI: 1.2, 3.0%). Some studies also showed that protection strategies for albedo on the urban pavement and building facilities can address heat-related health problems. Increasing green area and albedo of the urban surface can offset the 40 to 99% increase in heat-related mortality (Stone et al., 2014). Graham, Vanos, Kenny, and Brown (2016) studies the relationship between hard surface cover and heat-related ambulance call during hot weather. They found that the number of heat-related ambulance calls was increased with high percentage of hard surface cover. Kovach, Konrad II, and Fuhrmann (2015) and Gabriel and Endlicher (2011) studied how urban structures affect heat-related health by comparing of urban and rural environments. They used spatial regression to investigate how urban and rural green areas were related to emergency room visits and found that more health problems occurred in urban areas. Meanwhile, we found that more urban landscape elements in the simulation method than in the observational method. For example, Chen et al. (2014) used simulation model (UCM-TAPD model) and they considered urban form, vegetation type, vegetation coverage (%), leaf area index, building coverage (%), average building height (m), and building height to canyon width radio. Also, Stone Jr et al. (2014) used WRF simulation with various scenarios. In their scenarios, they can manipulate private & public greening and building & road albedo enhancement with type of modification.

2.4.2. Approaches for urban landscape and heat-related health

All the studies exploring the relationship between ULC and heat-related health were conducted in regions of North America, Europe, and Asia including 12 studies in USA (Clarke, 1972; Gronlund, Berrocal, White-Newsome, Conlon, & O'Neill, 2015; S. L. Harlan et al., 2013;

Johnson, Stanforth, Lulla, & Luber, 2012; Kilbourne, Choi, Jones, & Thacker, 1982; Kovach et al., 2015; Jaime Madrigano et al., 2013; Nayak et al., 2018; Stone Jr et al., 2014; Uejio et al., 2011; Zanobetti, O'Neill, Gronlund, & Schwartz, 2013), 2 studies in Canada (Graham et al., 2016; Smoyer, Rainham, & Hewko, 2000), one in China (J. Tan et al., 2010), one in Australia (Chen et al., 2014), two studies in South Korea (E. J. Kim & Kim, 2017; Son, Lane, Lee, & Bell, 2016) one in Vietnam (Dang, Van, Kusaka, Seposo, & Honda, 2018), one in Portugal (Burkart et al., 2016), one in Spain (Xu et al., 2013), and one in Germany (Gabriel & Endlicher, 2011) and most of which are developed countries (Table 1). These studies provided empirical evidence for the effects of ULC including urban green, tree canopy, and pavement albedo on heat-related human health including chronic health problems such as mortality, and acute health problems such as heat stroke, emergency medical service, hospital admission, and ambulance call. While micro-scale studies utilized a variety of urban climate components such as air temperature, relative humidity, wind speed, and solar & terrestrial radiation, most studies on the macro-scale used surface temperature and mean & maximum air temperature to describe urban microclimate condition. In addition, most studies considered the populations of all ages. Six studies considered different age groups. J. Madrigano et al. (2015) focused on the adult population aged 19 over. Gronlund et al. (2015), Burkart et al. (2016), and Smoyer et al. (2000) conducted an analysis of elderly population. Uejio et al. (2011) Johnson et al. (2012), and Nayak et al. (2018) used the elderly population over 65 as an independent variable in their analysis.

Most of the studies on the relationship between ULC and HRH have been analyzed at a macro-scale, including metropolitan, county, and city levels, except Chen et al. (2014) that used the simulation method and analyzed the relationship at a macro-scale around the CBD area. For the unit of analysis, most studies were conducted at or above the census block group level. In addition, in some studies, zip code-level was used as unit if analysis (Gronlund et al., 2015; Kovach et al., 2015). Studies in countries that cannot be defined with U.S. census Bureau Geographical Entities used their own geographic units corresponding to US census units. For example, Seoul, South Korea, consists of 25 districts throughout the city, which were used as analysis units (E. J. Kim & Kim, 2017; Son et al., 2016). Also, Burkart et al. (2016) used 213 civil parishes. In most studies, the unit of analysis is generally higher than the census block group level, which is macro-scale. In the micro-scale studies, primary data of ULC was obtained from field measurements, but macro-scale studies required ULC information over a wide range of areas. There was a limit to collecting primary data for ULC at macro-scale studies. Thus, macro-scale studies generally used secondary data such as land use dataset or Landsat satellite images such as LIDAR-based Cover classified surface, Normalized Difference Vegetation Index (NDVI), MODIS Vegetation Continuous Fields (VCF) data, National Land Cover Database (NLCD), etc.

Table 1. Characteristics of Studies about ULC and Heat-related Health

Reference	Category: Vegetation	Category: Water body	Category: Surface	Category: Urban Structure	Study area	Unit of analysis	Time period	Target	Study design	ULC elements	Health outcome	Key findings
Kilbourne, Choi, Jones, and Thacker (1982)	●				St Louis and Kansas, US	City level	1980, Jul-Aug	All	Case-control study: linear logistic regression	Urban tree cover (LLUD), Urban shrubbery cover (LLUD)	Heatstroke	"Factors associated with decreased heatstroke were using home air conditioning, spending more time in air-conditioned places, and living in a residence well shaded by trees and shrubs."
Harlan, Declet-Barreto, Stefanov, and Petitti (2013)	●				Maricopa County, Arizona, US	Census block group level	2000–2008, May-Sep	All	Time-series study: binary logistic regression & spatial analysis	Urban vegetation cover (NDVI)	Heat-related death: heat exposure, heat stress, heat stroke, and hyperthermia	"Unvegetated area had a weak but significant positive association with the odds of at least one heat death in a census block."
Dang, Van, Kusaka, Seposo, and Honda (2018)	●				Ho Chi Minh, Vietnam	24 districts of the City	2010-2013, Apr	All	Simulation: WRF-UCM model	Urban Canopy Model (UCM)	Daily mortality	"Every increase in green space of 1 km2 per 1000 people can prevent 7.4 mortalities (95% CI = 1.3, 13.5) attributable to heat in HCM City."
Xu et al. (2013)	●				Barcelona metropolitan area, Spain	Census tract level	1999-2006, Heat waves	All	Time-stratified case-crossover study: conditional logistic regression	Tree cover (MODIS)	All causes of mortality	"The effect of heat on mortality was higher in the census tracts with a large percentage of old buildings (RR=1.21, 95% CI 1.00 to 1.46), manual workers (RR=1.25, 95% CI 0.96 to 1.64) and residents perceiving little surrounding greenness (RR=1.29, 95% CI 1.01 to 1.65)."

Reference	Category: Vegetation	Category: Water body	Category: Surface	Category: Urban Structure	Study area	Unit of analysis	Time period	Target	Study design	ULC elements	Health outcome	Key findings
Kim and Kim (2017)	●				Seoul, South Korea	25 local districts in Seoul	2009 -2012	All	Time-stratified case-crossover study: conditional logistic regression	Rooftop green space (LLUD), Urban vegetation cover (LLUD), Park area per 1 person (LLUD), Green area around the public buildings (LLUD)	All causes of mortality: non-accidental	"Death during heat waves was more likely to occur in districts with a low proportion of green space around buildings (OR=1.178; 95% CI: 1.016–1.366) and a low proportion of rooftop green space (OR=1.207; 95% CI: 1.042–1.399), or those that had fewer hospitals (OR=1.186; 95% CI: 1.019–1.379)."
Chen et al. (2014)	●				Melbourne, Australia	Local meso-scale	2009, 2030, and 2050.	All	Simulation: UCM-TAPM model	Urban vegetation cover (NDVI)	All causes of mortality	"Around 37-99% reduction in heat related mortality rate have been estimated by doubling the city's vegetation coverage and transforming the city into parklands."
Son, Lane, Lee, and Bell (2016)	●				Seoul, South Korea	25 local districts in Seoul	2000-2009, May-Sep	All	Time-series study: over dispersed Poisson generalized linear model	Urban vegetation cover (NDVI)	All causes of mortality	"The association between total mortality and a 1°C increase in temperature above the 90th percentile (25.1°C) was the highest with low vegetation level. The heat effect was a 4.1% (95% confidence interval (CI) 2.3, 5.9%), 3.0% (95% CI 0.2, 5.9%), and 2.2% (95% CI -0.5, 5.0%) increase in mortality risk for low, medium, and high NDVI group, respectively."

Reference	Category				Study area	Unit of analysis	Time period	Target	Study design	ULC elements	Health outcome	Key findings
	Vegetation	Water body	Surface	Urban Structure								
Gronlund, Berrocal, White-Newsome, Conlon, and O'Neill (2015)	●				8 counties in Michigan, US	Zip code level	1990-2007, May-Sep	Elderly (+65)	Case-crossover study: conditional logistic regression	Urban vegetation cover (LLUD)	Heat-related death: heat-related disease, cardiovascular, and respiratory	"The odds of cardiovascular mortality during extreme heat (99th percentile threshold) vs. non-EH were higher among individuals in ZIP codes with high (91%) non-green space (1.17, 95% CI=1.06-1.29 vs. 0.98, 95% CI=0.89-1.07 among individuals in ZIP codes with low (39%) non-green space)."
Kovach, Konrad II, and Fuhrmann (2015)	●				North Carolina, US	Zip code level	2007-2012, May-Sep	All	Descriptive study: spatial error regression model	Urban forest cover (NLCD)	Heat-related illness: emergency department visit (heat stroke, heat cramps, heat exhaustion, etc.)	"Risk factor for heat-related mortality such as decreased vegetation was associated with increases in Heat-related Illness."
Zanobetti, O'Neill, Gronlund, and Schwartz (2013)	●	●			135 US cities	Zip code level	2004–2006, Cold (Nov-Mar) and warm (May-Sep)	All	Case-only study: logistic regression model	Urban vegetation cover (NLCD), Water body cover (NLCD)	Cardiovascular hospital admissions	"With less water (1.03, 95% CI:1.01–1.05) modifying the effect of water-vapor pressure on mortality, and less green space (1.03, 95% CI:1.01–1.05) modifying the effect of temperature in warm months on mortality."

Reference	Category				Study area	Unit of analysis	Time period	Target	Study design	ULC elements	Health outcome	Key findings
	Vegetation	Water body	Surface	Urban Structure								
Jaime Madrigano et al. (2013)	●	●			Worcester, US	Census block group level	1995, 1997, 1998, 1999, 2001, and 2003 Cold (Nov-Mar) and warm (Apr-Oct)	All	Case-crossover study: conditional logistic regression	Urban vegetation cover (NDVI), Water body cover (LLUD)	Myocardial Infarction mortality	“Subjects who had a large (> 100,000 m2) lake or reservoir within a 400 m radius of their home were less susceptible to the effects of a decrease in temperature (0.90, 95% CI:0.63–1.28) than those who did not (1.20, 95% CI:1.04–1.39) at p=0.02.”
Burkart et al. (2016)	●	●			Lisbon, Portugal	212 civil parishes in Lisbon	1998 -2008	Elderly (+65)	Poisson generalized additive model	Urban vegetation cover (NDVI), Distance to water bodies (SRTM)	All causes of mortality	“The association between mortality and a 1°C increase in universal thermal climate index (UTCI) above the 99th percentile (24.8°C) was stronger for areas in the lowest the Normalized Difference Vegetation Index (NDVI) quartile (14.7% higher; 95% CI: 1.9, 17.5%) than for areas in the highest quartile (3.0%; 95% CI: 2.0, 4.0%). In areas > 4 km from water, a 1°C increase in universal thermal climate index (UTCI) above the 99th percentile was associated with a 7.1% increase in mortality (95% CI: 6.2, 8.1%), whereas in areas ≤ 4 km from water, the estimated increase in mortality was only 2.1% (95% CI: 1.2, 3.0%).”
Stone Jr et al. (2014)	●		●		Three US Cities (Atlanta /	Census tract level	2010-2050	All	Simulation: GISS-WRF model	Urban vegetation cover (NLCD),	Heat–related mortality: Non-accidental	“Combinations of vegetation and albedo enhancement to offset

Reference	Category				Study area	Unit of analysis	Time period	Target	Study design	ULC elements	Health outcome	Key findings
	Vegetation	Water body	Surface	Urban Structure								
					Philadelphia / Phoenix)					Albedo of building roof surfaces (NLCD), Albedo of paved surfaces (NLCD)		projected increases in heat-related mortality by 40 to 99%."
Uejio et al. (2011)	●		●		Phoenix, Philadelphia, US	Census block group level	1999, Jul-Aug	All +65	Time-series Study: Generalized Linear and Mixed Models (GLMM)	Impervious surface (NLCD), Urban vegetation cover (NDVI)	Extreme heat mortality , extreme heat distress call	"The urban heat island as measured by impervious surface (1.01, 95% CI: 1.01–1.02) and maximum nighttime surface temperature (1.17, 95% CI: 1.09–1.25) increased heat distress call."
Graham, Vanos, Kenny, and Brown (2016)	●		●		Toronto, Canada	Census tract level	27–30 June, 2005 29 July–2 August, 2006 24–27 May, 2010 29 August–2 September, 2010	All	Descriptive study: correlation analysis	Tree canopy cover (LLUD), Hard surface cover (LLUD)	Heat-related ambulance calls	"Neighborhoods with less than 5% canopy cover had approximately five times as many heat-related calls as those with greater than 5% tree canopy cover, and nearly fifteen times as many heat-related calls as Census Tracts with greater than 70% tree canopy cover. * Even a marginal increase in the tree canopy cover from <5% to >5% could reduce heat-related ambulance calls by approximately 80%."
Johnson, Stanforth, Lulla, and Luber (2012)	●			●	Chicago, US	Census block group level	1995, Summer	All +65	Descriptive study: principal component analysis	Urban vegetation cover (NDVI), Built-up volume (NDBI)	Daily mortality	"UHI (LST, NDVI, NDBI) accounts for 18.80% of the variance in heat vulnerability."

Reference	Category				Study area	Unit of analysis	Time period	Target	Study design	ULC elements	Health outcome	Key findings
	Vegetation	Water body	Surface	Urban Structure								
J. Madrigano, Ito, Johnson, Kinney, and Matte (2015)	●			●	New York City, US	Census tract level	2000-2011, Heat waves	Adult (>19)	Case-only study: logistic regression	Urban vegetation cover (LiDar-Based), Grass/shrub cover (LiDar-Based), Built-up volume (LiDar-Based)	Heat wave–related mortality - Cardiovascular disease - Myocardial infraction - Congestive heart failure - Chronic obstructive pulmonary disease	"Deaths during heat waves were more likely among residents in areas of the city with higher relative daytime. Summer surface temperature and less likely among residents living in areas with more green space. Individuals living in greener areas of the city were less likely to die during and immediately after heat waves with an OR = 0.96 (95% CI: 0.94, 0.99) for those living in census tracts with a proportion of grass and shrubs above the median value, and an OR = 0.97 (95% CI: 0.94, 1.00) for those living in census tracts with a proportion of trees above the median value."
Nayak et al. (2018)				●	New York City, US	Census tract level	2008-2012, May-Sep	All +65	Descriptive study: negative binominal analysis	Built-up volume (NLCD), Urban vegetation cover (NLCD)	Heat-stress emergency department (ED) visits	"The most heat vulnerable areas were observed in 20% of census areas with a high proportion of environmental/urban factors, including building density."
Gabriel and Endlicher (2011)				●	Berlin and Brandenburg, Germany	districts of Berlin	1990-2006 Heat waves	All	Descriptive study of a time series	Urban sprawl	Daily mortality	"Mortality rates are up to 67.2% higher during extreme heat waves, in the city center of Berlin."

