The impact of anthropogenic modification of rural areas on surface urban heat island intensity

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THE IMPACT OF ANTHROPOGENIC MODIFICATION OF RURAL AREAS ON SURFACE URBAN HEAT ISLAND INTENSITY

by

Michelle Dornath-Mohr

A THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Science in The Department of Atmospheric and Earth Science to The School of Graduate Studies of The University of Alabama in Huntsville

HUNTSVILLE, ALABAMA

2020
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Michelle Dornath-Mohr

July 13, 2020

Michelle Dornath-Mohr

(date)
Submitted by Michelle Dornath-Mohr in partial fulfillment of the requirements for the degree of Master of Science in Earth System Science and accepted on behalf of the Faculty of the School of Graduate Studies by the thesis committee.

We, the undersigned members of the Graduate Faculty of The University of Alabama in Huntsville, certify that we have advised and/or supervised the candidate of the work described in this thesis. We further certify that we have reviewed the thesis manuscript and approve it in partial fulfillment of the requirements for the degree of Master of Science in Earth System Science.

Leiqiu Hu  2020-July-14  Committee Chair

Leiqiu Hu  (Date)

Thomas L. Sever

July 14, 2020  (Date)

Walter Lee Ellenburg

July 15, 2020  (Date)

John Mecikalski  2020-July-14  Department Chair

John Mecikalski  (Date)

John Christy

20 July 2020  College Dean

John Christy  (Date)

David Berkowitz  Digitally signed by David Berkowitz

David Berkowitz  Date: 2020.08.27 13:48:43 -05'00'

David Berkowitz  (Date)
Abstract

The School of Graduate Studies
The University of Alabama in Huntsville

Degree: Master of Science      Program: Earth Systems Science
Name of Candidate: Michelle Dornath-Mohr

**Title:** THE IMPACT OF ANTHROPOGENIC MODIFICATION OF RURAL AREAS ON SURFACE URBAN HEAT ISLAND INTENSITY

In the quantification of Urban Heat Islands (UHI), anthropogenic modification of the rural area is an understudied yet vital area of interest. This research explores the influence of anthropogenic modification of vegetation in the rural reference area on surface urban heat island intensity (SUHII) by examining two research objectives. MODIS daily land surface temperature (LST), annual Cropscape landcover maps, and MODIS weekly smoothed NDVI are used. The first research objective is to characterize the different impacts of cultivated and natural vegetation on SUHII. Seasonal, diurnal, and regional differences are studied by quantifying the LST response to phenology changes in two contrasting domains, one predominantly surrounded by cultivated vegetation (Chicago) and the other predominantly surrounded by natural vegetation (Atlanta), from 2007 to 2018. The influence of cultivated vegetation is more pronounced during the daytime in spring and fall than during the summer or at night, resulting in up to a 6 °C underestimation of SUHII relative to natural vegetation. This underestimation of SUHII in spring and fall is linked to reduced vegetative activity in cultivated areas
during those seasons. Chicago, at a higher latitude and surrounded by cultivated land, resulted in larger changes in SUHII and NDVI than Atlanta over the growing season. Further characterizing the seasonal relationship between phenology and SUHII with Fourier approximations revealed unique SUHII/ΔNDVI curves for each species as well as between the two domains. These unique curves can potentially be used to develop regional vegetation patterns, enhancing city-to-city and region-to-region UHI comparisons. The second research objective is to characterize the impact of different LST responses of cultivated and natural vegetation on SUHII as a result of the timing and intensity of extreme heat. The spring and summer 2012 heatwaves were studied by comparing them with the 2007-2018 multi-year mean. The spring heatwave increases the underestimation of SUHII by cultivated vegetation up to 2.8 °C, but only negligible differences were found during the summer heatwave. The contrasting impact on SUHII between spring and summer heatwaves is linked to the increased difference in vegetative activity between cultivated and natural vegetation during the spring heatwave. Daytime SUHII was impacted more than nighttime SUHII and regional differences were minimal. The results of this research show that the impact of anthropogenic modification of vegetation on SUHII is greatest during the spring and fall and the smallest during summer even during periods of extreme heat; therefore, it is recommended that future UHI studies take into account the differences between anthropogenically modified and natural vegetation when choosing the rural reference area, especially for comparative seasonal studies.
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I would like to thank the many professors and students at The University of Alabama in Huntsville who have supported and mentored me throughout my graduate career. I am grateful for Dr. Leiqiu Hu, Dr. Tom Sever, and Dr. Lee Ellenburg for offering essential guidance and direction while serving on my committee. I would also like to thank my husband who provided encouragement and understanding during the development of this thesis. Lastly, I would like to thank Tania Klug for her never-ending and patient support through all stages of my graduate experience at UAH.
This thesis is dedicated to my daughters, who encouraged me to pursue my dreams, supported me every step of the way, and reminded me that it’s never too late to start.
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Chapter 1

Introduction

1.1 Thesis Organization

This thesis is divided into 4 chapters. Chapter 1 provides an introduction to the broader issue of Urban Heat Islands and phenology in the rural biome. Chapter 2 presents a study characterizing the extent anthropogenic modifications in rural landscapes affect local LST by quantifying the phenological differences between cultivated and natural vegetation and the response of LST to those differences and their effect on SUHII. Chapter 3 presents a study characterizing the impact of heatwaves on SUHII due to the potential differences in the responses of cultivated and natural vegetation using the 2012 heatwave as an example to quantify the changes in phenology and SUHII for both cultivated and natural vegetation. Chapter 4 provides a brief summary of Chapters 2 and 3, offers general conclusions, limitations, and offers future research possibilities.

1.2 Literature Review

Background: Urban Heat Islands (UHI), clear examples of unintended anthropogenic climate modification, have been documented across the globe (Yow 2007; Eliasson and Holmer 1990), beginning with Luke Howard’s studies of London
weather patterns in 1820 (Howard 1833; Mills 2008). As Howard (1833) described and current research confirms (Zhang et al. 2010; Chen et al. 2006; Anderson, Gough, and Mohsin 2018) there are a number of anthropogenic activities which alter the local energy balance resulting in UHI: thermal and physical properties of building materials can cause radiation build-up, trapping heat energy within urban canyons; building geometry can obstruct free radiation to the sky; commercial and industrial complexes can directly release heat energy into the environment; street orientation and tall, dense building topography (surface roughness) can impede cooling winds thus hindering sensible heat loss; absence of vegetation can result in decreased evapotranspiration; pollution can increase albedo and re-emit longwave radiation; the presence of impervious surfaces can amplify sensible heat flux; and impervious surfaces can also provide places for standing water to collect, possibly increasing overall humidity.