Reference	Category				Study area	Unit of analysis	Time period	Target	Study design	ULC elements	Health outcome	Key findings
	Vegetation	Water body	Surface	Urban Structure								
Tan et al. (2010)				●	Shanghai, China	11 districts of urban and suburban	1974-2004, May-Oct	All	Descriptive study: linear regression	Urban sprawl	Daily mortality	"The excess mortality rate in the urban area is about 27.3/100,000, compared to only 7/100,000 in the exurban districts in the 1998 heat wave."
Clarke (1972)				●	New York City, US	City level	1955, July	All	Descriptive study: cross-section	Urban sprawl	Daily mortality	"During heat waves, the death rate due to heat-related ailments is often significantly higher in urban areas than nonurban areas."
Smoyer, Rainham, and Hewko (2000)				●	Toronto, Canada	City level	1980-1996, Jun-Aug	Elderly (+65)	Descriptive study: linear regression	Urban sprawl	Daily heat-related mortality Non-accidental causes of death	"Ongoing urban development and sprawl was expected to intensify heat-stress mortality."

2.5.Discussion

2.5.1. Urban landscape and heat-related health at macro-scale

Previous studies found that there is a relationship between urban landscape and heat-related human health. However, there is a lack of review in their relationship, which requires a comprehensive review. The results of this review provide evidence on how ULC affects heat-related health. The point is that ULC contributes to addressing heat-related mortality from extreme heat. Mitigating the urban temperature has a positive impact on solving human health problems, and design strategies for ULC contribute to this reduction of heat.

The results of this review indicate that green space, the most important element of urban landscape, is closely related to heat reduction in urban areas. This is consistent with previous studies that claimed that green spaces improve the thermal environment of urban areas. (Bowler, Buyung-Ali, Knight, & Pullin, 2010; Jaganmohan, Knapp, Buchmann, & Schwarz, 2016; Oliveira, Andrade, & Vaz, 2011). However, it's worth noting that some studies have shown that green areas were not a significant factor in explaining heat-related health. Vaneckova, Beggs, and Jacobson (2010) conducted a study on spatial analysis of heat-related mortality among the elderly in Sydney, Australia. According to their results, proportion of vegetation was not a significant factor. Also, Uejio et al. (2011), selected for this study, found that the percentage of impervious surface in the center block groups in Phoenix affected heat distress calls reduction, but showed that green areas and impervious surface were not related to heat-related deaths in Philadelphia. Therefore, further studies are needed to clarify the impact of urban vegetation on heat-related health outcomes. In particular, urban green areas and urbanization should be defined accurately and focused on whether the results vary depending on regional characteristics and populations.

There are two types of health outcome, which are affected by urban microclimates; chronic and acute health. Most studies referred to mortality for their chronic health outcome. The findings indicated that cardiovascular disease, myocardial infarction, and congestive heart failure cause heat-related mortality. On the other hand, studies investigating the relationship between ULC and acute health typically utilized heat-related diseases data such as heat, heat stroke, emergency department visits, and heat-related ambulance calls. Of the 22 studies, only six used acute health data to analyze the effects of ULC on morbidity. It means that more research has been published relating to chronic than acute health issues and ULC affects acute health outcomes caused by prolonged exposure to extreme thermal environments, but the evidence may not be enough to draw a solid relationship.

The concern of the elderly is increasing because they are particularly vulnerable to environmental changes and less resistant to heat wave than younger adults (Vandentorren et al., 2006). Meanwhile, many studies have provided evidence on the health effects of the thermal environment on older adults. For example, Åström, Bertil, and Joacim (2011) conducted a systematic review on heat wave impact on morbidity and mortality in the elderly population. They analyzed six studies on the relationship between temperature and disease and 24 studies on the relationship between temperature and death, and their findings showed a consistent increase in cardiovascular, respiratory, and respiratory morbidity and mortality in older adults due to the heat wave on hot days. However, as the results of this study confirm, there is a lack of research on the effects of ULC on the heat-related health in older adults. According to the findings in this study, only three studies including Smoyer, Rainham, and Hewko (2000), Gronlund, Berrocal, White-Newsome, Conlon, and O'Neill (2015), and Burkart et al. (2016) conducted a study of the elderly and showed that ULC contributed to alleviating heat-related mortality among older adults.

For health-related health studies, it is important to compare cases with controls to analyze the degree of exposure to the cause of disease and explain the exact causality using the appropriate type of study (Gronlund, 2014). According to the results of the review, types of research can be divided into two main categories: observational studies and experimental studies, which are mainly used in the health field. Among 22 studies, most of them used observational methods, except for three using experimental methods (Chen et al., 2014; Dang, Van, Kusaka, Seposo, & Honda, 2018; Stone Jr et al., 2014).

Observational studies are related to time, location, and patients, and in most observational studies, time series and case cross-crossover design, which are common design methods for health data, are widely used (Stuart, DuGoff, Abrams, Salkever, & Steinwachs, 2013). Most of the studies used in the review of this study analyzed the changes over time and seasonal flow between ULC and health through time-series analysis. Son, Lane, Lee, and Bell (2016) used an over-dispersed Poisson generalized linear model. Their research period was between 2000 and 2009. They analyzed the impact of urban green areas on heat-related mortality as time series changes, and investigated how temperature-health associations in particular are affected by individual levels and environmental characteristics. Also, Burkart et al. (2016) identified the impact of urban vegetation and water bodies on heat-related mortality for the older populations aged 65 and over between 1998 and 2008. They used Poisson generalized additive models for the relationship between equivalent temperature (UTCI) and the Normalized Difference Vegetation Index (NDVI) and distance to water bodies (more than 4km vs. less than 4km). Time-series analysis uses time-series data to extract significant statistics and information. Time-series data has information about a set of specific periods or intervals. Time-series analysis can be an alternative to case-crossover design for analyzing the health-related issues because case-crossover design may create some biases with lower statistical productivity than time-series analysis (Wei, 2006). Meanwhile, the case-crossover method can be controlled by design for potential confounding, but time-series analysis can be controlled by modeling because time-series analysis can be used when more sophisticated consideration of trends and seasonality over time is desired because it has more complicated statistical modeling compared to case-crossover analyses (Lu & Zeger, 2006).

Some studies have used time-stratified case cross-analysis, an advanced form of case cross-analysis. This method has the advantage of being suitable for short-term exposures, such as heat-related health, because the group is compared by defining the day of the week as the day of the case. To investigate the effects of individual and regional-scale characteristics on heat wave-related mortality, Kim and Kim (2017) used a time-stratified case-crossover analysis for the period from 2009 to 2012. Gronlund et al. (2015) they utilized time-stratified case-crossover design to find how sociodemographic features affect heat-related mortality through a comparison between non-extreme heat and extreme heat day, May-September, 1990-2007. Y. Xu et al. (2013) also used a time-stratified case-crossover analysis using daily mortality in the Barcelona, Spain during the warm seasons from 1999 to 2006. The three studies used conditional logistic regression (CLR), which is commonly used in case-crossover approach, to estimate a relative risk as the measure of association. CLR considers its matching with stratification in observational studies as an extension of logistic regression. While logistic regression analysis can find the relationship between a binary dependent variable and independent variables with a logit model, CLR matches case subjects with a particular condition with ‘n’ control subjects without some condition (Navidi, 2008).

Meanwhile, for investigating the effects of urban environmental characteristics on heat-related human health, we classified the simulation method as an experimental study because main exposure can be controlled through this. The three simulation studies conducted with three different models including the GISS -WRF model, the WRF-UCM model, the UCM-TAPD model. Stone Jr et al. (2014) used the GISS-WRF model. The GISS-WRF model means that wide-area weather data obtained through the Goddard Institute for space Studies–Global Atmosphere-Ocean ModelE (GISS ModelE) are downscaled through the Weather Research Forecasting (WRF) to obtain climate data for the future. The WRF model is a mesoscale numerical weather prediction model. The WRF model considers vegetation enhancement differentiated by property type such as private and public land, and albedo enhancement differentiated by material types such as roof and surface pavement. Dang et al. (2018) used the WRF-UCM model that the WRF model was combined with the urban canopy model (UCM). The UCM model is designed to explore the physical environments of urban surfaces. They considered urban surface such as albedo and emissivity, land use such as vegetation cover and impervious pavement cover, and water body such as distance to lake. The UCM-TAPD model means the UCM model was combined with The Air Pollutants Model (TAPD). Chen et al. (2014) analyzed the relationship between heat-related mortality and urban vegetation coverage by using this model.

2.5.2. Urban landscape and heat-related health at micro-scale

In contrast to macro-scale studies, so many studies have been conducted on the relationship between urban environment and thermal comfort at the micro-scale. Studies of the relationship between urban landscaping and human health on the micro-scale mainly utilize thermal stress and thermal comfort as the main health outcome. Heat stress is an important factor that causes heat-related health (Sharon L. Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006). Thermal comfort is defined as a state of mind that shows satisfaction with the thermal environment and is used as a measure of evaluating heat stress (M. Xu, Hong, Mi, & Yan, 2018). Urban landscape elements for micro-scale, like macro-scale, can be roughly divided into four categories: vegetation, surface, water body, and urban structure, as well as macro-scale. However, small-scale studies include more diverse and specific urban environments than macro - scale studies. The comprehensive urban landscape elements for each category used in micro-scale studies were shown in Figure 7.

The methodology for assessing the relationship between urban landscape and thermal comfort at micro-scale is relatively consistent compared to the macro-scale studies. According to Lai, Liu, Gan, Liu, and Chen (2019), in the micro-scale studies, most research methodologies can be divided between field measurement and simulation, although some studies are conducted in combination of both methods. Macro-scale studies use secondary data due to limitations in data availability, while micro-scale studies used primary data obtained from measurements. Most studies obtain microclimate data from on-site measurements for analyzing the impact of urban landscape on human thermal comfort. For on-site measurement, we need variables for the certain environment to study the effect of the environment, and we have to monitor thermal environment components such as air temperature, relative humidity, solar and terrestrial radiation, and wind speed. For example, Irmak, Yilmaz, and Dursun (2017) selected botanical garden as the certain environment to investigate the influence of different urban pavement on thermal environment. They conducted measurement at the site for nine different pavement materials and used infrared thermometer to monitor and measure the thermal environment. Mobile measurement or weather station can be used to monitor microclimatic components for long-term or short-term period. Measured microclimate data can be used in two main ways: first of all, the differences in thermal environment according to neighborhood environmental characteristics can be investigated through descriptive analysis. Then, measured microclimate data can be applied to energy budget models to measure human thermal comfort. For example, Kosaka et al. (2018) used the thermal comfort model (COMFA model) to estimate runner's thermal comfort for designing 2020 Tokyo Olympic marathon course. They measured microclimate conditions including air temperature, relative humidity, solar radiation, surface temperature, and wind speed by using vehicle and bicycle equipped with weather observation instruments. Then applied the thermal data into energy budget model, COMFA model, and calculated energy budget of runners to assess their thermal comfort. In addition to the COMFA model, a number of other models, such as Universal Effective Temperature (ETU), Index of Thermal Stress (ITS), MENEX model, Physiologically Equivalent Temperature (PET), Predicted Mean Vote (PMV), Perceived Temperature (PT), Universal Thermal Climate Index (UTCI), and so on, are being used to measure human thermal comfort using the data obtained from the measurements (Coccolo, Kämpf, Scartezzini, & Pearlmutter, 2016).

On the other hand, one of weakness of field measurement is lankness of experimental control. To solve this issue, simulation method can be used. However, analysis using simulation requires careful design (Lai et al., 2019). Among the various models, Energy Balancing Model

(EBM) and Computational Fluid Dynamics (CFD) are the most used, and ENVI-met model is the most utilized among CFD methods (Lai et al., 2019). Simulation method has advantage for the outdoor environment. It can be carried out on a variety of scales, from microlevel to macro-level. Certain models may normally fit on one scale but may not be suitable for other scales, so multiple-scale modeling systems can be utilized according to the objectives of the study. For example, Dang et al. (2018) used the WRF-UCM model that the WRF model was combined with the urban canopy model (UCM). The UCM model is designed to explore the physical environments of urban surfaces at neighborhood scale and the WRF model consider the urban thermal environment at multi-scales.

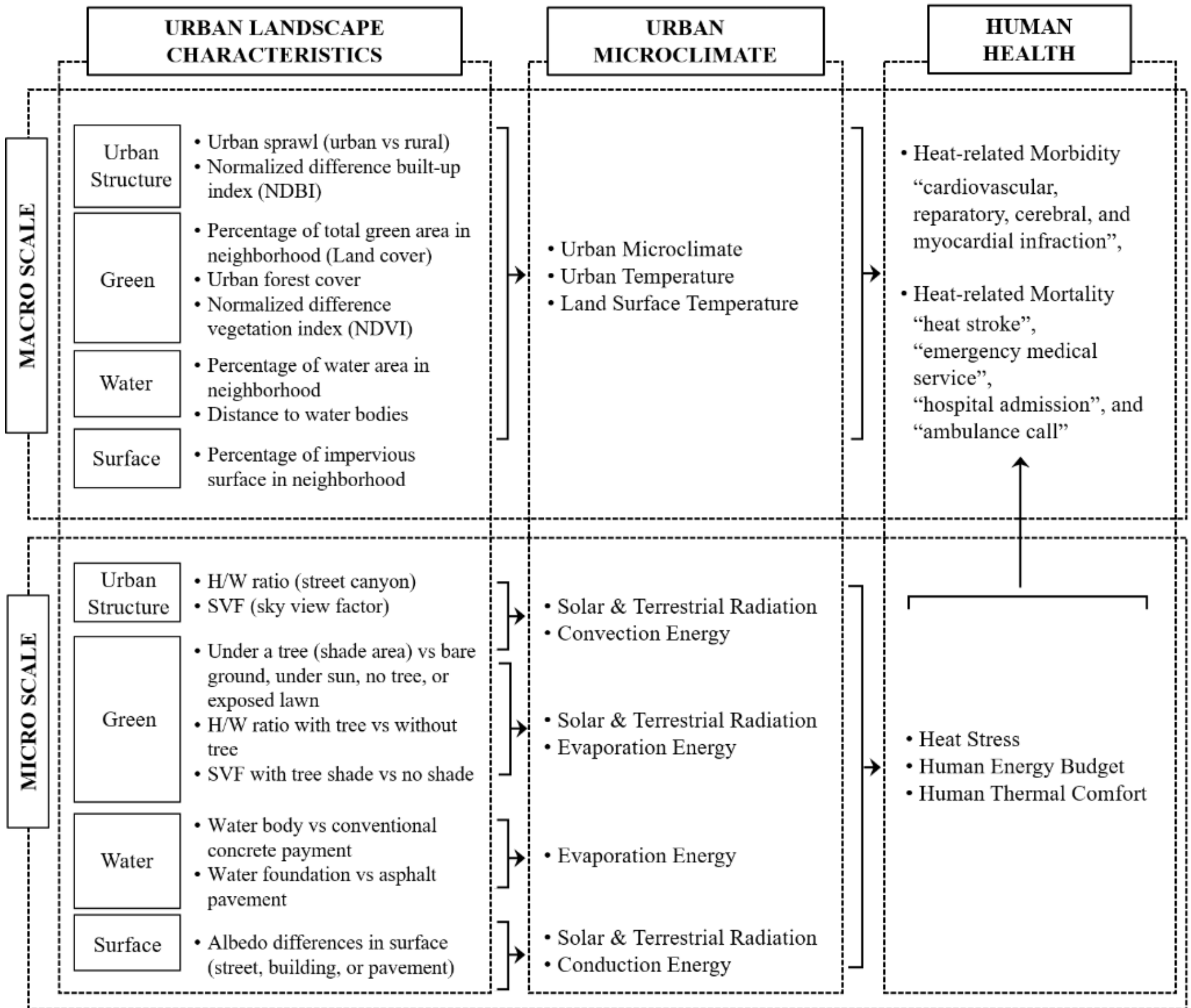

Figure 7. Comprehensive Framework for Urban Landscape Characteristics, Urban Microclimate, and Human Health at Micro and Macro-scales

2.5.3. Knowledge gaps and suggestions for the future research

This study is meaningful in that it provides an initial comprehensive review of the effects of ULC on thermal health using systematic criteria. Meanwhile, future research on the effects of urban landscape on heat-related health should consider the following for a more systematic and meaningful analysis of relationships. First, there is a lack of research on vulnerable groups such as children and the elderly. The results show that there is no study of the relationship between ULC and heat-related health of children. Also, few studies have focused on the effects of ULC on heat-related health in children under the age of 1. There are only three studies of older adults. According to previous studies, various age groups, including infants, children, and elderly are most vulnerable to heat-related death because they are more sensitive to excessive heat stress (Epstein & Moran, 2006). In particular, infants have been identified as at higher risk for heat-related health issues because of inadequate thermal regulatory responses (Basu & Ostro, 2008). Thus, more studies should be needed to assess the ULC effects on heat-related health vulnerability on vulnerable groups through depth consideration. Second, there is no information on the exact optimal threshold for urban temperature mitigation effects that ULC needs to address heat-related health problems. It may be impossible to investigate specific thresholds for all the population because of their different characteristics and climate conditions. However, identifying detailed thresholds for the temperature reduction effect of UCL on heat-related health in various regions and populations can be used as useful information. Lastly, most of the selected studies were conducted in high-income countries or regions in this review. People in developing countries are generally more vulnerable to heat-related health because their low-income, large population, and lack of infrastructure. Thus, more attention should be paid to developing countries in Asia and Africa.

2.6. Conclusion

This review investigated the effect of ULC on heat-related human health on various spatial scales through a systematic review of macro-scale studies and a comprehensive review of micro-scale studies. This study found that heat-related mortality from cardiovascular and respiratory diseases and heat-related morbidities such as heat stroke, emergency medical service, hospital admission, and ambulance calls after exposure to extreme thermal environments were the main health outcomes on humans at macro-scale studies. In the micro-scale studies, thermal stress and thermal comfort were the health consequences of exposure to thermal environments. In this regard, our findings showed that ULC have positive or negative effects on these heat-related health issues. Meanwhile, the impact of UCL on heat-related health differed by the various spatial scales. For four main categories, including vegetation, water body, surface, and urban structure, macro-scale studies have used elements that could contain comprehensive information about large areas such as percentage of total green area in the neighborhood, percentage of water area in the neighborhood, percentage of impervious surface in the neighborhood, and urban sprawl status. In the micro-scale studies, more specific and diverse ULC such as H/W ratio (street canyon), SVF, comparing under a tree with no tree, comparing water body with conventional concrete pavement, and albedo of different materials were considered for the four main classes, as in macro-scale studies. Further research should focus on the following. More studies should identify the effects of ULC on heat-related health in more diverse climate zones. Older adults and children are most vulnerable to heat-related health, so further research is needed on them. Also, with accurate information on urban temperature mitigation effects of ULC to address heat-related health problems, better strategies should be derived to address heat-related health problems.

3. STUDY TWO: EFFECTS OF URBAN LANDSCAPE AND SOCIODEMOGRAPHIC CHARACTERISTICS ON HEAT-RELATED HEALTH USING EMERGENCY MEDICAL SERVICE INCIDENTS

3.1. Summary

It is well known that extremely hot weather causes heat-related health. Health problems, especially in urban areas, are becoming increasingly important due to global climate change and urban heat island intensification. Understanding the impact of neighborhood characteristics is an important process for extensive research on the relationship between thermal environments and human health. The objectives of this study were to explore the urban landscape and sociodemographic characteristics affecting heat-related health and identify spatial inequalities for vulnerable groups in Cincinnati, Ohio from 2016 to 2020. A total of 27,807 heat-related EMS incidents were used at the census block group level (n=285). We used land cover database and Landsat satellite images for urban landscape variables, and used 2019 U.S. Census data for sociodemographic variables. Negative binomial regression was used to identify the neighborhood variables associated with the count of heat-related EMS in each block group. Heat-related health problems have been alleviated in block groups with high green areas. However, the effects of thermal environments on health were higher in areas with high percent of impervious surface, over 65 years, non-white people, no high school diploma, or unemployment. Socially vulnerable groups were also vulnerable to heat-related health, and the effect of neighborhood variables increased with increasing urban temperature. The results indicate that heat-related health problems can be addressed through prevention strategies for block group variables. Local intervention efforts to address health issues should target more vulnerable areas and groups.

3.2.Introduction

Adverse effects of high ambient temperatures and extremely hot days on human health is well established (Limaye, Vargo, Harkey, Holloway, & Patz, 2018; Romeo Upperman et al., 2015; Tan et al., 2010). Prolonged exposure to extremely high ambient temperatures can lead to increased heat-related morbidity (Luber & McGeehin, 2008). A total of 10,527 deaths occurred from exposure to extreme heat between 2004 and 2018, with approximately 90% of deaths occurred on hot weather from May to September (Vaidyanathan, Malilay, Schramm, & Saha, 2020). In addition, there were more than 30,000 deaths because of exposure to heat wave during the summer in Western Europe, surpassing 739 heat-related deaths in the 1995 heat wave in Chicago, Illinois (Golden, Hartz, Brazel, Luber, & Phelan, 2008). Due to global climate change, hot weather conditions will become more intense, more frequent and last longer in the late 21st century(Meehl & Tebaldi, 2004).

Previous studies have shown that urban landscape characteristics such as vegetation, surface, water bodies, and urban structure play an important role in thermal environments by mitigating urban microclimate conditions (Chen et al., 2014; Graham, Vanos, Kenny, & Brown, 2016; Lai et al., 2019; Santos Nouri, Costa, Santamouris, & Matzarakis, 2018). These urban landscaping features have positive effects on heat-related health and have been used as essential factors for heat vulnerability assessment. (Kim & Kim, 2017; Peng, Xie, Liu, & Ma, 2016). Sociodemographic characteristics are also a crucial part that needs to be considered to address heat-related health problems (Gronlund et al., 2015; S. L. Harlan, Declet-Barreto, Stefanov, & Petitti, 2013). Heat-related health problems occur in most urban areas because more than half of the world population lives in urban areas (Robinson et al., 2011) and urban areas are more vulnerable to thermal environments due to higher temperatures than the surrounding areas

(Heisler & Brazel, 2010). Especially, heat-related health issues are more pronounced in vulnerable groups, such as demographic aging, which has emerged as a major demographic trend (Lloyd-Sherlock, 2000). Various age groups, including infants, children, and elderly are most vulnerable to heat-related death because they are more sensitive to excessive heat stress (Epstein & Moran, 2006). Heat vulnerability index (HVI) can be used to identify the effects of sociodemographic characteristics on human health. HVI describes statistical and spatial patterns of heat vulnerability and consists of spatial explicit indices of exposure, sensitivity, and adaptability to heat (Nayak et al., 2018). We can also use HVI to construct vulnerability maps to determine areas requiring heat-related health mitigation policies on extreme heat days (S. L. Harlan et al., 2013; Johnson, Stanforth, Lulla, & Luber, 2012).

Most studies on heat vulnerability have been limited at a spatial resolution no finer than census tract or county-level to identify the impact of neighborhood environments on health outcomes. In addition, some of the sociodemographic characteristics at the neighborhood level cause different results due to their correlation. For example, several studies found that heat-related mortality increase with low socioeconomic status, such as education level and old buildings (Gronlund et al., 2015; Y. Xu et al., 2013), while others have found no significant results (Basu & Ostro, 2008; Kenney, 2001). Different results of the relationship between neighborhood characteristics and health depending on different populations and regional characteristics suggest that heat vulnerability associated with social properties is highly contextual and not easy to draw one clear conclusion. Several studies have attempted to explore the effect of neighborhood characteristics on heat-related health to address heat-related urban problems. However, there is a lack of empirical research that considers variability of the relationship according to various environmental conditions.

Therefore, this study explored neighborhood effects on heat-related health using emergency medical service (EMS) incident data in Cincinnati, Ohio, over a 5-year period (2016–2020). There were two neighborhood categories: urban landscape and sociodemographic characteristics. Normal and extreme heat days were considered to analyze the impact of hot weather on human health. This study aimed to explore neighborhood environmental factors that affect heat-related health, identify spatial inequalities in heat-related EMS incidents, find the most heat-vulnerable areas by mapping heat vulnerability, and provide a foundation of knowledge for local interventions.

3.3. Method

3.3.1. Study design

We used daily heat-related incident data for warm season between June and September (2016 – 2020) in the City of Cincinnati, OH, which is located in the mid-latitudes at around 39°N 84°W. Cincinnati is classified as a humid subtropical climate zone (Cfa, Köppen climate classification) and the mean daily high temperature of normal heat days, 95th, and 97.5th extreme heat days were 84, 91, and 95 °F respectively during the study period. Cincinnati demonstrates increasing trends and significance for the much less frequent yet more extreme hot and humid weather type (Vanos, Kalkstein, & Sanford, 2015). While many related studies used census tract level (Graham et al., 2016; Madrigano, Ito, Johnson, Kinney, & Matte, 2015; Y. Xu et al., 2013), we used census block group level as the unit of analysis to get more relative samples and improve the accuracy of the analysis. Census block groups are more socially homogeneous than census tracts level since they are subdivisions of census tract (S. L. Harlan et al., 2013; Johnson et al., 2012). There are 285 census block groups in Cincinnati, with a total population of about 302,000 in 2019.

3.3.2. Heat-related Health Data

Heat-related Emergency Medical Service (EMS) incident data was used as a proxy for heat-related health. EMS data from 2016 to 2020 was obtained from the City of Cincinnati. The data provide information about date, time, latitude/longitude coordinates, type of incident. Under the Privacy Laws, latitude/longitude coordinates have been randomly skewed to represent values within the same block area of the incident. The Medical Priority Dispatch System (MPDS) determinant code is a way of categorizing and prioritizing EMS incidents. MPDS determinant code consists of 32 categories. We used subcategories of heat-related MPDS codes as described in the previous studies (Graham et al., 2016; Luber & McGeehin, 2008): code 06 (Breathing Problems), code 09 (Cardiac or Respiratory Arrest & Death), code 10 (Chest Pain, Non-traumatic), code 18 (Headache), code 20 (Heat & Cold Exposure), code 28 (Stroke & Cerebrovascular Accident), and code 31 (Unconscious & Fainting). The total daily heat-related EMS incidents for each code were calculated as the sum of 24-hour EMS incidents. Latitude/longitude coordinates of each heat-related EMS incident were geocoded and assigned to census block group using ArcGIS 10.7 to calculate the total number of daily EMS counts for each block group.

3.3.3. Heat Exposure Assessment

Daily maximum air temperature data were obtained from the Cincinnati Municipal-Lunken, OH weather station. Weather conditions were divided into normal heat (NH) days and extreme heat (EH) days. We defined the extreme heat with daily maximum temperatures above 95th and 97.5th percentiles of the time period (Madrigano et al., 2015; Steadman, 1984; Y. Xu et al., 2013), and extreme heat day means daily maximum temperature above each threshold

3.3.4. Urban Landscape and Sociodemographic Characteristics

Previous related studies dealing with thermal environmental issues have mainly focused on four urban landscape characteristics including vegetation, surfaces, water bodies, and urban structure (Lai et al., 2019; Santos Nouri et al., 2018), and these features were used in this study as urban landscape characteristics. Land cover database at a resolution of 30 m was obtained from the US Geological Survey (USGS) in 2016 and classified into tree covers, grass areas, impervious surfaces, and water bodies. The percentage of each classification for each block group was calculated using the TIGER/Line Shapefile sensor in ArcGIS 10.7. Urban density should be regarded as a key concept in the description of urban spatial structures (Krehl, Siedentop, Taubenböck, & Wurm, 2016). Density is the population density of a city and it not only accounts for a significant portion of the compact city-related literature, but is also used as an attribute for estimating urban compactness (Angel, Franco, Liu, & Blei, 2018; Burton, 2002). We calculated population density for each block group using 2019 American Community Survey (ACS) data from the U.S. Census. Urban spatial structure can be explained by the volume of the built-up (Parr, 2014). Thus, we calculated the normalized difference built-up index (NDBI) to measure the distribution of urban structure within the block groups using the band 5 Near-Infrared (0.85 - 0.88 μm) and 6 SWIR 1(1.57 - 1.65 μm) of Landsat 8 satellite images at a resolution of 30 m. We also calculated land surface temperature (LST) using the band 10 TIRS 1 (10.6 - 11.19 μm) of Landsat 8 satellite images on July 2020, which showed the highest average temperature during the target period, at a resolution of 100 m for each block group (Avdan & Jovanovska, 2016). To measure the average value of NDBI and LST, pixel scores were aggregated to each block group.

For the sociodemographic characteristics, we used HVI-based variables suggested by Nayak et al. (2018) and Reid et al. (2009). We included 1) percentage of over 65 years of age, 2) percentage of over 65 years of age and living alone, 3) percentage of living alone, 4) percentage of race other than white, 5) percentage with less than a high school diploma, 6) percentage below the poverty line, 7) percentage that are not employed, and 8) percentage of houses built before 1939. 2019 ACS data from the U.S. Census were collected for each block group. Based on the STFID coordinates, variables were geocoded and assigned to the corresponding block group using ArcGIS 10.7.

3.3.5. Statistical Analysis

The analysis evaluated how the potential relationship between neighborhood environments and heat-related health outcomes differed depending on the level of spatial characteristics. We used negative binomial regression to predict the odds because the dependent variable, the daily count of heat-related EMS incidents in each block group, showed the skewed distribution and overdispersion. When dependent variable is the frequency of occurrence of events, count models are typically used to analyze the results, and negative binomial regression is commonly used to count variables when the dependent variable shows the skewed distribution and over-dispersed counts (Ver Hoef & Boveng, 2007).

We evaluated the three models according to heat-related EMS categories including normal heat days, 95th extreme heat days, and 97.5th extreme heat days. There were three stages of analysis. First, univariate analysis was conducted for each of the independent variables. Second, multivariate analysis was performed after checking the multicollinearity of the variables, and the final model contained only statistically significant independent variables that showed differences with a p-value < 0.05. RStudio version 1.3 was used to perform statistical analysis. Lastly, we created the heat vulnerability (HVI) map that represents the relative risk (RR) of morbidity associated with hot days. The values of each variable were normalized to have a mean of 0 and a standard deviation of 1. The normalized variables were then classified into six groups and scored from 1 to 6 points for each classification. 1 represents a low vulnerability and 6 represents a high vulnerability. HVI was calculated by summing all the scores for each block group and the final results were mapped to visualize.

To use count models, we need to identify the area in which the counts were generated. There are statistical effects of different census block group sizes on the possibilities of EMS incidents because the size of block groups varies and more incidents may occur in larger block group. To control these effects, we included block group size in the statistical analysis as a control variable. Also, to control the statistical probability that more incidents can occur in block groups with a larger population, we used population data of each block group as an exposure variable. Negative binominal regression can be used to describe expected rates when the rate is a count data divided by a specific unit of exposure such as population, and exposure variable can be used to modify each observation from a count into a rate per area (MacDonald and Lattimore,2010).

3.4. Results

3.4.1. Summary statistics of heat-related EMS incidents and neighborhood factors.

There was a total of 29,270 heat-related EMS incidents during the warm season (2016 – 2020) in Cincinnati, OH. The daily count of heat-related EMS incidents ranged from 17-65, with an average of 39.9 (incidents/day). Figure 8 shows the comparison of the average daily count of heat-related EMS incidents during normal heat days and extreme heat days, including heatwave days that were defined using extreme heat days and minimum duration of at least 2 or 3 days (Cheng et al., 2016). Overall, the number of EMS incidents on extreme heat days was higher than normal heat days, and it slightly increased with heatwave days.