UHI have been studied across the globe in diverse climate zones, including tropical wet climates, tropical savanna climates, subtropical steppe climates, hot dry arid climates, tropical highland climates, and polar/arctic climates (referenced in Yow 2007). It has been found that each city has a unique UHI signature with regard to timing and intensity dependent on its spatial characteristics and surrounding biome (Stewart et al. 2012). UHI signatures share certain attributes, including a horizontal temperature gradient within the urban area that generally increases toward the urban core although intra-urban areas such as parks and lakes can disrupt the temperature gradient and influence the UHI signature. Local geography and meteorological conditions such as cloud cover, wind speed and direction, air-flow, albedo, emissivity, humidity, and precipitation are also significant factors in a city’s UHI unique signature. Generally, as wind speed and cloud
cover increase, the UHI magnitude decreases. Large bodies of water moderate the UHI magnitude due to advection. Wind flow is mostly downslope at night and upslope during the day; however, this pattern can be disrupted by larger scale synoptic weather patterns, landforms, and urban canyon corridors. Complex terrains often create variable wind flow which can also influence temperature patterns. Seasonal variations in weather can impact each city’s unique UHI; for example, in some mid and high latitude cities, the UHI magnitude is higher in winter due to direct anthropogenic heat, while in the tropics, UHI magnitude is greatest in the dry season because of rapid nighttime cooling (Yow 2007; Shastri et al. 2017).

Significant effort has been made to correct air temperature biases when comparing UHI across different regions (Imhoff et al. 2010b), but the large variation between UHI signatures makes it difficult to directly compare cities and their effects on the local climate. Therefore, understanding the individual UHI signature and its influences is essential for accurate comparisons. As human populations increase and urban areas continue to expand, a greater understanding of UHI effects and magnitude will provide critical information to help builders and city planners create intelligent urban design, such as green roof technology, and other mitigation tactics to reduce the negative effects of UHI magnitude (Gaffin et al. 2012).

Types of UHI: The effects of urban activities on the temperature have been found all the way from high in the atmosphere to underground; consequently, four types of UHIs have been defined: subsurface, surface, canopy, and atmospheric boundary.
The subsurface layer can increase ground temperature, affecting permafrost and threatening infrastructure such as roads, bridges, buildings, and pipelines. One beneficial effect of subsurface warming is the potential for increased groundwater temperatures and improved efficiency of geothermal energy systems.

The surface layer is defined as the skin layer. Surface UHI (SUHI) frequently are found where an abundance of impervious surfaces exist (Gluch, Quattrochi, and Luvall 2006). Surfaces heat and cool quicker than air, so land surface temperature (LST) provides a direct link to the physical and biophysical processes that relate to land cover (Imhoff et al. 2010b). Remotely sensed LST is easy to gather, widely available, reliable, with high spatial and temporal coverage (D. R. Streutker 2002; Yow 2007; Hu and Brunsell 2015). LST is derived from surface emittance, and therefore can be higher and more variable than the concurrent air temperatures due to the complexity of the surface and variations in topography.

The canopy layer is defined as the air below roof height, and is easiest to measure due to access and simplicity of the instrumentation used. The temperature conditions within the canopy layer are primarily a result of the unique characteristics at the specific location. Canopy UHI are primarily nocturnal and are capable of reaching in excess of 10°C (Yow 2007). Materials with high heat capacities and high thermal emittance are prime drivers of canopy UHI resulting in reduced nighttime cooling rates in urban areas. The fact that rural areas generally cool at a faster rate than urban areas is a significant cause of increasing UHI magnitude after sunset, reaching maximum magnitude near the middle of the night and diminishing shortly after sunrise (Yow 2007).
The atmospheric boundary layer is defined as the air above the roof height and is typically measured via weather balloons, aircraft, and remote sensing. The temperature conditions within this layer are created by a broad mix of atmospheric conditions (Oke 1982), and therefore the boundary layer tends to maintain a more consistent UHI magnitude over the diurnal period than does its canopy layer counterpart. Boundary layer UHI routinely extend over 1 km in height during the day but only in the 100s of meters during the night (Oke et al. 1991). The importance of the boundary layer UHI is its influence on airflow and the consequential dispersion of air pollution.

Impact of UHI: The increased temperatures resulting from UHI have consequences that can be either positive or negative depending upon the local macroclimate. In cold areas, UHI benefits include cheaper residential heating, improved outdoor comfort, reduced road weather hazards such as surface ice or fog, and an increased growing season. However, in hot climates UHI can create unfavorable economic and social consequences by increasing energy and water demands (Stewart et al. 2012) as well as raising the threat of heat stress and mortality via the spread of infectious diseases, heat stroke, heat exhaustion, and excessive dehydration. Excessive heat kills more people than any other weather event in both developed and undeveloped countries (Fouillet et al. 2006; Brooke Anderson and Bell 2011; Ly et al. 2005; Whitman et al. 1997; Rooney et al. 1998; Lan et al. 2012; Huang, Kan, and Kovats 2010). As more people move into urban areas and are exposed to the extreme temperatures caused by UHI, health risks to the population are expected to increase (Gabriel and Endlicher 2011).
UHI has several indirect effects. The increased temperatures affect soil composition and productivity by influencing leaf decomposition rates and net nitrogen mineralization rates. Warmer temperatures encourage earlier flowering and an increased growing season, changing the ability of species to survive and grow (Meng et al. 2020). A general phenology shift has been observed between urban and rural areas, causing a 3 day earlier green-up per 1 degree increase in temperature (D. Zhou, Zhao, et al. 2016). As the phenology changes, it is possible that a mismatch between pollinators and flowers could occur, negatively influencing food production (Kudo, et al. 2004).

UHI both influence and are influenced by local weather as some UHI have been shown to have increased humidity, cloud cover, and convective precipitation. Maximum rainfall rates downwind to the urban area can exceed the mean value by 48 – 116% relative to the upwind area (Shepherd, Pierce, and Negri 2002). Air pollution can also provide condensation nuclei, reducing cloud droplet size and suppressing precipitation amounts over and downwind of the UHI. UHI can also have a significant impact on the transport of air pollutants within urban areas, often increasing the concentration of pollutants in urban areas during their most populated time periods (Eliasson and Holmer 1990). In general, UHI can experience increased lightening episodes, as well as a change in freezing rain and snow events depending on the location (Oke 1982). Finally, UHI are suspected in compromising the observational data used to assess climate change and contaminating the global air temperature record. This suspected compromise in the observational data is because anthropogenic influences can cause artificial trends of increasing temperatures near specific weather stations that might not be indicative of larger scale climatic trends (Stewart 2011; Karl et al. 1988).
The rural counterpart: It has been shown that the UHI resulting from energy budget variability between urban and rural areas depends greatly on the unique rural biome; therefore, UHI signatures are dependent upon defining the conditions both in the rural biome as well as within the urban area (Stewart et al. 2012). Comparisons between UHI are hampered by the lack of objectively quantifiable definitions for urban and rural. There have been many definitions of both urban and rural used in the scientific literature, making it difficult to draw broad scientific conclusions. Urban areas are defined as cities or towns and are densely populated with clusters of buildings. Rural areas are agricultural or pastoral, distinct and distant from urban areas, less populated with fewer built structures and more abundant natural spaces. Suburban areas are adjacent to a town or city, with structure and population numbers in between those of rural and urban areas. Each urban area is unique without a universally defined physical structure. As Stewart (2012) poetically explains:

“the term urban incorporates wooden quarters in old Hiroshima, Japan,
parks and playing fields of Preotia, South Africa, courtyards and
stonework streets of London, England, skyscraper canyons of Dallas, TX,
industrial plants and refineries of Ashdod, Israel, shaded avenues and
lawns of New Delhi, India, school and college grounds of Nairobi, Kenya,
factories and workshops of Cairo, Egypt, brick and tin shanties of Sao
Paulo, Brazil, high rise housing estates of Singapore.”

As each urban area is unique, so is the surrounding rural area unique. Many rural areas surrounding large urban centers consist of a combination of forests, water bodies,
open grasslands, pastures, scrublands, wetlands, and seasonal cropland. The diversity in rural areas is so great that some researchers have suggested a complex classification system to categorize rural areas (Stewart et al. 2012).

The urban side of the UHI has been well studied, but a comprehensive understanding of the UHI mechanism is still lacking and can be improved by a full characterization of what is occurring in the surrounding rural biome in regards to land cover and its effects. Despite acknowledgements that a full understanding of the rural biome is required for sound scientific conclusions, there has been relatively little research into the drivers of the rural contribution. Although many studies use a rural site for comparison, most neglect to specify the conditions of or the variability within the surrounding rural biome, treating the land composition of rural areas uniformly, disregarding its complexity, with many studies simply assigning the rural area as a ‘reference, leading to results that are often scientifically flawed (Stewart 2011). It has been suggested that a more rigorous method of rural analysis is required because up to three quarters of the observational UHI literature fails to provide adequate quantitative metadata of the rural. Specifically, the literature is missing explicit consideration of rural temperature variability caused by land cover effects (Stewart et al. 2012). This gap in literature has changed in recent years as many researchers are quantifying their methods of defining rural areas. Several studies have investigated the various methods used to define the rural area and found a lack of consistency (Schwarz, Lautenbach, and Seppelt 2011; Yao et al. 2018; Niu et al. 2020).
Both anthropogenic and natural conditions are expected to impact rural LST values including elevation changes, water bodies, vegetative species type, crop cover, irrigation, husbandry operations, and vegetation variety (Ellenburg, McNider, Cruise, Christy, 2016). Studies suggest there is enough temperature and dew point variation at the small farm scale to question the validity of using a single value to represent the rural side of the UHI equation (Hawkins et al. 2004). Distinct microclimates have been shown to exist within regions, with leaf onset variations exceeding 2 weeks at fine spatial scales of < 1 km (Fisher, Mustard, and Vadeboncoeur 2006). These variations in temperature and dew point come from the variation in land cover, specifically the phenology i.e., the presence or absence of vegetation and differences in soil condition. It has not been determined if the linkage between land cover and temperature and dew point is a local effect only, or if land cover affects temperature and dew point at a regional scale (Fisher, Mustard, and Vadeboncoeur 2006). Rural phenology, topography, rivers, wind, soil conditions and type, elevation, and water bodies all influence UHI intensity. Because rural areas are more connected with the annual seasonal cycle than are urban areas, being influenced by both anthropogenic and non-anthropogenic drivers, an understanding of rural biome phenology is required to fully understand UHI. It is unknown how the rural seasonal connection influences the seasonality of UHI. It is also unclear to what, if any, extent the current literature overestimates or underestimates the seasonality of UHI.

The Impact of Phenology: Phenology, the study of the timing of re-current biological events, the causes of this timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species (H. 1974), controls many of the biotic feedbacks to the climate system by influencing the seasonality of albedo,
surface roughness, canopy conductance, and fluxes of water, energy, CO₂, and biogenic volatile organic compounds (Richardson et al. 2013). Phenology varies significantly across climate zones, vegetation type, and timing of the growing season. It also plays a key role in determining how individual biomes are structured. Photosynthesis is influenced by seasonal and diurnal cycles: more active during the day than at night, active in summer and dormant in winter. Warming trends in the last 4 decades have noticeably affected the growing season, causing an overall increase in the length of the growing season with earlier onset of flowering especially within urban areas (Fisher, Mustard, and Vadeboncoeur 2006). Temperature is considered to be the largest driver of this phenological shift (Ide and Oguma 2010). Vegetation can affect climate and influence the exchange of moisture and heat as well as absorb sunshine and shade the soil (Imhoff et al. 2010b). The phenology of cropland has been found to be somewhat independent of natural phenological influences, instead being dependent on crop type and anthropogenic management and is not necessarily in sync with the surrounding natural flora (Buyantuyev and Wu 2012). Models based only on natural vegetation cues are unlikely to be accurate at predicting crop phenology and growth cycles. To understand crop phenology, genotype, planting time, fertilization, pest and weed control, irrigation, and harvest time need to be considered.

The phenology cycle of the major agricultural crops, corn and soybeans, in the Midwestern USA can be characterized similarly to the transition dates suggested by Zhang, et al. 2003.
1. Green-up: the date of onset of photosynthetic activity – mid-May
2. Maturity: the date at which plant green leaf area is at a maximum – July
3. Senescence: the date at which photosynthetic activity and green leaf area begin to rapidly decrease – early September
4. Dormancy: the date at which physiological activity becomes near zero – mid September
5. Harvest: the date at which the crops have completed their growing cycle and are harvested from the field, leaving mostly bare soil – mid September - October

As discussed in Cheng 2018, there are two main avenues from which to monitor plant phenology: field based and remote sensing. Field based results are limited by the number of in-situ observation sites making it difficult to get representative data across a large biome. Remote sensing has been shown to have repeatable and consistent temporal data over both regional and global scales (Tomlinson et al. 2011). Remotely sensed data of LST vegetation index and other surface characteristics have been widely used to describe UHI. Several methods have been used to remotely sense biomass and vegetative greenness (Imhoff et al. 2010b; Ide and Oguma 2010). Lower phenology response is associated with lower vegetation density. Relationships between various vegetation indices and percent vegetation cover have been established by using regression analysis such as Ratio Vegetation Index (RVI), Normalized Difference Vegetation Index (NDVI) and Perpendicular Vegetation Index (PVI) (Chen et al. 2006). NDIV, in particular, has been widely used to study land cover phenology and has been found to be sensitive to indicators of canopy parameters (Cheng et al. 2018).
Vegetation Indices: Vegetation indices are dimensionless, radiometric measures that serve as indicators for green vegetative activity. Normalized Difference Vegetation Index (NDVI), developed in 1974 (Rouse et al. 1974), is based on the science that green vegetation absorbs solar radiation in the photosynthetically active spectral region (0.4 – 0.7 microns), i.e., the energy source for the process of photosynthesis. The plant’s leaf also re-emits solar radiation in the near-infrared (NIR) spectral region (0.7 – 1.1 microns) because absorption of these wavelengths would overheat the plant and damage its tissues. Because of this, live green plants appear relatively dark in the photosynthetically active spectral region and relatively bright in the NIR. In contrast, clouds appear bright in the visible region and dark in the NIR. Chlorophyll, the pigment in green plants, absorbs visible light for photosynthesis while the cell structure of the plant reflects NIR. The more leaf area a plant has, the stronger both the absorption and reflection of the respective wavelengths occurs. NDVI is calculated by equation 1-1

\[ \text{NDVI} = \frac{\rho_{\text{NIR}} - \rho_{\text{RED}}}{\rho_{\text{NIR}} + \rho_{\text{RED}}} \]  