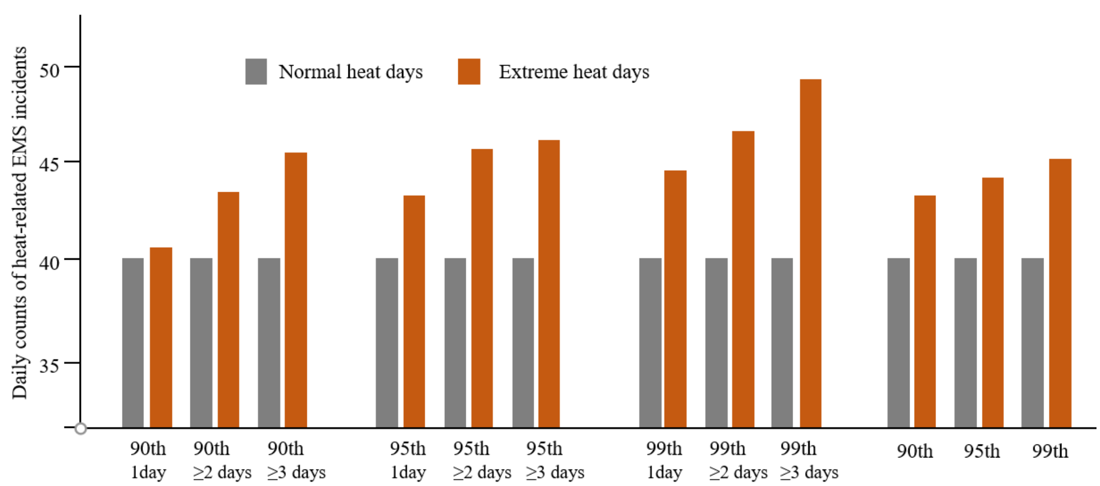

Figure 8.Comparison of daily counts of heat-related EMS incidents between normal heat days and extreme heat days. An extreme heat day was defined using the intensity (90th, 95th, 99th) and duration (1day, ≥ 2days, ≥ 3 days).

A total of 27,807 spatially geocoded data were used in the analysis, except for 1,463 incidents missing location information. Of these, 66% (18,436) occurred on normal heat days, with 24% (6,556) and 10% (2,815) occurring on 95th and 97.5th percentiles of extreme heat days, respectively. Table 2 shows descriptive statistics for all census block group variables, and most of them showed a wide range of variation. Overdispersion occurs when the observed variance is higher than the variance of a theoretical model (Berk & MacDonald, 2008). The mean and standard deviation of EMS counts at 95th extreme heat days were 48.78 and 37.20. The relatively higher mean value was the same for other variables. According to the result of the qqc overdispersion test using RStudio, the p-value for the EMS counts at normal heat days, 95th, and 97.5th extreme heat days was less than 0.05. A p-value < 0.05 indicates spatially overdispersion. This means that the incidents were not equally distributed throughout the study areas because there are certain physical or sociological characteristics that affect this spatial overdistribution. Among the variables on urban landscape characteristics, water bodies showed the greatest variation, with the mean was 0.64%, and some block groups were more than 23% of water bodies. On average, 12% of the population were over 65 years of age, and in some block group, half the population was elderly. Similarly, the percentage of people living alone showed a high variability. Some block groups consisted almost entirely of people living alone, while others had relatively low rates.

Table 2. Descriptive Statistics for census block group variables in Cincinnati, OH

Category	Variable	Abbreviation	Mean	SD	Min	Max
Heat-related Morbidity	Normal heat days daily EMS	NH	48.78	37.20	2.50	275.50
	95^{th} extreme heat days daily EMS	95^{th} EH	23.00	17.03	0.00	125.00
	97.5^{th} extreme heat days daily EMS	97.5^{th} EH	9.88	8.51	0.00	54.00
Urban Landscape	Percent of tree cover	Tree	34.48	16.50	2.94	84.38
	Percent of grass area	Grass	21.33	6.91	1.07	52.28
	Percent of impervious surface	Imper	41.00	17.72	5.48	92.34
	Percent of water area	Water	0.64	2.68	0.00	23.33
	Population density (urban density)	Dense	9.27	5.97	0.23	32.41
	Average of NDBI* (built-up)	NDBI	-0.11	0.04	-0.20	0.02
	Average of LST**	LST	22.89	1.52	18.40	26.50
Socio-demographic	Percent of over 65 years of age	+65	12.93	8.76	0.68	47.53
	Percent of over 65 years of age and living alone	65+ alone	43.39	24.95	2.27	97.28
	Percent of living alone	Live alone	19.89	11.66	1.13	74.18
	Percent of non-white	Non white	51.47	29.19	3.32	97.95
	Percent of no high school diploma	No HS	13.45	11.39	0.23	61.29
	Percent below the poverty line	Poverty	26.04	19.45	0.18	86.23
	Percent of unemployment	Unemployment	10.05	10.00	0.48	64.41
	Percent of building before 1939	Old Building	43.01	25.06	1.05	95.83
Confounding Variables	Population	-	188	246	19	2781
	Size of block group	-	1085	553	155	4405

* Normalized difference built-up index **Land surface temperature (N=285)

Table 3 shows the correlations between block group variables. Relatively strong and positive correlations were observed between variables such as impervious surface, built-up area, and land surface temperature. Percent of tree cover was strongly and negatively correlated with these variables. Also, there were positive and strong correlations between variables associated with social vulnerability, such as percent of unemployment, percent below the poverty line, and percent of no high school diploma. The results were used as basic information to identify the multicollinearity of variables for multivariate analysis.

Table 3. Correlations for census block group variables in Cincinnati, OH

Variable	Urban Landscape							Socio-demographic							
	Tree	Grass	Imper	Water	Dense	LST	NDBI	+65	65+ alone	Live alone	Non white	No HS	Poverty	Unemployment	Old Building
Tree	1														
Grass	.079	1													
Impervious	-.856**	-.426**	1												
Water	-.059	-.024	-.160**	1											
Density	-.367**	-.137*	.493**	-.290**	1										
LST	-.897**	-.367**	.923**	.033	.326**	1									
NDBI	-.906**	-.183**	.900**	-.062	.458**	.897**	1								
65+	.044	.186**	-.128*	.047	-.310**	-.105	-.062	1							
65+ alone	-.138*	-.044	.144*	-.060	.144*	.147*	.149*	.091	1						
Live alone	-.026	-.114	.111	-.141*	.080	.053	.048	.125*	.082	1					
Non white	-.103	.146*	.094	-.204**	.059	.163**	.153**	.036	.100	.003	1				
No HS	.001	-.056	-.023	.045	-.114	.088	-.017	-.033	.053	-.019	.426**	1			
Poverty	-.094	-.043	.095	-.055	.098	.159**	.080	-.192**	.065	-.048	.453**	.514**	1		
Unemployment	-.093	-.122*	.128*	-.023	.135*	.181**	.092	-.243**	.124*	-.054	.519**	.638**	.600**	1	
Old Building	-.244**	-.268**	.318**	.045	.105	.274**	.254**	-.174**	-.101	-.022	-.173**	-.012	.003	-.044	1

**. Correlation is significant at the 0.01 level. *. Correlation is significant at the 0.05 level. (N=285)

3.4.2. Neighborhood effects on heat-related EMS incidents.

Figure 9 shows the relationship between neighborhood effects and heat-related EMS incidents and how this effect depends on the block group level variables. We conducted an analysis on three models according to heat-related EMS categories, including normal, 95th, and 97.5th extreme heat days. The results showed that several variables have an increasing effect on heat-related incidents as the temperature increases and the effects of EMS categories showed the same significant level for each variable. For example, in urban landscape characteristics, variables such as green areas, impervious surfaces, NDBI, and LST variables were statistically significant. We found that the effect of percent of tree cover on the relationship between hot weather and health was stronger with higher temperatures, and the effects of percent of grass area were strongest in the 95th extreme heat days. As confirmed in correlation analysis, variables such as impervious surface, NDBI, and LST, which had high correlation with each other, showed similar results in a univariate analysis. Their effects became stronger in extremely hot weather. Among the sociodemographic characteristics, variables such as percent of over 65 years of age, percent of over 65 years of age and living alone, percent of non-white, percent of no high school diploma, percent below the poverty line, and percent of unemployment were statistically significant. Percent of buildings before 1939 and percent of living alone were not significant in this analysis.

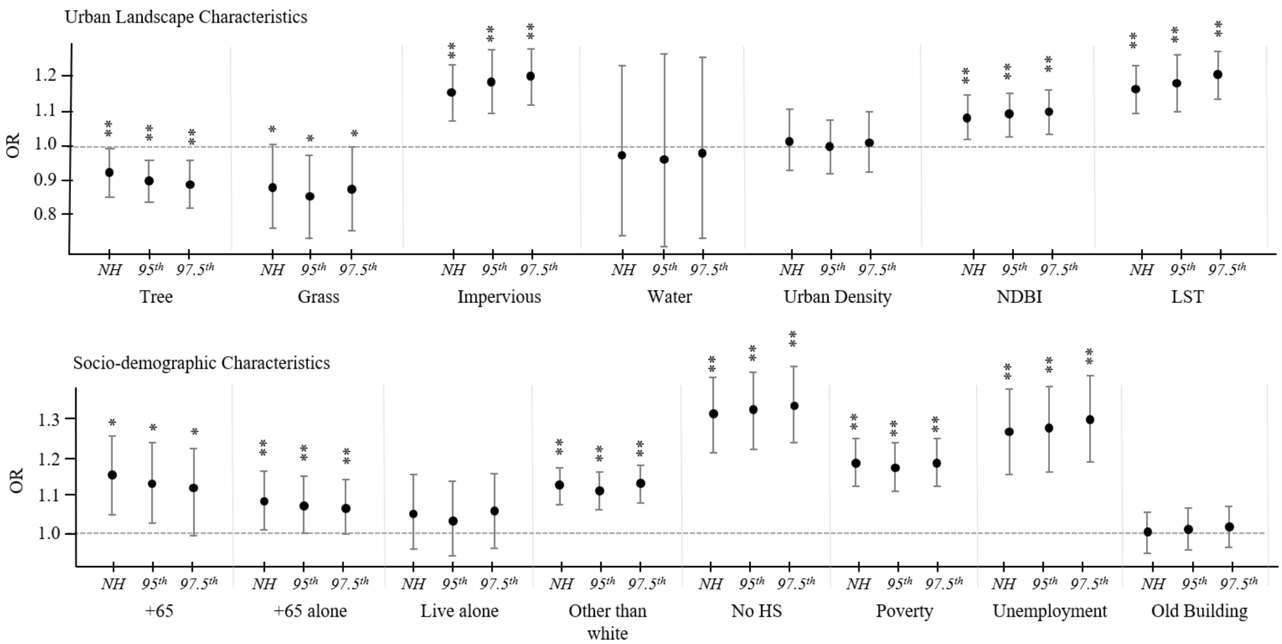

Figure 9. Odds ratios (ORs) and 95% confidence intervals for normal heat days, 95th, 97.5th heat days

Table 4 shows the results of the multivariate analysis of three models. Variables that did not find significance ($p > 0.05$) in univariate analysis, such as percent of water area, population density, percent of living alone, and percent of buildings before 1939, were excluded from multivariate analysis. Also, NDBI and LST variables, which were highly correlated with the percent of impervious surface, were excluded from further analysis to avoid the multicollinearity issue. The effects of grass areas on heat-related health reduction were usually more effective on 95th extreme heat days (OR = 0.839, 95% CI: 0.750 - 0.940, $p < 0.01$) than normal heat days (OR = 0.847, 95% CI: 0.755 - 0.951, $p < 0.01$). In contrast, the negative effects of impervious areas on heat-related health increased as temperatures increased from normal heat (OR = 1.120, 95% CI: 1.065 - 1.177, $p < 0.01$) to 95th (OR = 1.141, 95% CI: 1.087 - 1.198, $p < 0.01$), 97th

(OR = 1.157, 95% CI: 1.099 - 1.219, p < 0.01) extreme heat levels. In sociodemographic variables, a high percentage of over 65 years of age showed a negative impact on heat-related health as temperatures increased from normal heat (OR = 1.320, 95% CI: 1.209 - 1.441, p < 0.01), to 95th (OR = 1.300, 95% CI: 1.194 - 1.415, p < 0.01), 97th (OR = 1.277, 95% CI: 1.166 - 1.399, p < 0.01), extreme heat levels. This may be due to the tendency of the elderly to reduce their outdoor activities on hot days because the total volume of physical activities in the elderly is influenced by meteorological factors such as mean ambient temperature. (Aoyagi & Shephard, 2010). Percent below the poverty line was only significant on normally heat level (OR = 1.083, 95% CI: 0.987 - 1.189, p < 0.01) and percent of unemployment was only significant on 97.5th extreme heat level (OR = 1.141, 95% CI: 1.038 - 1.255, p < 0.01).

Table 4. Odds ratios (ORs) and 95% confidence intervals for heat-related EMS incidents during normal heat days, 95th, 97.5th extreme heat days with multivariate analysis in Cincinnati, Oh, 2016-2020

Category	Variable	Model 1 (Normal heat)		Model 2 (EH 95th)		Model 3 (EH 97.5th)	
		OR	95% CI	OR	95% CI	OR	95% CI
Urban landscape	Grass area	0.847 **	0.755 - 0.951	0.839 **	0.750 - 0.940	0.861 **	0.765 - 0.972
	Impervious surface	1.120 **	1.065 - 1.177	1.141 **	1.087 - 1.198	1.157 **	1.099 - 1.219
Socio-demographic	Age > 65 years	1.320 **	1.209 - 1.441	1.300 **	1.194 - 1.415	1.277 **	1.166 - 1.399
	Age > 65 living alone	1.016	0.982 - 1.051	1.012	0.980 - 1.045	1.009	0.975 - 1.044
	Race other than white	1.070 **	1.033 - 1.109	1.069 **	1.033 - 1.107	1.081 **	1.042 - 1.121
	No HS diploma	1.084	1.021 - 1.152	1.130 **	1.035 - 1.234	1.119 *	1.018 - 1.229
	< Poverty line	1.083 **	0.987 - 1.189	1.056	0.996 - 1.120	1.044	0.982 - 1.111
	Unemployment	1.099	0.999 - 1.208	1.111	1.014 - 1.217	1.141 **	1.038 - 1.255
Confounding variable	Area	1.109 **	1.080 - 1.138	1.105 **	1.077 - 1.134	1.109 **	1.079 - 1.140
	Population	exposure	-	exposure	-	exposure	-

**. Correlation is significant at the 0.01 level. *. Correlation is significant at the 0.05 level. (N=285)

Figure 10 shows the heat vulnerability map and the number of heat-related EMS for each block group. The most vulnerable areas included the downtown of Cincinnati and several northern outskirts areas. In addition, the map showed how heat-related EMS incidents were spatially distributed and their relevance to HVI. We can see the tendency of a lot of heat-related EMS accidents in regions with high HVI.

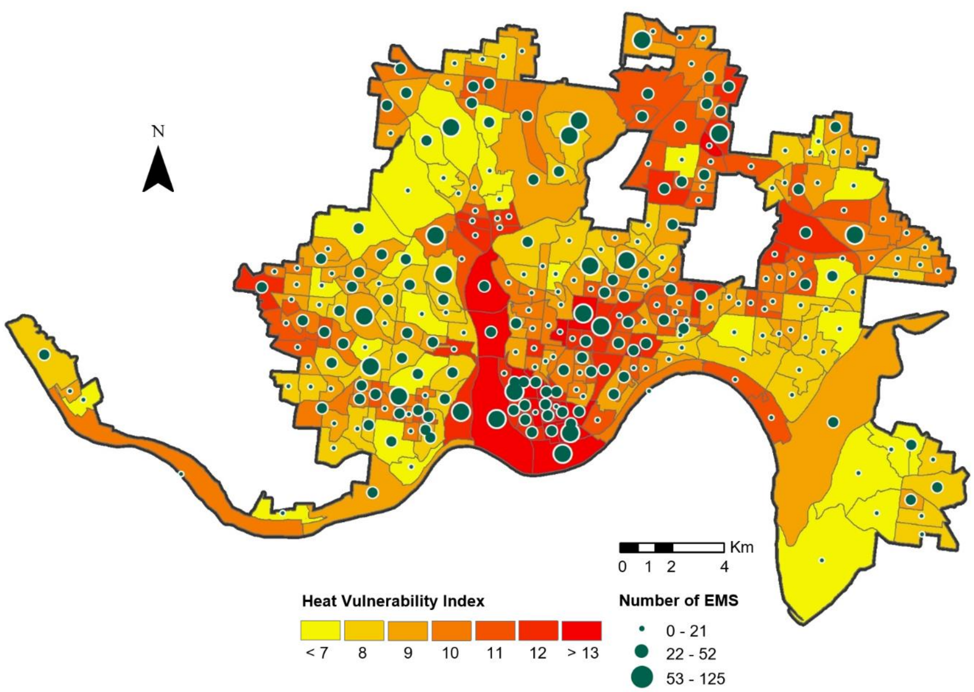

Figure 10. Heat vulnerability map and spatial distribution of heat-related EMS incidents for census block groups in Cincinnati

3.5. Discussion

This study explored neighborhood environmental influences on heat-related health using daily EMS incidents data. Statistics and spatial analysis were used to investigate vulnerable areas to heat and to identify the spatial characteristics of these areas. The results showed that heat-related accidents occurred more often on extremely hot days than normally hot days. We evaluated the potential effects of block group variables, including individual and area-level, through univariate approach that analyzes each variable individually. Also, multivariate approach that is frequently applied in heat epidemiology was used to consider various variables together (Gronlund et al., 2015; Y. Xu et al., 2013). Multivariate analysis found that the following variables have a statistically significant influence on heat-related health: percentage of grass area, percentage of impervious surfaces, percentage over 65 years of age, percentage of a race other than white, and percentage below the poverty line. Considering all variables comprehensively, the risk of heat-related EMS incidents in the most heat-vulnerable areas has been investigated to increase significantly compared to relatively less vulnerable areas.