(1-1)

where \( \rho \) is the reflectance in the respective spectral bands. Soil typically does not show a distinct spectral difference between visible and NIR, enabling the differentiation between vegetation and its background soil. NDVI is a normalized indicator with a theoretical range of -1 to 1. Vegetation areas show a positive value, typically greater than 0.3. Although NDVI has a lower sensitivity to changes in the vegetation cover than more recently developed vegetation indices, NDVI is considered a robust measurement in the study of vegetative activity (Pettorelli 2014).
The magnitude of LST can influence NDVI. Increased LST in the springtime results in an increase of NDVI for most vegetation. However, extreme LST events can cause a decrease in plant health leading to a decrease in NDVI (Baumbach et al. 2017).

**Evapotranspiration:** Evapotranspiration (ET), an essential part of both the atmospheric system and hydrological cycle, is the combination of evaporation from the ground and transpiration from plants, moving water from the ground to the atmosphere. Evaporation accounts for the movement of water to the air from sources such as the soil, canopy interception, and waterbodies. Transpiration accounts for the movement of water within a plant and the subsequent loss of water vapor through its leaves. ET results from the solar radiation hitting the leaves of vegetation causing water to evaporate from the leaves. The mechanism of ET simultaneously releases latent heat and reduces the amount of energy available for sensible heat, resulting in a net cooling of the immediate area (Peng et al. 2012). ET and NDVI are strongly correlated (Senay, Budde, and Verdin 2011), indicating that high NDVI values will be accompanied by high ET values, dependent on the availability of water. Increasing LST generally causes an increase in NDVI and therefore an increase in ET. However, a strong inverse linear correlation also exists between LST and ET (J. Li et al. 2011), resulting in a decrease in LST when ET is present. We can expect that when NDVI is high, ET will also be high, causing a general cooling effect in the local area. Therefore, when the landcover is primarily composed of vegetation, the LST will generally be lower than neighboring areas without vegetation. This relationship between ET and LST indicates that rural areas that have high vegetative activity can be expected to have lower LST than the neighboring urban areas, causing an overall increase in SUHII.
ET is also responsible for water loss from drainage basins and is significantly affected by both vegetation foliage and land use. ET is dependent on plant growth, soil coverage fraction, solar radiation, humidity, temperature, and wind. In non-irrigated areas, depending on the soil’s ability to hold water, ET will usually be less than precipitation because some water will be lost due to percolation and surface runoff. However, if the water table is easily accessible, capillary action can cause water from groundwater to rise through the soil matrix to the surface leading to increased ET independent of precipitation.

If there is insufficient water available in the soil, ET will decrease as the plants regulate their water use. If leaf area is compromised, due to wilting or disease for example, ET will decrease because there is less leaf area intercepting the light and losing water to the atmosphere. During heat waves ET will generally increase because of increased atmospheric demand more strongly pulling water through the plants. ET is dependent upon both water availability and temperature magnitude, being limited by either lack of water or solar energy. Extreme events such as droughts and heat waves can change the normal limiting factor. It can be expected that irrigation will provide enough water during drought periods to compensate for the lack of moisture, reducing the threat of a water limiting event. During drought conditions, ET continues and may continue at an increased rate if the drought is accompanied by high temperatures (energy availability), further depleting the remaining water in the soil and the cultivars. Once ET can no longer continue, ET activity will decrease, leading to an increase in LST and resulting in a decrease in SUHII.
Several methods are available for measuring ET. The ASCE-EWRI Penman-Monteith combination is recommended by the American Society of Civil Engineers – Environmental and Water Resources Institute as the standard for equation for estimating ET (Rojas and Sheffield 2013).

1.3 Research Questions and Objectives

UHI were originally defined as the temperature changes caused by anthropogenic modification of natural surfaces. It must be acknowledged that both urban and rural areas contain anthropogenically modified areas. The current research standard for defining UHI intensity is to directly compare the urban temperature with one value for rural areas (Yow 2007; Stewart 2011). This method is not adequate because it ignores the variation in surface features that exist in the rural biome, including anthropogenically modified surfaces, and fails to account for their diverse effects on rural LST, causing either an overestimation or an underestimation of the UHI intensity.

The specific questions that will be answered by this thesis work are:

Knowing that anthropogenic modifications occur in both rural and urban landscapes 1) to what extent do anthropogenic modifications in rural landscapes affect local land surface temperature (LST) and 2) to what extent should those changes be considered when assessing the Surface Urban Heat Island Intensity (SUHII)?
Specifically, this thesis will address two separate questions under the broader questions above:

- When defining natural vegetation as the optimal rural reference area, how does anthropogenic modification of rural areas, specifically cropland, influence the quantification of the optimal signal of SUHII?
- When defining the multi-year mean (MYM) as the normal regional climate condition, how does the timing and intensity of heatwaves modify the LST of cultivated and natural vegetation when acting as the rural reference area in the estimation of SUHII?

To answer these questions, this project will synthesize information from multiple satellite observations that reflect land surface temperature, agriculture activities, and crop conditions surrounding Chicago, IL, and Atlanta, GA. The specific objectives of this project are to:

- Identify major land covers over the domain and map the annual changes.
- Examine and quantify phenology differences between natural vegetation and major crop types, for both normal and stressed conditions.
- Identify the impact of extreme heat on the rural area and determine to what extent it influences SUHII.
Chapter 2

Characterization of the impact of anthropogenically modified and natural vegetation LST response on SUHII

2.1) Introduction

*Anthropogenically modified land cover*: As of 2017 more than 4 billion people (55%) live in urban areas throughout the world, and it is projected that by 2050, more than two-thirds of the world population will occupy urban areas ("World Urbanization Prospects - Population Division - United Nations" n.d.). This increasing urbanization is the result of anthropogenic modification; however, rural areas can also be modified by human activity. Globally, agricultural areas (pasture, rangeland, and cropland) account for 38% of Earth’s ice-free land surface (Ramankutty et al. 2008) making it the largest anthropogenic modification of all land (Bigelow and Borchers n.d.). Cropland alone accounts for 12% of ice-free land (Ramankutty et al. 2008). While the quantity of urban land is often considered in scientific literature, agricultural land use is far greater than that of developed. For example, in the US, agricultural areas account for 18.6% of land cover, while developed areas account for only 4% (Brown et al. 2005). Agricultural land cover increased 3% between 1985 and 2005 (Foley et al. 2011) and is expected to further
expand globally by 4% in the next 30 years (Alexandratos and Bruinsma, 2012). While agricultural land in developed countries is contracting, significant expansion is occurring in emerging areas such as the tropics. These changes are a consequence of the fact that most arable land not currently under cultivation lies beneath tropical forests (Molotoks et al. 2018). Although cropland in developed countries is decreasing, yield is expanding due to increased anthropogenic practices such as double cropping, nutrient and water amendments, herbicides, and pest control (Gao, Liang, and He 2019).

*Urban Heat Islands:* The result of anthropogenic modification in urban areas leads to Urban Heat Islands (UHI), the phenomena of urban areas having higher temperatures than the surrounding rural biome (Oke 1973). UHI are clear examples of unintended anthropogenic climate modification and have been documented across the globe in cities of varying sizes and climates (Yow 2007). In its simplest form, UHI is determined by calculating the difference between the urban temperature and a rural reference area (Yow 2007; Stewart 2011). A number of anthropogenic activities alter the local energy balance resulting in UHI, including the thermal and physical properties of buildings, the geometry of the landscape, direct release of heat into the atmosphere, loss of vegetation, pollution, and the presence of impervious surfaces (Lo, Quattrochi, and Luvall 1997a). In turn, UHI can alter local climate, intraurban phenology patterns, and pollinator behavior (Meng et al. 2020), increase energy and water use (Stewart et al. 2012) and pollution (H. Li et al. 2018), and have dire impacts on human health (Gabriel and Endlicher 2011).

*Remote sensing of UHI:* Early work in UHI generally focused on air temperatures (Voogt et al. 1997), but the advent of readily available, inexpensive remote sensing data enabled measurement of land surface temperatures (LST) across a large area, providing
measurements of surface urban heat island intensity (SUHII), leading to more detailed information of spatial variability than the traditional point-based atmospheric UHI studies (Du et al. 2016a; Peng et al. 2012). Surfaces heat and cool quicker than air, so LST provides a direct link to the physical and biophysical processes related to land cover (Imhoff et al. 2010b). Remote sensing has the added benefit of being able to track temperature changes over extended periods of time through revisits and relatively high spatial and temporal resolution. Remotely sensed LST has been shown to be a reliable way to measure and quantify surface temperature (D. R. Streutker 2002; Yow 2007; Hu and Brunsell 2015).

_Spatial and temporal SUHII patterns:_ Although there are many benefits to using SUHII to measure the anthropogenic impact on temperature due to urbanization, it is crucial to accurately measure the required parameters to correctly characterize this impact. Quantification of SUHII, similar to the atmospheric UHI, is accomplished by calculating the temperature differences between urban and rural areas. Obtaining useful results is complicated because urban and rural areas are spatially fragmented, leading to variations in LST, and requiring the need for additional investigation (Esau and Miles 2018; Stewart et al. 2012).

_Inconsistent SUHII patterns:_ Despite a multitude of studies in Asia (Quan et al. 2016; Y. Li, Wang, Liu, et al. 2019), Europe (B. Zhou, Rybski, and Kropp 2013), India (Kumar et al. 2017; Bala et al. 2019), North America (Walker, de Beurs, and Henebry 2015a; L. Zhao et al. 2014b; Imhoff et al. 2010c), South America (Palme, Lobato, and Carrasco 2016) and globally (Peng et al. 2012), there is not a clear consensus on the temporal behavior of SUHII (Schwarz, Lautenbach, and Seppelt 2011; Niu et al. 2020;
Yao et al. 2018); and direct city-to-city, region-to-region comparisons are not yet practical. In some locals, SUHII is higher in the summer and in other places it is higher in the winter or spring (D. Zhou, Zhang, et al. 2016a). Some studies have concluded that SUHII is larger during daytime (Peng et al. 2012; Imhoff et al. 2010a); others have found globally SUHII is similar for daytime and nighttime (Clinton and Gong 2013); and still others have found contrasting diurnal patterns (D. Zhou, Zhang, et al. 2016a). UHI in similar climatic regions have been found to exhibit different intensities in the spring and fall (B. Zhou, Rybski, and Kropp 2013). These inconsistent results call into question the underlying assumptions of the SUHII analysis, in particular whether the differences in cultivated or naturally vegetated rural land cover could account for the variations presented in the studies. It has been found that different land covers exert influence on LST in the rural areas and therefore, SUHII is strongly dependent on the choice of both urban and rural pixels (Schwarz, Lautenbach, and Seppelt 2011), indicating the current knowledge gap could be caused by treating cultivated and natural areas the same.

*Rural anisotropy:* Although generally treated as homogenous in SUHII investigations, rural areas are a heterogenous mixture of land covers with widely varied properties. In comparison to urban areas, barren lands tend to be hotter, especially in arid areas (Shastri et al. 2017). Forested areas tend to be cooler than urban areas, bare ground, and cropland (Ellenburg, McNider, Cruise, and Christy 2016). Elevation plays an often-ignored part in LST, with higher elevations being generally cooler than lower elevations (Yao et al. 2018). Tall forests that block the wind behave differently than open areas such as grass and cropland. Rural anisotropy is both seasonal and spatial, meaning that the rural areas change throughout the seasons with possible snow in the winter, bare
fields in the spring, fully developed forests and lush cropland in the summer. In particular, the LST of the surrounding rural biome significantly influences the amplitude of summer daytime SUHII (Imhoff et al. 2010c) and is suspected to influence SUHII during other seasons.

*Disadvantages of inconsistent methods:* Urban expansion and activities in and around developed areas create uncertainty in the boundary between urban and rural areas. Therefore, studies have used a myriad of methods to define spatial and temporal location of the rural reference area (Niu et al. 2020; Schwarz, Lautenbach, and Seppelt 2011; Yao et al. 2018). These ambiguous definitions of rural and urban areas lead to inconsistent conclusions. Additionally, it is important to keep in mind that rural areas are also influenced by human activities, most notably agriculture. Human activities such as agriculture can alter the intensity of SUHII, especially during summer daytime (Peng et al. 2012). Human influences must be taken into account in order to understand the true impact of anthropogenic modification on regional climate. There are several methods used in the literature to define the rural reference: administrative boundaries (Niu et al. 2020), simplified urban extent algorithm (Chakraborty and Lee 2019), creating a buffer zone a set distance from the urban area, using equal area, masking water bodies, and removing high elevation areas (Yao et al. 2018). However, all of these methods lack vital quantitative information because they make little attempt to distinguish variations of land cover type within the rural area, making these large uncertainties in the definitions of urban and rural areas one of the most urgent issues in SUHII studies (D. Zhou, Zhang, et al. 2016a).
**Weaknesses of current studies:** While there is literature investigating the interaction between rural land cover type and SUHII, the studies currently available have several drawbacks, generally concentrating on summer only (Bala et al. 2019; Manoli et al. 2019) or summer and winter (Imhoff et al. 2010c; G. Zhao et al. 2017). The phenological trends of vegetation are generally omitted, missing the interesting changes that occur to SUHII during spring planting and fall harvest (Du et al. 2016b).