The findings indicate that heat-related EMS incidents increase in block groups with less green space, consistent with the results from previous epidemiological studies exploring whether heat-related health associations vary by social and physical environmental characteristics. Urban green areas mitigate the urban heat island effect and play an important role in reducing heat stress during extreme heat days (Priyadarsini, Hien, & David, 2008; Son et al., 2016). A study of U.S. Medicare participants resulted in increased mortality rates due to warmer temperatures with a high percentage of non-green space (Zanobetti, O'Neill, Gronlund, & Schwartz, 2013). Gronlund et al. (2015) conducted time-stratified case-crossover analysis using daily mortality in Michigan. They analyzed the modification effect of individual and ZIP code-level sociodemographic characteristics on extreme heat-related mortality among the elderly. Their results showed that green space is a significant modifier of the association between mortality and extreme heat. In the study of heat-related deaths in Phoenix from 2000 to 2008, the increase in vegetation space showed a weak but significant association with the decrease in heat-related mortality probability in the target area as a separate variable (S. L. Harlan et al., 2013). These findings suggest that understanding the regional variations and characteristics of urban green spaces is crucial in heat vulnerability assessment along with the fact that green space is an essential factor to mitigate thermal environments and address heat-related problems.

Results from this study indicate that the sociodemographic variables that have significant effects on heat-related health are as follows: percent of over 65 years of age, percent of no high school diploma, percent of non-white, and percent of unemployment. The percentage of the population over 65 years was a statistically significant predictor of increased incident risk, consistent with the results of previous relevant studies. Benmarhnia, Deguen, Kaufman, and Smargiassi (2015) found that heat vulnerability and heat-related health problems increased in the vulnerable groups, such as older adults aged over 65 and 75 and low individual socioeconomic status. Hendel, Azos-Diaz, and Tremeac (2017) showed that the population most affected by the heat wave was those aged 65 or older, with night temperatures having the highest impact on heat wave mortality. As such, vulnerable groups such as infants and children as well as the elderly are most vulnerable to heat-related health because they are more susceptible to excessive heat stress (Epstein & Moran, 2006).

Meanwhile, the percent of no high school diploma, percent of non-white, and percent of unemployment variables that have shown significant results in this study are also essential factors in social vulnerability assessment as well as heat vulnerability issue. Social vulnerability means that human health problems caused by external stress, including natural or human-caused disasters, can negatively affect communities (Bergstrand, Mayer, Brumback, & Zhang, 2015). Flanagan, Hallisey, Adams, and Lavery (2018) developed social vulnerability index (SVI) including four sections: socioeconomic status, household composition & disability, minority status & language, and housing & transportation. They defined the variables such as education, race, poverty, and unemployment as indicators for evaluating social vulnerability. Therefore, the results of this study indicate that addressing heat-related problems for socially vulnerable groups is an essential challenge in urban areas along with the fact that socially vulnerable groups are also vulnerable to heat-related problems.

The percent of building before 1939 was not a significant predictor of increased risks in this study, while previous studies found significant results. One possible explanation is that, according to Gronlund (2014), heat-related health problems were more serious in areas with a higher proportion of older buildings. However, he also found that housing conditions were not significant as an important predictor of heat vulnerability after controlling other characteristics such as a number of floors, how often left home in average week, and number and type of fans. It means that the characteristics of buildings may vary depending on their geographical characteristics, which may affect the relationship between older buildings and human health.

This study provides insights into prevention strategies to reduce heat-related problems, but there are several limitations. There was a lack of information on the air conditioning prevalence at block group level in this study. However, previous studies indicated that it is important not only to own air conditioners but also to have the financial resources to operate (Klinenberg, 2015; Sampson et al., 2013). Thus, air conditioning prevalence can be captured at the local level through the poverty levels used in this study (Gronlund et al., 2015). Nevertheless, the lack of detailed information on air conditioning prevalence is a significant limitation in heat vulnerability-related research and is also a limitation of this study.

This study only analyzed the modifying effects of urban landscape and sociodemographic variables on heat-related morbidity at the census block group level because individual-level data on a more detailed scale were not available, but did not necessarily consider individual associations. The EMS data used in this study included latitude/longitude coordinates of each incident. According to privacy laws, however, coordinates were randomly distributed within the same urban block. Thus, further research is needed using data on smaller units. In addition, further research is needed to use more detailed spatial information. This study used relatively coarse spatial resolution at the block group level. For example, the distinction of green areas using satellite images with a resolution of 30 meters cannot be accurately distinguished at the block group level. Spatial information about smaller spatial units may better explain the role of spatial properties of neighborhoods in health effects.

We used a cross-sectional approach that has limitations to sufficiently reflect causal inference between variables. Land cover database from 2016, American Community Survey (ACS) data from 2019, NDBI and LST Landsat satellite data from 2020 were used in this study. At the same time, our study covered a five-year period from 2016 to 2020. Other hard-to-control situations in the analysis beyond the scope of this study can affect the temporal and spatial distribution of incidents over the five-year period. In this regard, this study needs a premise that spatial patterns should remain largely unchanged to use data for different time periods. Thus, to identify causal relationships, longitudinal approaches should be considered in future research.

3.6. Conclusion

The findings of this study suggest that multifaceted strategies for communities to create thermally comfortable and safe neighborhoods could play an important role in preventing heat-related incidents. A summary of the findings of this study is as follows. First, green areas among urban landscaping variables mitigated the effects of hot weather on heat-related health. In contrast, other variables such as impervious surface, NDBI, and LST showed a negative effect on heat-related health, indicating that NDBI and LST might be used as indicators to identify heat-vulnerable areas. Sociodemographic variables such as percent of over 65 years of age, percent of no high school diploma, percent of non-white, and percent of unemployment significantly affected the relationship between hot weather and health outcomes; in particular, socially vulnerable groups were more vulnerable to heat-related health. Second, we compared various models according to EMS categories, including normal heat-related and extreme heat-related data, for more accurate analysis. The finding is that the higher the temperature, the stronger the effect of block group variables on heat-related incidents. This means that the effects of hot weather on health outcomes can be mitigated through intervention in various neighborhood characteristics. Third, there were spatial inequalities in heat-related EMS incidents. Spatial patterns showed substantial variability between heat vulnerability, social vulnerability, and heat-related health. Urban center and downtown areas showed higher heat vulnerability and more heat-related incidents, while suburban areas with high-income people, younger white populations, and greener environments linked to reduced heat vulnerability and heat-related incidents. Finally, the heat vulnerability map of Cincinnati created in this study provides a foundation of knowledge for local interventions through information on where heat-related accidents occur what environmental factors affect. Policy makers may use this map to make decisions on the selection of locations where additional medical facilities are needed. Also, urban planners can use the map to establish strategies to enhance the accessibility of rescue activities to vulnerable areas from heat-related accidents.

4. STUDY THREE: ESTIMATING TERRESTRIAL RADIATION FOR HUMAN THERMAL COMFORT IN OUTDOOR URBAN SPACE

4.1. Summary

Cities inadvertently create warmer and drier urban climate conditions than their surrounding areas through urbanization that replaces natural surfaces with impervious materials. These changes cause heat-related health problems and many studies suggest microclimatic urban design (MUD) as an approach to address these problems. In MUD-related research, although terrestrial radiation plays an important role in human thermal comfort and previous studies use thermal comfort models to identify human heat stress, few studies have addressed the effect of terrestrial radiation. This study develops the ground ratio factor (GRF) model to estimate the different terrestrial radiation according to different ground conditions. Three types of ground materials (asphalt, concrete, and grass) were considered in the model, and field studies were conducted in Humid Subtropical Climate (Cfa) zone during the hot season (July 13 to September 19, 2020). The model was validated by comparing the predicated terrestrial radiation (PTR) from the model with the actual terrestrial radiation (ATR). The results showed there is a statistically significant strong correlation between PTR and ATR. The model can contribute to MUD strategies by updating existing human energy budget models, which can lead to measuring more accurate human thermal comfort for mitigating thermal environments.

4.2. Introduction

There is no doubt that global climate change is causing serious urban warming (Limaye et al., 2018) and due to the rapid urbanization, cities often inadvertently create warmer and drier urban climate conditions than their surrounding areas which is known as the urban heat island (UHI) phenomenon. These thermal environments cause heat-related health problems (Memon, Leung, & Chunho, 2008; Zhao, Liu, & Liu, 2016). Meanwhile, heat stress, which can be assessed by human energy budget models, plays an important role in causing heat-related health. According to Epstein and Moran (2006), various age groups, including infants, children, and adults over 65, are most vulnerable to heat-related death because they are more sensitive to excessive heat stress. Heat stress can also reduce workers' productivity and cause more serious heat-health problems, especially in vulnerable groups (Abdel-Ghany, Al-Helal, & Shady, 2013).

While individuals have little control over the impact of global issues on heat-related health, there is evidence that urban design ameliorates health problems by increasing human thermal comfort and contributing to reduced heat stress at the urban level (Estoque, Murayama, & Myint, 2017; Mohammad, Goswami, & Bonafoni, 2019). In this regard, researchers suggest microclimatic urban design (MUD), which is the process of determining the physical organization of buildings and open spaces in urban areas to mitigate thermal environments (Lenzholzer & Brown, 2016). Many studies are underway on MUD and they have found that MUD has positive impacts on urban microclimate and heat-related health (Chen et al., 2014). Their strategies focus on green areas (Gunawardena, Wells, & Kershaw, 2017; Susca, Gaffin, & Dell'osso, 2011), surface of building and pavement (Estoque et al., 2017; Liu, Li, & Peng, 2018), water bodies (Jenerette, Harlan, Stefanov, & Martin, 2011; Nakayama & Hashimoto, 2011;

Vahmani & Jones, 2017), and structure of streets and buildings (Johansson & Emmanuel, 2006; Yang, Wong, & Li, 2015) at the micro and meso-scale.

According to MUD-related research, terrestrial radiation plays an important role in outdoor human thermal comfort. Brown and Gillespie (1995) demonstrated the effect of terrestrial radiation on human thermal comfort through the COMFA model. They found that terrestrial radiation absorbed by a person has negative effects on human thermal comfort during hot summer weather. All materials on Earth emit invisible terrestrial radiation as a function of their surface temperature (Brown & Gillespie, 1995), and the warmer the object is, the more terrestrial radiation it emits. This invisible energy has a significant effect on outdoor human thermal comfort. Also, Shahidan et al. (2010) demonstrated that the solar radiation filtering capacity of trees reduces the terrestrial radiation by cooling the ground, and it is related to improve outdoor thermal comfort in tropical open spaces.

Among MUD elements including green, surface, water body, and urban structure, terrestrial radiation is related to surface. However, surface-related studies have mostly focused on the energy that varies with the albedo of different ground materials, and has rarely considered the amount of terrestrial radiation emitted. Also, previous studies have used thermal comfort models to calculate energy budgets that can identify thermal stress level (Santos Nouri et al., 2018), and there have been 165 thermal indices developed for estimating indoor and outdoor thermal comfort levels (Staiger, Laschewski, & Matzarakis, 2019). However, the impact of terrestrial radiation is not considered in most of the existing models. The existing models typically use air temperature, solar radiation, relative humidity, and wind speed as the main microclimate parameters. For example, Coccolo et al. (2016), conducted a comprehensive review of models and standards of outdoor thermal comfort and stress. A total of 21 thermal comfort models were analyzed in their study. Among them, 11 models consider solar radiation, 21 models consider air temperature, 19 models consider relative humidity, and 15 models consider wind speed. Only one model, the COMFA, considers the terrestrial radiation absorbed by a person, but it does not take into account the surrounding ground conditions at the point where the subject is standing. It only considers the terrestrial radiation of the point where the subject is standing.

By developing a model which can consider the various ground conditions, the ground ratio (GR) of each material, and their terrestrial radiation, this study can contribute to creating MUD strategies by updating existing energy budget models, which can lead to measuring more accurate human thermal comfort. Therefore, the goals of the study are to 1) present the need to consider terrestrial radiation for human energy budgets, 2) develop a ground ratio factor (GRF) model that can estimate the differences in terrestrial radiation according to different ground conditions, and 3) validate the GRF model through field testing, and 4) propose how the model can be used in microclimatic urban design to ameliorate urban heat islands.

4.3. Methods

4.3.1. GRF (Ground Ratio Factor) Model

4.3.1.1. GRF

Terrestrial radiation will be emitted differently depending on ground conditions. For example, a person standing on a place with 95% concrete and 5% grass will absorb more terrestrial radiation from the ground than a person standing on a place with 100% grass. This is because concrete emits more energy in hot weather because of its higher temperature than grass

(Figure 11). Therefore, GRF represents the ratio of different ground materials to the location where a person is standing. In this study, the spatial range of GRF was a radius of 3 m where a person is standing. The CNR4 instrument used to measure terrestrial radiation has a lower detector with a view of 150 degrees. Theoretically, a detector with a view of 150 degrees installed at a height of 1.5 m has a measurable range of a radius of 5.6 m. However, the actual measurements showed that the measurable range was a radius of 3 m. The range has been established for the analysis of this study. The application of additional space is possible depending on the results of the study.

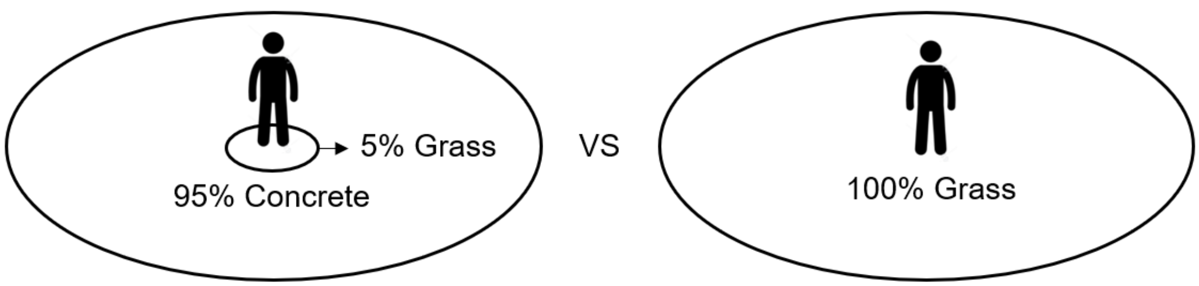

Figure 11. Concept of GRF

4.3.1.2.GRF Model

To develop better thermal comfort models, this study attempted to develop the GRF model that can calculate the different terrestrial radiation depending on ground cover ratio of various materials. Austrian physicists Stefan-Boltzmann, who made a significant contribution to radiation and gases theory in the late 19th century, suggested that energy-temperature relations should follow the law when temperature is in Celsius degrees (equation 1). According to the law, terrestrial radiation can be calculated by surface (ground) temperature.

$$Energy = \sigma\ (\mathrm{T}+273)^4 \tag{1}$$

where σ (Greek letter sigma) represents the constant of proportionality, called the Stefan-Boltzmann constant. This constant has a value of $5.67 * 10^{-8}$ watt per meter squared per kelvin to the fourth (W/m^2 K^4). T is the ground temperature in Celsius degree.