There currently is not a satisfactory understanding of the differences between cultivated and natural land covers (Yao et al. 2018), nor how their behavior impacts the LST of rural areas in the spring and fall. Although many methods have been developed to determine the rural reference LST, those methods will not provide accurate measurements until the difference in LST response between cultivated and natural vegetation is quantified (Schwarz, Lautenbach, and Seppelt 2011).

**Influence of vegetation on rural LST:** Daytime SUHII is significantly and negatively correlated with changes in vegetation activity (Lo, Quattrochi, and Luvall 1997b; Y. Li, Wang, Liu, et al. 2019; Yao et al. 2019), leading to the conclusion that increased vegetation reduces daytime LST (Wu et al. 2019), and the most significant impact on daytime LST is vegetation including both cultivated and natural land cover (Yang, Cai, and Yang 2017). Increased vegetation in rural areas is a significant driver for increased daytime SUHII around the world (Yao et al. 2019). In contrast, the lack of vegetation, especially in arid areas, can increase LST leading to decreased or even negative SUHII (Shastri et al. 2017).

**Anthropogenic modification of rural areas:** One important, as yet unacknowledged, aspect in SUHII studies is the fact that rural areas have been modified as well as urban
areas, specifically in the form of agriculture. Although it is known that cultivated and natural land covers have different impacts on SUHII and that changes occur throughout the diurnal and seasonal cycles (D. Zhou, Zhang, et al. 2016b), a clear understanding of these different impacts on SUHII has yet to emerge in the literature (G. Zhao et al. 2017). Rural biome type influences daytime SUHII, with forested areas having the largest SUHII (Imhoff et al. 2010b). Agricultural activities such as land preparation, planting time, nutritional and water amendments and harvest time, change how the cultivated vegetation behaves in comparison with natural vegetation. This manipulation leads to a different phenological cycle, different growth of vegetation, coverage of soil, canopy height, anisotropy, etc., when compared to natural vegetation, directly changing the amount of vegetative activity. Therefore, manipulation of vegetative activity results in the manipulation of the local LST response. This modification of LST can lead to a biased magnitude of SUHII if not taken into account when using vegetation as the rural reference. Additionally, this bias might vary seasonally due to the differences between native vegetation and dominant crop types. Further, because phenology of both cultivated and natural vegetation changes by region based on local background climate and dominant crop type, additional regional biases can be introduced.

UHI were originally defined as the temperature changes caused by anthropogenic modification of natural landscape. It must be acknowledged that both urban and rural areas contain anthropogenically modified areas. The current research standard for defining SUHII is to directly compare the urban LST with one value for rural areas (Yow 2007; Stewart 2011). This method is not adequate because it ignores the variation in surface features that exist in the rural biome, including anthropogenically modified
surfaces such as agriculture, and fails to account for their diverse effects on rural LST, causing either an overestimation or an underestimation of SUHII.

**Solution to problem:** One way to provide accurate SUHII measurements is to quantify each land cover throughout the growing season specifically capturing the SUHII of cultivars, the landcover undergoing the biggest changes. There has been significant investigation devoted to understanding the urban drivers of UHI based on air temperature and LST, but little investigation into the drivers of rural temperatures.

A barrier to UHI mitigation is the lack of quantitative understanding of the various contributions to SUHII. This study intends to fill these gaps in the literature by quantifying the drivers of LST for both cultivated and natural vegetation when used as rural reference temperatures to improve the understanding of the full anthropogenic influence on local temperature changes as a whole.

Therefore, to understand to what extent anthropogenic modifications in rural landscapes affect local LST, this study has the following specific objectives: (a) to quantify the phenological differences between cultivated and natural vegetation and (b) to quantify the response of LST to those differences and their effect on SUHII. This study considers two major cities in the USA, Chicago, IL, and Atlanta, GA, to explore the relationship between rural phenology and the LST response to those different phenologies on SUHII quantification. The two cities represent different rural biomes with the Chicago domain representing an agricultural biome and Atlanta representing a forested biome. This study is further expected to provide a better understanding of the potential uncertainties that make interpretation of the results comparable across cities and regions and to provide
guidance on the extent to which the differences between cultivated and natural vegetation be considered when assessing SUHII.

2.2) Methodology and Data Processing

2.2.1) Study Area

To characterize the contrast between cultivated and natural vegetation, this research focuses on two domains having contrasting vegetation types: cultivated, represented by the Chicago domain, and natural, represented by the Atlanta domain as shown in Figure 2.1.

The Chicago domain covers an area of 72,160 km$^2$ (over 17.8 million acres), including the Chicago Metro Area with a population in excess of 9.5 million (Bureau, n.d.). The Koppen climate type is Dfb (warm-summer humid continental) with an annual average precipitation of 990 mm, 2/3 of which falls during the growing season. Daytime highs average between 16 – 32 °C and nighttime lows average between 4-18 °C during the growing season. Lake Michigan, with a surface area of 58,030 km$^2$, lies to the northeast, influencing regional weather patterns (US Department of Commerce n.d.). The elevation of the Chicago domain varies from approximately 150 m to 360 m.

The Atlanta domain covers an area of 72,380 km$^2$, including the Metro Atlanta Area with a population in excess of 5.95 million (Bureau, n.d.). The Koppen climate type is Cfa (humid subtropical climate) with an annual precipitation of 1,263 mm, distributed evenly
throughout the year. During the growing season average highs range from 22.5 to 31.7 °C and lows range 10.8 to 21.8 °C (Weather Atlas” n.d.). The elevation of the domain ranges from 10 – 1676 m, with a mean elevation of 300 m (standard deviation 178 m). The city of Atlanta resides at 320 m elevation.

Developed areas compose 17% of the Chicago domain and 12% of the Atlanta domain (Figures 2.1 and 2.2) and include both high and low intensity development. The rural biome surrounding Chicago is dominated by cultivars, 44%, the largest of which are corn, 25%, and soybeans, 16%. Agricultural practices in the Chicago domain typically include the annual rotation of corn and soybeans. Soybeans have seen a fairly steady increase in acreage (~12%), replacing some corn and fallow acreage. Because of their small coverage, other cultivars were not evaluated in the Chicago domain. In the Atlanta domain, cultivars comprise 4% of the rural biome, with no particular cultivar dominant. Forested land cover is only 7% of the Chicago domain, but is the dominant land cover in the Atlanta domain (61%). Grass, 7% of the Chicago domain and 16% of the Atlanta domain, consists of open areas such as sod, fallow cropland, and pasture.
Figure 2.1 The Study area: Chicago domain (left) and Atlanta domain (right) showing their respective land covers.

Figure 2.2 Percentage of land cover in the Chicago domain (left) and the Atlanta domain (right).
2.2.2) Data and Data Processing

2.2.2.1) Data Sets

Remotely sensed LST: Remotely sensed LST was used to characterize the SUHII over various land covers. The LST data from MODIS Aqua daily (MYD11A1 V6) were obtained for 2007-2018 for both domains with image acquisition at approximately 0130 and 1330 local time, a revisit time of 1 day, and spatial resolution of 1km under clear sky conditions (99% confidence) using a split-window algorithm (Wan 2014). MODIS LST has been validated with biases less than 1K in general (Wan 2008) and 2K for bare soil (Wan 2014). Further information regarding this product can be found at http://lpdaac.usgs.gov/products/modis_products_table/mod11a1.

Remotely sensed phenology: The temporally smoothed weekly MODIS derived NDVI product (Aqua C6), developed by the USGS EarthResources Observation and Science Center, from 2007-2017 (7-day, 250 m resolution) was used to capture the phenology of each land cover over the growing season. This product employs a de-spiking methodology and temporal smoothing process to reduce artificial spikes and anomalies which could reduce NDVI value and disturb the temporal profile of the vegetation signal (Ide and Oguma 2010).

Ancillary data: The Cropland Data Layer (CDL) from the United States Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) was used to spatially characterize the land covers in the domains. CDL is the annual land cover map with mapping accuracies in the 85% - 95% range for major crops (Boryan et al. 2011). The
CDL is based on mid-resolution satellite data and high-quality ground truth. It is a comprehensive, raster-formatted, geo-referenced, crop specific land cover classification with a spatial resolution of 56 or 30 m depending on the year (Han et al. 2012). The CDL layer is developed by using satellite imagery from the Advanced Wide Field Sensor (AWiFS) and Landsat Thematic Mapper (TM) 5 and ETM+ 7. USDA Farm Service Agency (FSA) Common Land Unit (CLU) data and associated Administrative Data 578 attribute data, NASS’s June Agricultural Survey (JAS) data, and US Geological Survey (USGS)’s National Land Cover Datasets (NLCD) are used as ground truth to produce the categories. NLCD derived products such as the National Elevation Dataset (NED), percent tree canopy, and the percent impervious product data are used as an ancillary dataset for classification (Han et al. 2012).

Digital elevation model tiles from the U.S. Geological Survey National Map 3DEP Downloadable Data Collection were used to provide elevation data for the Atlanta domain. The elevations in this model represent the topographic bare-earth surface and are produced from high resolution light detection and ranging (lidar) source data of one-meter or higher horizontal and three-meter vertical resolution ("1 Meter Digital Elevation Models (DEMs) - USGS National Map 3DEP Downloadable Data Collection - Data.Gov" n.d.). Table 2.1 summarizes the remote sensing datasets used in this study.

To provide ground truth for LST data, the average mean monthly air temperatures for Chicago and Atlanta were extracted from Weather Underground ("Chicago, IL Weather History; “Atlanta, GA Weather History).
<table>
<thead>
<tr>
<th>Data Set</th>
<th>Data Product</th>
<th>Operating Agency</th>
<th>Temporal Resolution</th>
<th>Spatial Resolution</th>
<th>Time Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land Surface Temperature (LST)</td>
<td>AppEERS MODIS MYD11A1v6</td>
<td>NASA</td>
<td>Day and Night</td>
<td>927m</td>
<td>2007 - 2018</td>
</tr>
<tr>
<td>Land Cover (CDL)</td>
<td>Cropscape</td>
<td>USDA</td>
<td>Annually</td>
<td>56m or 30m</td>
<td>2007 - 2018</td>
</tr>
<tr>
<td>Phenology (NDVI)</td>
<td>MODIS Aqua C6 Smoothed</td>
<td>USGS</td>
<td>Weekly</td>
<td>250m</td>
<td>2007 - 2017</td>
</tr>
<tr>
<td>Digital Elevation Model</td>
<td>3DEP Downloadable Data Collection</td>
<td>USGS</td>
<td></td>
<td>1 m</td>
<td></td>
</tr>
</tbody>
</table>

To determine the effect of land cover phenology on SUHII, all data sets were clipped to the desired domain and projected to NAD 1983 UTM 16N. All data sets were resampled to fit the size of the MODIS LST pixel, and aggregated, enabling pixel by pixel comparison of LST, land cover, and phenology. Both monthly and multi-year LST data was created to afford the study of both spatial and temporal relations. To provide temporal alignment with the LST data, the smoothed weekly phenology data was averaged into monthly periods before aggregating.

Because this study focuses on capturing the growing season of corn and soybeans in the midwestern USA, the temporal period was set from April through October of each year (Xu and Katchova 2019). The number of years of the study was constrained by available Cropscape data and therefore limited to 2007 – 2018.
2.2.2.2) Processing LST Data

*Monthly LST Composite:* Clouds absorb IR radiation emitted from the surface, preventing the sensor from getting accurate readings of LST. Williamson (2013) found that 13-17% of clouds are missed by MODIS quality algorithm. Therefore, cloudy days were screened from each pixel prior to calculating the monthly mean LST for each domain. Possible cloud contamination was removed by setting a minimum acceptable temperature threshold based on record low air temperatures (Team, n.d.) and eliminating lower values from further calculations. To ensure a good spatial representation of LST patterns, only images with more than 50% cloud-free pixels were considered. Daily LST values were aggregated into monthly averages (Hu and Brunsell 2013). Monthly LST was estimated only if at least 5 clear sky days were available in each domain. The use of only cloud-free pixels might bias the data toward warmer conditions, but due to the nature of remote sensing, LST cannot be directly measured when clouds are present (Hu and Brunsell 2015). The number of scenes were comparable between domains with 1149 daytime and 1354 nighttime scenes in the Chicago domain and 1192 daytime and 1207 nighttime scenes in the Atlanta domain. Additional scene information can be found in the appendix.

*Seasonal LST Trends:* The mean LST for the domains was calculated after masking water bodies, including Lake Michigan, in the Chicago domain and high elevation regions over 525 m in the Atlanta domain. Notably in the Chicago domain the highest daytime LST occurred in May and June averaging above 30°C. By contrast, the highest LST in the Atlanta domain occurred in June and July. For both domains, nighttime LST is
the highest in July (Figure 2.3). Monthly mean LST values were verified with air temperatures to determine the cause of outliers in each domain. The daytime outliers in the Chicago domain occurred during the extreme heat of the summer of 2012, while the outliers in Atlanta were of varied years (Weather Underground n.d.).

There is greater variation in daytime LST during the April, May, June, and October in Chicago domain than in the Atlanta domain, reflecting in part their regional climate differences as higher latitudes experience wider LST shifts (Walker, de Beurs, and Henebry 2015a; Karnieli et al. 2010; Quan et al. 2016) and in part the influence of anthropogenic modification of rural areas.
Because the SUHII may vary interannually due to regional climate variability, disease, and data quality, the multi-year average LST was calculated to provide a general trend for the study period (D. Zhou, Zhang, et al. 2016b).