4.3.1.2.1. Ground temperature-based GRF (GRF-G) model

The Stefan-Boltzmann law was used to develop the model. The amount of different terrestrial radiation depending on ground cover ratio of various materials can be calculated by the GRF-G model (equation 2). Ground temperature of various materials can be used in the model. To calculate the ground ratio (GR), a radius of 3 m where a person stands is considered. GR values from 0 to 100 percent (%). Then, the amount of terrestrial radiation emitted by each different ground material was multiplied by the GR of the corresponding material.

$$\begin{aligned} R_T = &\ Material\ A's\ GR * \sigma\ (T_{AG} + 273)^4 + Material\ B's\ GR * \sigma\ (T_{BG} + 273)^4 + \\ &\ Material\ C's\ GR * \sigma\ (T_{CG} + 273)^4 + Material\ D's\ GR * \sigma\ (T_{DG} + 273)^4 + \ldots \\ &+ Material\ n's\ GR * \sigma\ (T_{nG} + 273)^4 \end{aligned} \tag{2}$$

where R_T is the predicted terrestrial radiation (W/m^2), σ is the constant of proportionality with a value $5.67 * 10^{-8}$ W/m^2K^4, GR is the ground ratio, and T_{AG} is the ground temperature of material A, T_{BG} is the ground temperature of material B, T_{CG} is the ground temperature of material C, T_{DG} is the ground temperature of material D, and T_{nG} is the ground temperature of material n in Celsius degree.

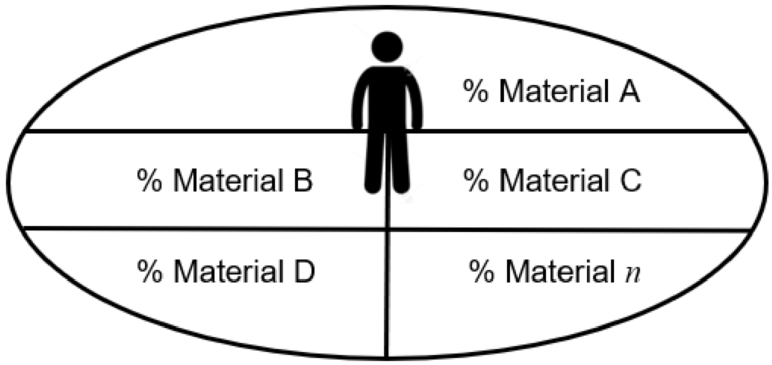

Figure 12. Concept of the GRF model with various ground materials

4.3.1.2.2. Air Temperature-based GRF (GRF-A) Model

Air temperature data can be easily obtained through local weather stations, but ground temperature data are generally not available (Khan, Islam, Tarefder, & Engineering, 2019). Since only ground temperature can be used in the model, an air temperature-based model was developed by converting air temperature to ground temperature. To estimate the ground temperature, regression analysis was used for each of three ground materials (equation 3). Shamsipour, Azizi, Ahmadabad, and Moghbel (2013) and Ariawan, Subagio, and Setiadji (2015) proposed regression analysis to estimate ground temperature using air temperature. Ground temperature was used as a dependent variable and air temperature as an independent variable. The results of the regression analysis for asphalt, concrete, and grass were applied to the GRF-G model (equation 4).

$$Y_i = \beta_0 + \beta_1 X_i + \varepsilon_i \tag{3}$$

where Y_i is dependent variable (ground temperature), β_0 is population Y intercept, β_1 is population slope coefficient, X_i is independent variable (air temperature), and ε_i is random error term.

$$R_T = \text{Material A's GR} * \sigma\,(Y_A + 273)^4 + \text{Material B's GR} * \sigma\,(Y_B + 273)^4 + \text{Material C's GR} * \sigma\,(Y_C + 273)^4 + \text{Material D's GR} * \sigma\,(Y_D + 273)^4 + \ldots + \text{Material n's GR} * \sigma\,(Y_n + 273)^4 \quad (4)$$

where R_T is the predicted terrestrial radiation (W/m^2), σ is the constant of proportionality with a value of 5.67 * 10^{-8} W/m^2K^4, GR is the ground ratio, and Y_A is the ground temperature of material A obtained from the regression analysis, Y_B is the ground temperature of material B obtained from the regression analysis, Y_C is the ground temperature of material C obtained from the regression analysis, Y_D is the ground temperature of material D obtained from the regression analysis, and Y_n is the ground temperature of material n obtained from the regression analysis in Celsius degree.

4.3.2. Field Study

Microclimate data may vary depending on the climate zone, time, and season (Barman et al., 2017). Thus, the scope of the study was narrowed to the Cfa climate zone (Humid subtropical climate) from the Köppen climate classification. The City of College Station, Texas, which is located in the Cfa climate zone, was selected for the study. College Station has hot and humid weather in summer and cold and mild weather in winter.

To develop the model, three types of ground materials were selected: asphalt, concrete, and grass. They cover most of the pavement types in College Station. Measurement spots were selected where the boundary of two or three materials could be clearly distinguished to accurately measure the GR. There was no shade with full sun at all measuring points (Figure 13). A total of nine measurement spots were selected: three spots for asphalt-concrete (A-C), two spots for asphalt-grass (A-G), two spots for concrete-grass (C-G), and two spots for asphalt-concrete-grass (A-C-G).

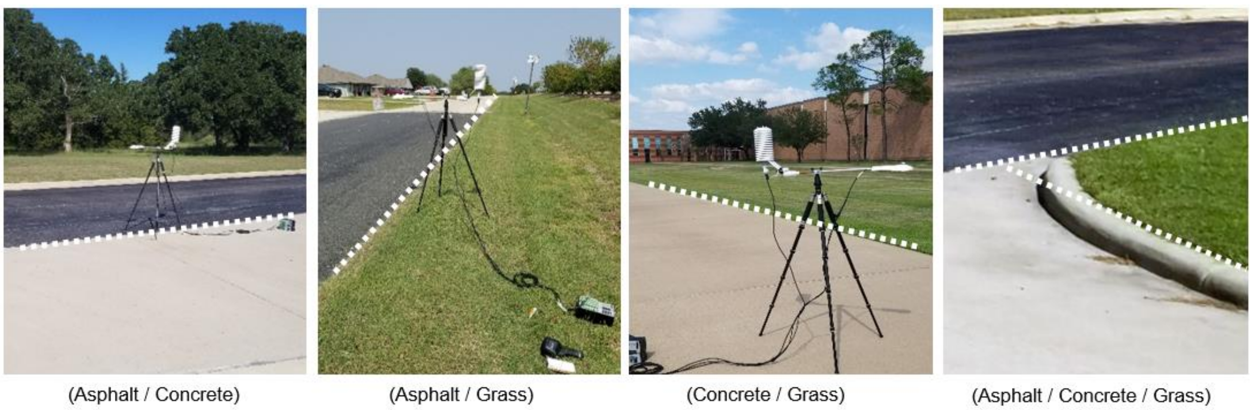

Figure 13. Various ground material conditions

Field measurements were conducted for 16 days during hot summer weather from July 13 to September 19, 2020. Measurement time was selected from 10 a.m. to 4 p.m., a time of the day when people could easily be exposed to vulnerable thermal environments. To develop the model for various weather conditions, warm (29.4 – 31.6 ℃), hot (31.7 – 35.0 ℃), and very hot (over 35.0 ℃) weather conditions were considered (Shak, Scarpa, & Knudsen, 1966). Measurements were conducted on sunny and mostly sunny days for accurate microclimatic data (Table 5).

Table 5. List of measurement days, time, max and min temperature, and sky conditions

Date	Time	Ta (℃)		Sky Condition
		Max	Min	
Jul 13, 2020	4-6 PM	38.33	37.79	Sunny
Jul 14, 2020	4-6 PM	37.71	36.82	Sunny
Aug 03, 2020	3-5 PM	36.86	36.37	Sunny
Aug 04, 2020	3-5 PM	37.15	35.45	Sunny
Aug 13, 2020	3-5 PM	38.92	38.58	Sunny
Aug 14, 2020	12-2 PM	37.61	35.39	Sunny
Aug 15, 2020	12-2 PM	37.68	35.37	Sunny
Aug 19, 2020	11-1 PM	34.88	32.83	Sunny
Aug 20, 2020	11-1 PM	34.57	33.73	Sunny
Aug 21, 2020	12-2 PM	34.56	32.80	Sunny
Aug 23, 2020	12-2 PM	35.94	33.12	Mostly Sunny
Aug 24, 2020	11-1 PM	35.52	32.81	Mostly Sunny
Aug 25, 2020	11-1 PM	31.90	29.32	Sunny
Sep 17, 2020	4-6 PM	31.77	29.26	Mostly Sunny
Sep 18, 2020	4-6 PM	31.75	30.24	Mostly Sunny
Sep 19, 2020	4-6 PM	29.49	28.12	Sunny

4.3.2.1.Model Validation

To validate the model, this study compared the predicted terrestrial radiation (PTR) calculated by the model with the actual terrestrial radiation (ATR). For this, ATR was measured simultaneously when measuring the microclimatic data for PTR for the nine measurement spots. For the A-C, A-G, and C-G, ATR was measured at a point where the GR value of ground material was 0%, 25%, 50%, 75%, and 100% by moving the measuring point (Figure 14). For the A-C-G, ATR was measured at the midpoint, where the GR of asphalt, concrete, and grass are 25%, 25%, and 50%, respectively.

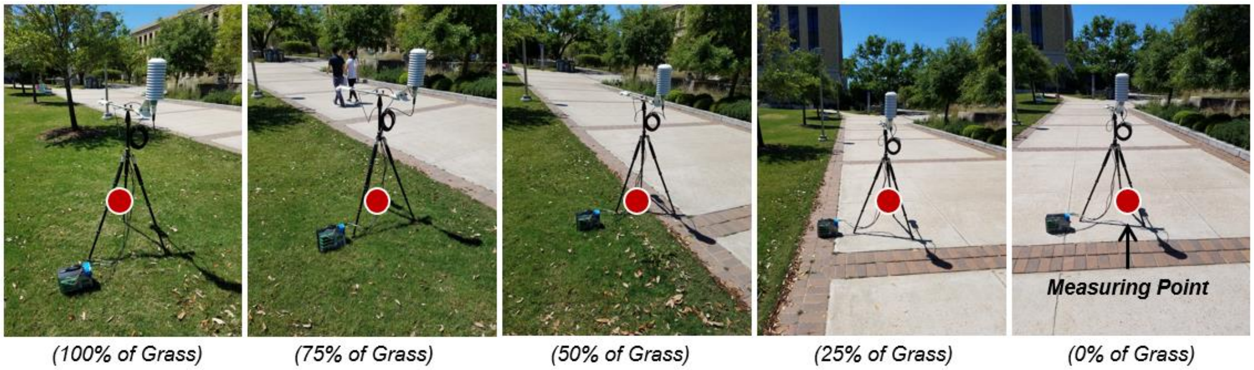

Figure 14. ATR Measurement points

4.3.2.2.Microclimatic Data

For the GRF-G model, this study measured ground temperature to calculate the predicted terrestrial radiation by the GRF-G model (PTR-G). Ground temperature was measured vertically downward using the FLIR E6 thermal camera and Etekcity Infrared Thermometer 774. For the GRF-A model, this study measured air temperature to calculate the predicted terrestrial radiation by the GRF-A model (PTR-A). Air temperature was measured by the HMP155A-L sensor at 5-seconds intervals. To validate the model, ATR was measured by CNR4, 4-Component Net Radiometer. The CNR4 Radiometer measures the energy balance between incoming short-wave and long-wave Far Infrared (FIR) radiation versus surface-reflected short-wave and outgoing long-wave radiation. Finally, CR3000 data logger was used to collect the data (Table 6). HMP 155A-L sensor and CNR 4 Radiometer were installed at 1.5 m above the ground.

Table 6. Microclimatic data measurement instruments

Instruments	Microclimate Variables	Interval
HMP155A-L Sensor	Air Temperature	5s
FLIR E6 Infrared Camera & Etekcity Infrared Thermometer 774	Ground (Surface) Temperature	1
CNR4 Net Radiometer	Terrestrial Radiation	5s
CR3000	Data Logger	-

4.3.3. Data Analysis

To validate the model, this study compared the PTR with ATR. Pearson correlation analysis was used to analyze the relationship. The model can be validated when the relationship has a strong correlation with a statistically significant value at 0.01 level. The analysis was conducted in two parts. 1) the PTR-G was compared with ATR to validate the GRF-G model and 2) the PTR-A was compared with ATR to validate the GRF-A model (Figure 15).

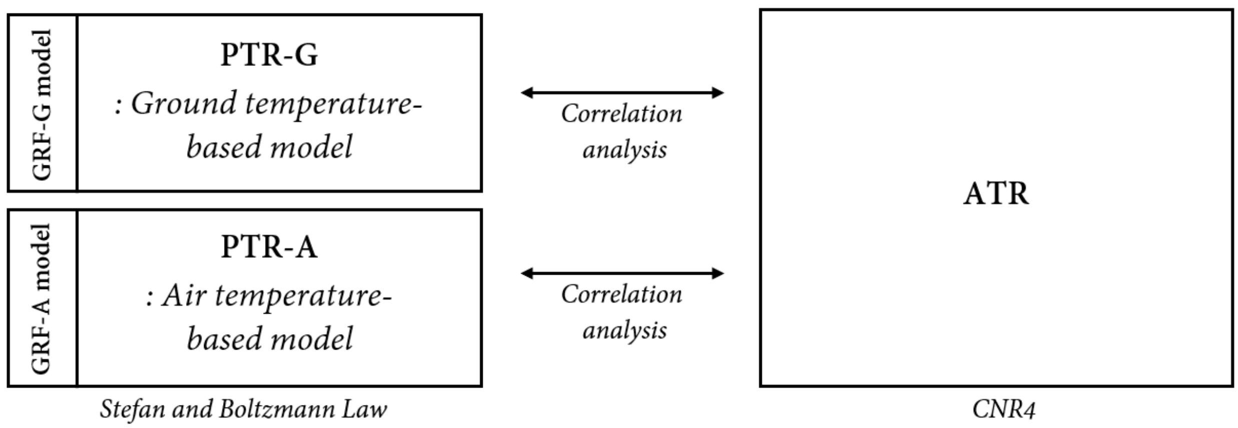

Figure 15. Concept of analysis

4.4. Results

4.4.1. Emissivity of the ground materials

Terrestrial radiation calculated by the Stefan-Boltzmann law should be multiplied by a correction factor called the emissivity. Emissivity of material means its effectiveness in emitting energy as thermal radiation. According to Brown and Gillespie (1995), emissivity is always greater than 0.9 for things of interest in landscape design. Thus, an uncorrected equation can usually be used when it is satisfied with the estimates within 10% of the reality. However, this study used the calculated emissivity values in the model for more accurate PTR calculation. The emissivity of asphalt, concrete, and grass was calculated by comparing the PTR and ATR, and their results were 0.94, 0.96, and 0.98, respectively. (Table 7).

Table 7. Emissivity and albedo of the ground materials

	Asphalt (Avg)	Concrete (Avg)	Grass (Avg)
Emissivity	0.94	0.96	0.98
Albedo	0.06	0.28	0.19

4.4.2. GRF-G Model

Four models were developed to calculate PTRs for A-C, A-G, C-G and A-C-G. The calculated PTRs were used in the model validation. Equation 5 is for A-C, equation 6 is for A-G, equation 7 is for C-G, and equation 8 is for A-C-G. Emissivity of asphalt (0.94), concrete (0.96), and grass (0.98) was applied to the model.

R_T = Asphalt's GR * $5.67 * 10^{-8}$ $(T_{Asphalt\_G} + 273)^4$ *0.94 + Concrete's GR * $5.67 * 10^{-8}$ $(T_{Concrete\_G} + 273)^4$ *0.96 (5)

R_T = Asphalt's GR * $5.67 * 10^{-8}$ $(T_{Asphalt\_G} + 273)^4$ *0.94 + Grass's GR * $5.67 * 10^{-8}$ $(T_{Grass\_G} + 273)^4$ *0.98 (6)

R_T = Concrete's GR * $5.67 * 10^{-8}$ $(T_{Concrete\_G} + 273)^4$ *0.96 + Grass's GR * $5.67 * 10^{-8}$ $(T_{Grass\_G} + 273)^4$ *0.98 (7)

R_T = Asphalt's GR * $5.67 * 10^{-8}$ $(T_{Asphalt\_G} + 273)^4$ *0.94 + Concrete's GR * $5.67 * 10^{-8}$ $(T_{Concrete\_G} + 273)^4$ *0.96 + Grass's GR * $5.67 * 10^{-8}$ $(T_{Grass\_G} + 273)^4$ *0.98 (8)

where R_T is the predicted terrestrial radiation (W/m^2), GR is the ground ratio, and $T_{Asphalt\_G}$ is the ground temperature of asphalt, $T_{Concrete\_G}$ is the ground temperature of concrete, T_{grass_G} is the ground temperature of grass in Celsius degree.

Table 8 shows the descriptive statistics of the PTR-G and ATR. The samples for each measurement points were 51 for A-C, 46 for A-C, 44 for C-G, and 39 for A-C-G. For the A-C-G model, the mean of the PTR-G and ATR were 532.12 and 537.77 W/m^2, the SD of the PTR-G and ATR were 26.52 and 31.45 W/m^2, and the range of the PTR-G and ATR were from 507.66 to 609.70 W/$m^2$and from 498.14 to 601.16 W/m^2, respectively. Other models for A-C, A-G, and C-G also showed similar distribution. Overall, the results showed that the maximum, minimum, mean, and SD values of the PTR-G and ATR have very similar distributions.

Table 8. Descriptive statistics of the PTR-G and ATR

Material		Max (W/m^2)	Mean (W/m^2)	Min (W/m^2)	SD (W/m^2)
A-C	PTR-G	659.69	574.80	521.00	37.21
	ATR	666.51	574.33	523.01	39.07
A-G	PTR-G	614.47	547.05	503.45	28.33
	ATR	628.66	550.34	506.91	32.80
C-G	PTR-G	560.77	518.49	491.47	17.74
	ATR	567.58	525.11	495.61	18.20
A-C-G	PTR-G	609.70	532.15	507.66	26.52
	ATR	601.16	537.77	498.14	29.45

4.4.3. GRF-A Model

To estimate the ground temperature using air temperature, regression analysis was used for each of the three ground materials (Ariawan et al., 2015; Shamsipour et al., 2013). Equations 9, 10, and 11 showed the result of asphalt, concrete, and grass, respectively. R^2 values of asphalt, concrete, and grass were 0.762, 0.663, and 0.567, respectively. Also, three equations were statistically significant at 0.01 level.

$$T_{asphalt} = -20 + 2 * T_{air} \ (R^2 = 0.762,\ p < 0.01) \quad (9)$$

$$T_{concrete} = 8.5 + T_{air} \ (R^2 = 0.663,\ p < 0.01) \quad (10)$$

$$T_{grass} = 13 + 0.6 * T_{air} \ (R^2 = 0.567,\ p < 0.01) \quad (11)$$

where $T_{asphalt}$ is the predicted ground temperature of asphalt, $T_{concrete}$ is the predicted ground temperature of concrete, T_{grass} is the predicted ground temperature of grass, T_{air} is the air temperature.

The ground temperature parts of the GRF-G model for each material were replaced by the equations created by the regression analysis as follows:

$$R_T = \text{Asphalt's GR} * 5.67 * 10^{-8} ((-20 + 2 * T_{air}) + 273)^4 * 0.94 + \text{Concrete's GR} * 5.67 * 10^{-8} ((8.5 + T_{air}) + 273)^4 * 0.96 + \text{Grass's GR} * 5.67 * 10^{-8} ((13 + 0.6 * T_{air}) + 273)^4 * 0.98 \quad (12)$$

where R_T is the terrestrial radiation (W/m^2), GR is the ground ratio, and T_{air} is the air temperature in Celsius degree.

Table 9 shows the descriptive statistics of the PTR-A and ATR. The results of the ATR were the same as in the GRF-G section. For the A-C-G model, the mean of the PTR-A and ATR were 532.96 and 537.77 W/m^2, the SD of the PTR-A and ATR were 20.39and 29.45 W/m^2, and the range of the PTR-A and ATR were from 488.90 to 563.10 W/$m^2$and from 498.14 to 601.16 W/m^2, respectively. Other models for A-C, A-G, and C-G also showed similar distribution. Overall, the value of the ATR is slightly higher than that of the PTR-A. According to the results, two values of the PTR-A and ATR showed similar distributions.

Table 9. Descriptive statistics of the PTR-A and ATR

Material		Max (W/m^2)	Mean (W/m^2)	Min (W/m^2)	SD (W/m^2)
A-C	PTR-A	614.62	570.79	506.61	37.81
	ATR	666.51	574.33	523.01	39.07
A-G	PTR-A	582.65	545.19	491.42	32.51
	ATR	628.66	550.34	506.91	32.80
C-G	PTR-A	547.30	522.41	490.44	21.68
	ATR	567.58	525.11	495.61	18.20

A-C-G	PTR-A	563.10	532.96	488.90	20.39
	ATR	601.16	537.77	498.14	29.45

4.4.4. Model Validation

4.4.4.1. Comparing ATR to PTR

4.4.4.1.1. GRF-G Model

The results showed that the PTR-G and ATR were significantly positively correlated. The results of the correlation analysis are as follows: the correlation coefficients of the PTR-G and ATR for A-C, A-G, C-G, and A-C-G are 0.918, 0.924, 0.903, and 0.841, respectively (Figure 16, Table 10). Most researchers may agree that correlation coefficients less than 0.1 are negligible and greater than 0.9 represent a very strong correlation. However, the interpretation of various correlation coefficients between 0 and 1 is still controversial. Thus, it is important that specific coefficients should be carefully interpreted as measuring the strength of the relationship in the context of the scientific questions presented (Schober, Boer, & Schwarte, 2018).

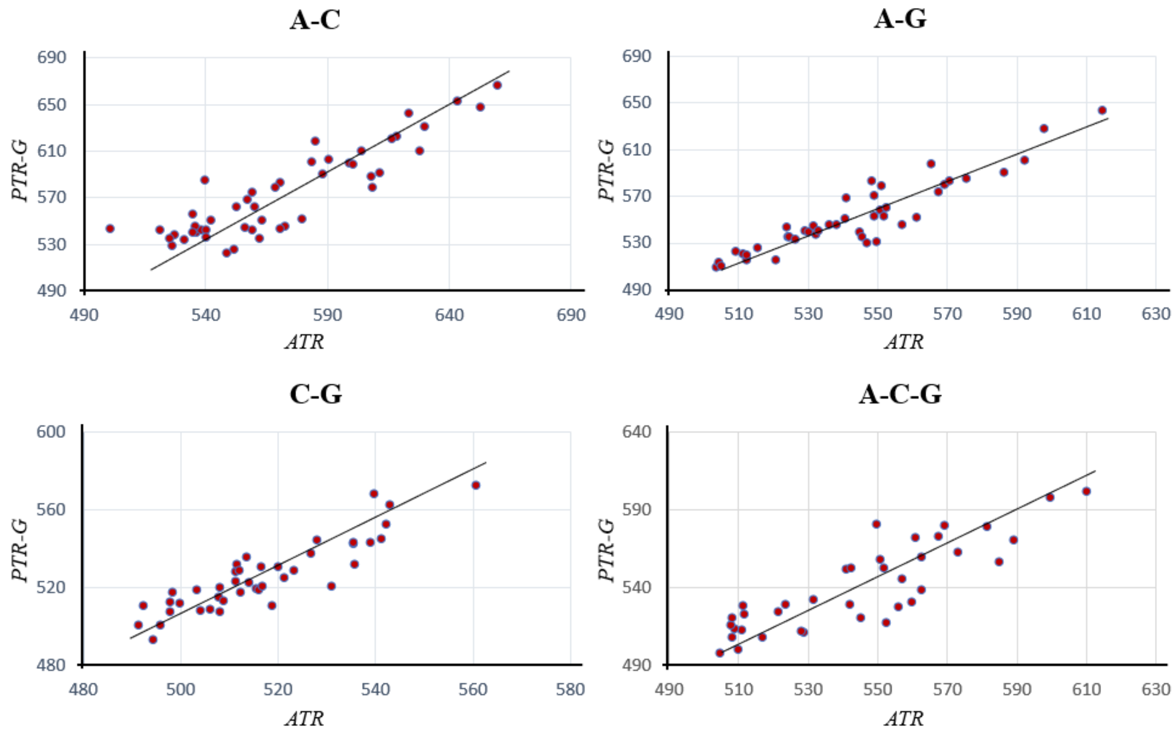

Figure 16. Correlation between PTR-G and ATR

Schober et al. (2018) attempted to interpret correlation coefficients (Table 11). They argued that if absolute magnitude of the observed correlation coefficient is between 0.70 and 0.89, it shows that there is a strong correlation. Also, if the observed correlation coefficient is greater than 0.9, there is a very strong correlation. According to their definition, the results of this study showed that there is a strong or very strong correlation between the PTR-G and ATR (correlation coefficients = 0.841 ~ 0.924). All results were statistically significant at 0.01 level. Thus, the GRF-G model can be used for calculating the terrestrial radiation using the ground temperature for different ground conditions.

Table 10. Correlation coefficient between the PTR-G and ATR

	PTR-G (A-C)	PTR-G (A-G)	PTR-G (C-G)	PTR-G (A-C-G)
ATR	0.918**	0.924**	0.903**	0.841**

** correlation is significant at the 0.01 level

Table 11. Example of a conventional approach to interpreting a correlation coefficient

Absolute Magnitude of the Observed Correlation Coefficient	Interpretation
0.00–0.10	Negligible correlation
0.10–0.39	Weak correlation
0.40–0.69	Moderate correlation
0.70–0.89	Strong correlation
0.90–1.00	Very strong correlation

* Source: Schober et al. (2018)

4.4.4.1.2. GRF-A Model

The results showed that there is a positive correlation between the PTR-A and ATR. The correlation coefficients of the PTR-A and ATR for A-C, A-G, C-G, and A-C-G are 0.781, 0.842, 0.821, and 0.779, respectively (Table 12). According to the definition of Schober et al. (Schober et al., 2018) , there is a strong correlation between the PTR-A and ATR, which is statistically significant at 0.01 level. Thus, the GRF-A model can be used for calculating the terrestrial radiation of various ground conditions using the air temperature.

Table 12. Correlation coefficient between the PTR-A and ATR

	PTR-A (A-C)	PTR-A (A-G)	PTR-A (C-G)	PTR-A (A-C-G)
ATR	0.781**	0.842**	0.821**	0.779**

** correlation is significant at the 0.01 level

4.5.Discussion

This study suggests the need to consider terrestrial radiation in thermal comfort measures to create MUD strategies. The findings indicate that terrestrial radiation is emitted differently depending on the proportion of different ground conditions. To recognize the need of terrestrial radiation, it is important to understand why terrestrial radiation is important and how terrestrial radiation affects heat-related human health (Figure 18).

Terrestrial radiation has a huge effect on human heat stress. As mentioned in the introduction, terrestrial radiation plays an important role in outdoor human thermal comfort, which is defined as a state of mind that shows satisfaction with the thermal environment (M. Xu et al., 2018). Previous studies have found that reducing the terrestrial radiation absorbed by a person improves human thermal comfort (Brown, 2011; Correa, Ruiza, Cantona, & GracielaLesinob, 2004; Shahidan et al., 2010). This study simulated the energy budgets to demonstrate the effect of terrestrial radiation on human thermal comfort using the COMFA model proposed by Brown and Gillespie (1995). An example can be used to illustrate the importance of terrestrial radiation on a person's thermal comfort. Assume that the air temperature is 25℃, the ground temperature is 35℃, the human surface temperature is 25℃, the ground material is grass, and a person is standing. The energy budget of terrestrial radiation emitted from the ground and absorbed by a person is 510 W/m^2. Energy budget refers to the degree of thermal comfort and results showed that terrestrial radiation accounts for a significant portion of the total energy budget (Figure 17).

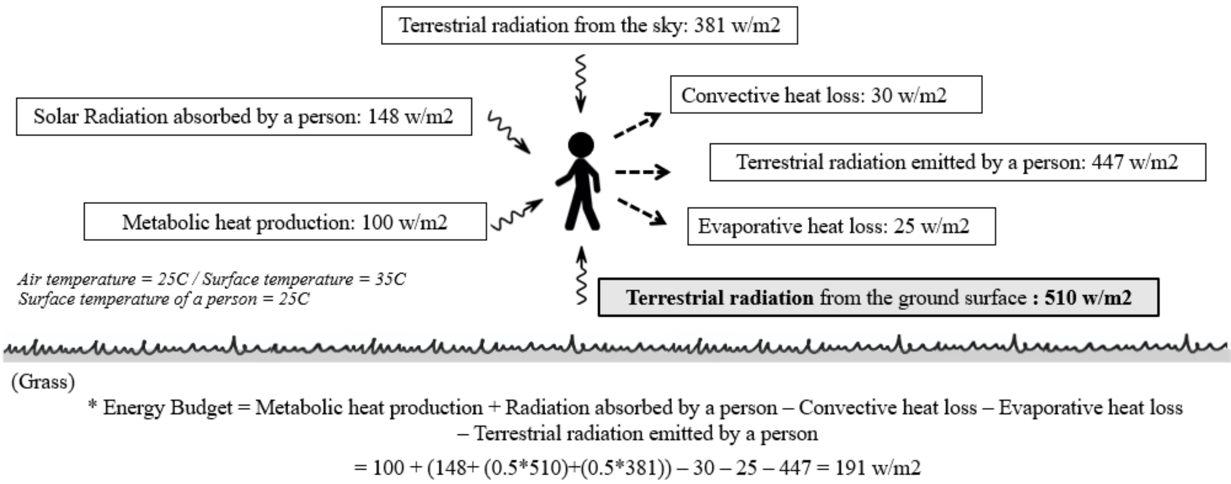

Figure 17. Energy budget calculation using COMFA model

High temperatures cause heat stress by making person thermally uncomfortable. These thermal stresses cause heat-related health problems. Rohat et al. (2019) showed that the heat stress risk, which is linked to the exposure to vulnerable people and extreme temperature events such as heat hazard, resulted in heat-related health impacts. Also, Di Napoli, Pappenberger, and Cloke (2018) assessed heat stress effects on mortality. Their results showed that there is an increase in the number of outpatients and deaths on hot days by comparing days without thermal stress. Kovats and Hajat (2008) also conducted a critical review on the relationship between heat stress and public health. Their results showed that heat stress causes heat-related illness (clinical signs), which eventually leads to heat death (Figure 18).

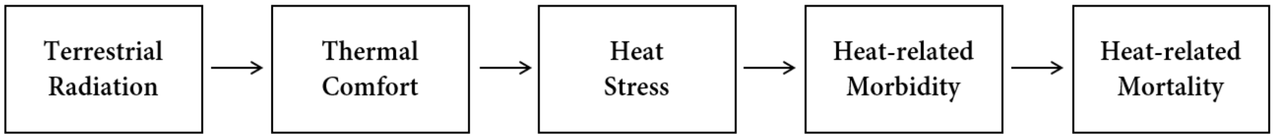

Figure 18. Causal chain from terrestrial radiation exposure to heat-related health

There are no thermal comfort-related studies considering the different terrestrial radiation according to the different ground conditions. Therefore, this study developed two versions of the GRF model: the GRF-G model that can use ground temperature and the GRF-A model that can use air temperature. The models were developed with the theories and compared with actual measurements to validate. According to the results, there are statistically significant strong correlations between the PTR and ATR for both models (correlation coefficients = about 0.8 ~ 0.9, $p < 0.01$).

This study also found that when considering two different ground materials, the correlation between the PTR and ATR was higher than considering three ground materials. For the GRF-G model, the average coefficient of correlation analysis is 0.903 for two different materials and 0.810 for three different materials. For the GRF-A model, the average coefficient of correlation analysis is 0.814 for two different materials and 0.779 for three different materials at 0.01 significant level. It means that the model is more accurate when considering fewer ground materials.

This study has some limitations that need further research. When measuring the terrestrial radiation emitted from the ground using instruments, it is important to know how instruments theoretically measure the terrestrial radiation and how terrestrial radiation is received by a real person. Ground temperature is usually measured vertically downward using a thermal camera (FLIR E6) or a pyrgeometer. Assuming that a person can be represented by a vertical cylinder, terrestrial radiation from the ground (Figure 19, A) should be translated into the amount of terrestrial radiation received by a vertical cylinder (Figure 19, B).

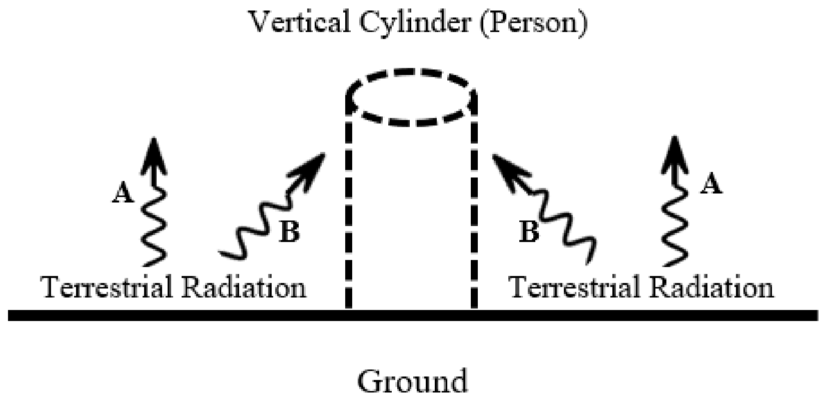

Figure 19. Concept of terrestrial radiation absorbed by a vertical cylinder

Theoretically, the CNR4's upper longwave detector has a view of nearly 180° and the lower detector has a view of 150° (Figure 20). It means it can measure all terrestrial radiation for the sky and ground hemisphere except for the space of 30°. It seems that the missing 30° might have only a minor effect on the amount of terrestrial radiation for a horizontal flat plate, but it might be quite important for a vertical cylinder. Therefore, further research needs to complement this limitation through theoretical and empirical grounds.

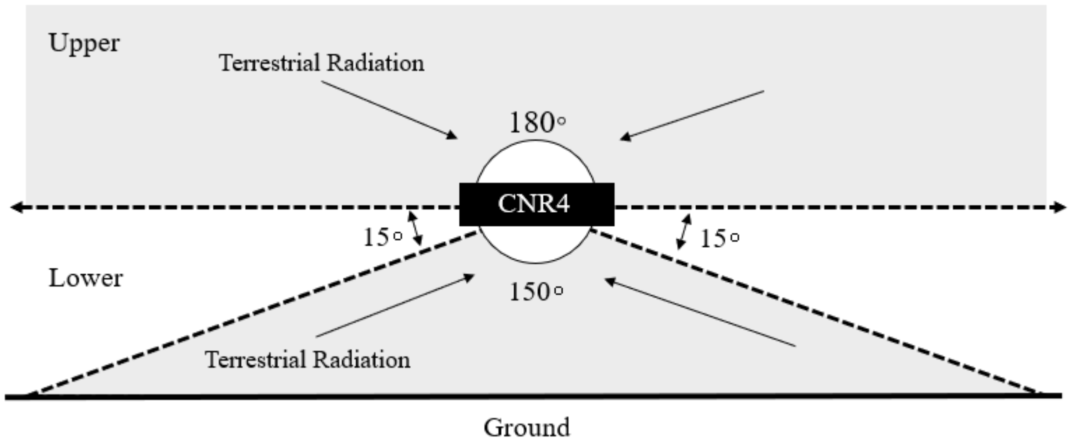

Figure 20. Concept of terrestrial radiation absorbed by CNR4

Further research should be conducted on more accurate conversion using various methods and considering additional microclimate parameters. Theoretically, ground temperature should be used to calculate the terrestrial radiation, which gives the most accurate value. However, previous studies attempted to calculate the ground temperature by using air temperature because of the data availability. Many methods for converting air temperature to ground temperature have been proposed. In this study, regression analysis was used. According to the results of this study, regression analysis showed R^2 values of 0.762 for asphalt, 0.663 for concrete, and 0.573 for grass, respectively. Although this study used the regression method, other methods need to be considered for more accurate conversion since there are various methods considering various microclimate parameters. For example, Khan et al. (2019) suggested the model for the asphalt ground temperature. In their model, various microclimate parameters such as wind speed (m/s), air temperature (F), relative humidity, and solar radiation (W/m^2) were considered to estimate the ground temperature (F). According to their results, the model has an R^2 value of more than 0.9. Also, according to Diefenderfer, Al-Qadi, and Diefenderfer (2006), their model included daily maximum ambient temperature (°C), calculated daily solar radiation (kJ/m_2), and depth from the surface (m) to calculate the predicted daily maximum ground temperature (°C). Their adjusted R^2 value of the model were 0.771 for maximum temperature and 0.798 for minimum temperature. Therefore, since each study has different results and perspectives on different ground material., further consideration of various methodologies is needed.

According to the Köppen climate classification, climatic conditions vary depending on the region, continent, country, etc. As a pioneering research, this study was limited to the City of College Station, located in the Cfa climate zone (Humid subtropical climate) for the increasing validity and reliability of the results, but additional research for different climatic regions is needed to use the GRF model in more diverse regions. The relationships between microclimate parameters vary depending on various climate zones. Mildrexler, Zhao, and Running (2011) conducted a global analysis to compare air temperatures with land surface temperatures using satellite data of every World Meteorological Organization station on Earth. Their results showed that the relationship varied by latitude and longitude. Emissivity, as well as the relationship between air and temperature, vary across regions. According to Wang et al. (2005), even the same material may have different emissivity depending on changes in the temporal or spatial distribution. Like this, additional models for various regions should be developed, because climate relationships and characteristics may vary depending on the location.

Finally, for better results, a wider range of ground materials, the consistent properties of each material, and securing more samples should be considered. This study considered three materials: asphalt, concrete, and grass. Soil was excluded because of difficulty in securing a target site due to a private issue. It is not often necessary to consider more than three ground materials for real design together. Nevertheless, it is deemed necessary to consider more ground materials. In addition, even if it is the same ground material, the characteristics of albedo and emissivity vary slightly depending on the different neighborhood environments. For example, according to the results of this study, grass has slightly different albedo and emissivity depending on measurement spots because they have different conditions depending on their management status. These differences need to be considered for accurate research results. Lastly, more samples must be obtained for statistically significant results. In this study, five spots for asphalt, five spots for concrete, and four spots for grass were selected to increase the utilization of the model. However, more samples for each ground material are needed to find more statistically meaningful values.

4.6.5. Conclusion

Previous studies have not conducted sufficient research on the effect of terrestrial radiation on thermal comfort. This study conducted pioneering research on improving terrestrial radiation estimates for human energy budget models. The primary findings are as follows. First, this study presents the need to consider different terrestrial radiation estimates for human thermal comfort because this study found and validated that terrestrial radiation is emitted differently depending on the proportion of different ground conditions. Second, to improve terrestrial radiation estimates, this study argued that the ground ratio factor (GRF) concept should be considered. GRF represents the ratio of different ground materials. At the same time, the ground ratio factor (GRF) models were developed to estimate the different terrestrial radiation according to the different ground conditions. Two models were developed to use ground and air temperature. The ground temperature-based GRF (GRF-G) model was developed using the Stefan-Boltzmann law to use ground temperature and the air temperature-based GRF (GRF-A) model was developed using regression analysis to use air temperature. Third, the models were validated through statical analysis. Actual terrestrial radiation (ATR) was measured through field measurement, which was utilized for the comparison with predicted terrestrial radiation (PTR) from the models. The results showed that the PTR and ATR have a statistically significant strong correlation. In conclusion, these findings can be used to update existing human energy budget models by considering more diverse landscape design factors. This enables more accurate measurement of human thermal comfort and development of microclimatic urban design (MUD) strategies to ameliorate urban heat islands.

5. SUMMARY AND CONCLUSIONS

This dissertation highlights the importance of neighborhood environmental characteristics by investigating the impact of the urban landscape on heat-related health, and present comprehensive considerations by creating new evidence on prevention strategies for thermal environments. There are three independent studies in this dissertation, including one systematic review and two empirical studies at the macro-scale in the City of Cincinnati (neighborhood-level) and micro-scale study on urban street to find out the urban landscape design strategies and suggestions.

The first study conducted a systematic review on the impact of urban landscape characteristics (ULC) on heat-related human health. According to the results, ULC has positive or negative effects on heat-related health and appropriate urban landscape design strategies for heat vulnerable areas can mitigate the impact of thermal environments on human health. However, more research should focus on vulnerable groups such as older adults and children, on more diverse climate zones to build more accurate relationships, and creating accurate information for more diverse environments. The second study analyzed the impact of urban landscape and sociodemographic characteristics on heat-related health using heat-related emergency medical service (EMS) incidents. The results showed that socially vulnerable groups were more vulnerable to heat-related health, and the effect of these variables has increased with increasing temperature. Heat-related health incidents have been decreased in block groups with high green areas and a low percentage of impermeable surfaces. The third study developed the ground ratio factor (GRF) model to estimate the different terrestrial radiation according to different ground conditions. The model was validated by comparing the predicated terrestrial radiation (PTR) from the model with the actual terrestrial radiation (ATR). The results showed that GRF model can measure terrestrial radiation for various environments and improve existing energy budget models.

In conclusion, the findings of this dissertation provide new insights into the urban landscape design strategies and a foundation of knowledge for local interventions. This dissertation found spatial inequalities in heat-related morbidity. Socially vulnerable groups are also found to be vulnerable to heat-related health. Therefore, efforts to improve the thermal environment and protect health problems must be continuously considered by landscape architects, urban planners, and policymakers, especially institutional support for the socially vulnerable.

5.1 Research Contributions

This dissertation presents a direction for further research. According to the results of Study 1, although the relationship between urban landscape and heat-related health is well established, there is not enough empirical research on their relationship. Also, study 1 suggests that more research needs to be done on more diverse climate zones and environments to establish more accurate evidence. Study 2 suggests that more research should focus on vulnerable groups such as older adults and children. Because the results showed they were exposed to heat vulnerability. Study 3 suggests that various microclimate conditions should be considered to measure a more accurate human thermal comfort. According to Study 1 and 2, some studies argued that the effects of green areas on heat-related health were not significant, while most related studies found a significant relationship. Therefore, further research based on the future research suggestions presented in Study 1, 2, and 3 is needed to clarify the relationship.

This dissertation provides a summary of the effects of various urban landscape variables on heat-related health through a comprehensive framework. Due to the collision between urban landscape features and its data across a wide range of domains, it is not easy to consider urban landscape features together in macro-scale studies. For example, there is a limitation using urban sprawl data for urban and rural areas along with other urban landscape factors such as green areas and water bodies since the effects of urban landscape exposure variables may conflict. Therefore, the results presented in Study 1 allow us to understand the direction and magnitudes of influence of various urban landscape elements.

This dissertation provides a comprehensive framework that can easily identify the research trends of the relationship for various scales from micro to macro-scale. There are limitations in analyzing relationships on various scales together in one study. Previous relevant review studies have analyzed the relationship on each scale, but analysis on various scales has not been considered together. In this regard, Study 1 summarized the macro aspects of studies through a systematic review and the relationships mentioned in micro-scale studies through a comprehensive review. Study 2 suggested the new evidence on the relationships through empirical study at the macro-scale, and Study 3 conducted an empirical study on the micro-scale and demonstrated the relationship with results.

This dissertation contributes to understanding the environmental inequality problems associated with heat-related health problems. In general, differences in health outcomes have different results depending on geographical location and socio-demographic characteristics. For example, people living in socially vulnerable areas have relatively little access to medical facilities and there are not enough spaces for social activities. Similarly, according to the results of this dissertation, heat-related health problems were more exposed to people who live in socially vulnerable areas. Thus, it is important to identify areas where vulnerable people reside, and through this process, environmental inequalities in urban areas can be identified. Study 2 created a heat vulnerability map to identify areas vulnerable to heat and groups vulnerable to heat. As a result, this dissertation identified areas where environmental inequalities are severe, and these data can be used as basic knowledge of local interventions to address heat-related problems.

The results of the dissertation contribute to improving existing energy budget models for thermal comfort measures. Study 3 has created a model that can measure terrestrial radiation according to various surface conditions that have not been considered in the existing models so far. Most of the existing studies only focused on urban climatic factors such as solar radiation, temperature, wind speed, and relative humidity, but did not consider terrestrial radiation. Although the COMFA model is the only one that considers terrestrial radiation to measure the amount of energy budget, it does not consider the surrounding ground conditions at which the subject stands. As has already been mentioned in Study 3, the effect of terrestrial radiation from the surface on human thermal comfort is significant. Therefore, the GRF model developed by Study 3 can be utilized to improve existing energy models, enabling accurate terrestrial radiation measurements for more diverse environments.

5.2 Practice and Policy Implications

Heat-related health caused by climate change and urban heat island phenomena is a crucial issue not only in the United States but also globally, and is directly or indirectly related to neighborhood characteristics. Therefore, creating safe environments help prevent heat-related health problems and encourages people to have outdoor activities. The findings in this dissertation on the relationship between urban landscape and heat-related health contribute to design guidelines and policy strategies to create thermally comfortable and safe environments. Therefore, this dissertation makes the following suggestions to help policymakers, urban planners, landscape designers, and facility managers interested in creating thermally comfortable environments by addressing heat-related health.

The results of this dissertation contribute to providing basic knowledge for local interventions. According to Study 1, various methods have been used to analyze the relationship between urban landscape and human health. Most studies noted the fact that the impact of urban landscape on mortality changes with time series from past to present. And, they argued that these changes in key environmental factors contribute to heat-related health problems. Therefore, local governments need to establish prevention strategies for major environmental factors identified in this dissertation. Study 2 created a heat vulnerability map using heat-related EMS incidents and urban landscape and sociodemographic data. The heat vulnerability map can be used to determine the preferred areas where planning is needed or to derive factors that require planning first when proposing new policies or strategies to address heat-related problems at the local level. Through the results of this dissertation, additional infrastructure can be planned to prevent heat-related accidents so that ambulances and nearby hospitals can be easily provided in areas with frequent heat-related accidents, and strategies can be established for urban landscape elements that require preferential maintenance planning, such as street trees, surface conditions, and green areas. Meanwhile, analysis of future heat vulnerability can be used to address heat-related health problems. Analysis of Study 1 showed that some studies predicted future land-use changes and climate change by using current data, and they argued that heat-related health problems can be solved through related adaptation strategies. For doing this, various scenarios for future urban developments can be utilized to solve heat-related problems, which can be an important foundation for policy makers and urban planners at the local-level. At an individual level, the results of this dissertation can be used to create urban landscape design strategies. Study 1 compiled urban landscape factors that affect heat-related stress at the micro-scale. In addition, Study 3 developed a GRF model that can measure terrestrial radiation for various environmental conditions to improve human thermal comfort. By using the model, we can measure thermal stress more accurately. These findings can be used to improve the thermal environment for socially heat vulnerable groups such as the elderly and children by creating thermally comfortable environments around the senior center or school playgrounds to ensure that the elderly or children can safely engage in outside activities.

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