2.2.2.3) Processing CDL Data

Reclassification of CDL categories: The CDL data was reclassified to provide broader classifications (Table 2.2) therefore yielding better accuracy and confidence across the temporal period (Lark et al. 2017). Cultivated land, as the dominant land-cover category in the Chicago domain, was broken down into subcategories for both domains to detect any difference in cultivars. Because of the low cultivated acreage in the Atlanta domain, cultivars were left as one broad category.
Table 2.2: Reclassified land cover categories

<table>
<thead>
<tr>
<th>Reclassified Category</th>
<th>Original CDL Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developed</td>
<td>Open, Low, Medium, and High Intensity</td>
</tr>
<tr>
<td>Cultivated</td>
<td>All agriculture</td>
</tr>
<tr>
<td>Grass/Pasture</td>
<td>Sod, Pasture, Fallow</td>
</tr>
<tr>
<td>Wetlands</td>
<td>Woody and Herbaceous</td>
</tr>
<tr>
<td>Lake Michigan</td>
<td>Lake Michigan</td>
</tr>
<tr>
<td>Forest</td>
<td>Deciduous, Evergreen, Mixed</td>
</tr>
<tr>
<td>Water</td>
<td>Open Water</td>
</tr>
</tbody>
</table>

Temporal and spatial patterns of land cover: To avoid uncertainties caused by mixed pixels only pixels with >70% of a particular land cover are considered. If no land cover was >70% of a specific land cover classification, the pixel was assigned no-data (Imhoff et al. 2010b). This resulted in 56% no-data pixels in the Chicago domain and 51% no-data pixels in the Atlanta domain.

The spatial extent of cultivated land cover as shown in Figure 2.4 is extensive and distributed fairly evenly throughout the Chicago domain. Forest pixels are also distributed throughout the domain. There was relatively little change in the acreage totals for land covers over the course of the study: developed areas increased less than 0.5% percent; corn acreage decreased 2.7%; soybean acreage increased 3.8%; and forested acreage increased 0.6%.

As seen in Figure 2.4 forests dominate the Atlanta domain’s landcover, with only a few cultivars in the southeast corner of the domain. Because the USDA Cropscape
product contained no data for the Atlanta domain in 2007, 2008 data was used as a proxy due to lack of significant change in the domain over the study period. During the study period, developed areas increased 1%, cultivated increased 0.5%, and forests decreased 2%.

![Figure 2.4: Pixels containing > 70% of a specific land cover.](image)

**2.2.3) Analysis Methods**

To discover the spatial variations, land covers were grouped into 3 general categories: developed areas representing urban including high, low, and medium intensity development; forested areas representing natural vegetation; and cultivated representing anthropogenically modified land cover. In the Chicago domain, the cultivated classification was subdivided into its main cultivars, corn and soybeans, to detect possible differences between the major cultivars. Wetlands and water bodies, including Lake Michigan, were not evaluated because they are not typically used as reference points.
The pixel to pixel relationship of LST, land cover, and phenology was used to develop and examine diurnal and seasonal trends and quantify the relationship between land cover and phenology, specifically the quantitative difference between natural and anthropogenically modified land covers and their consequent impact on SUHII.

The SUHII is defined as the difference in mean LST between the urban area (developed) and a rural reference point using equation 2-1

\[
SUHII = LST_{\text{urban}} - LST_{\text{rural land cover}}
\]  

(2-1)

where the LST is the average LST of all the pixels in the designated land cover. The SUHII was examined for both cultivated and natural land covers.

The goal of this study was to determine the consequence of rural anthropogenic modification on SUHII, and discover if different cultivated species yield different responses. Therefore, the difference in the response of cultivated vegetation and natural vegetation was examined. In the Chicago domain, cultivated vegetation is represented by two unique cultivar species: corn and soybeans. These are the dominant land covers in the Chicago domain. In the Atlanta domain, because of the relatively small amount of acreage dedicated to cultivation, this category is represented by all cultivars. Natural vegetation is represented by forests in both domains.

To investigate the impact of using cultivated vegetation (anthropogenically modified) rather than natural vegetation (the standard) as the rural reference point for SUHII, SUHII(NV-CV) was calculated using equation 2-2

\[
SUHII(\text{NV-CV}) = SUHII(\text{NV}) - SUHII(\text{CV})
\]  

(2-2)
where cultivated vegetation (CV) is represented by corn and soybeans in the Chicago domain and by multiple cultivars in the Atlanta domain. SUHII(CV) is SUHII as calculated using cultivated vegetation as the rural reference point. Natural vegetation (NV) is represented by forests in both domains. SUHII(NV) is SUHII as calculated using natural vegetation as the rural reference point.

To remove regional climate bias present in the data and focus on the direct links between LST and NDVI, the difference in both the NDVI and LST of the various land covers was calculated by subtracting rural from urban. ∆NDVI was calculated for all land cover categories in a similar manner to SUHII using equation 2-3

\[
\Delta \text{NDVI} = \text{NDVI}_{\text{urban}} - \text{NDVI}_{\text{rural land cover}}
\]

The relationship between SUHII and ∆NDVI for major land covers was evaluated over the study period using Pearson’s correlation analysis with 95% confidence levels. Pearson’s correlation coefficient is the measure of the statistical relationship between two continuous variables. A dimensionless measure, its values range from -1 to 1 where -1 indicates a perfect negative correlation and 1 indicates a perfect positive correlation. Pearson’s correlation coefficient, r, is given by equation 2-4

\[
r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2} \sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}
\]

where \( \bar{x} \) and \( \bar{y} \) are the mean of the variables x and y and n is the sample size.

The seasonal behavior of both LST (Quan et al. 2016; B. Zhou, Rybski, and Kropp 2013) and NDVI (Xu and Katchova 2019) are cyclic, typically rising through spring to a
peak in summer and falling through the fall into winter and repeating the same pattern the following year. SUHII has been found to vary significantly through the seasonal cycle (D. Zhou, Zhang, et al. 2016a), making it important to use time and site specific measurements in SUHII studies.

Fourier approximation can be used to study time and frequency behavior of cyclical patterns and have been used to characterize the seasonality of SUHII in European cities, finding that the individual city’s curves have unique shape based on seasonality relative to the boundary temperature (B. Zhou, Rybski, and Kropp 2013). The city curve shapes were used to identify regional SUHII patterns, grouping specific cities into distinct categories. B. Zhou (2013) hypothesized that the phenology of vegetation in the surrounding rural biome contributed to the shape of the curves, however, they were unable to verify their claims. Based on the above findings, it is believed that Fourier approximation curves can be used to identify regional vegetation patterns between SUHII and ΔNDVI; therefore, Fourier approximation curves were used to further characterize the time and site specific nature of the SUHII/ΔNDVI relationship of different vegetation species and in the two domains using the Matlab Fourier2 (n=2) fit function, eq 2-5

\[
F(t) = a_0 + \sum_{i=1}^{n} a_i \cos(iwx) + b_i \sin(iwx)
\]  

(2-5)

where \(a_0\) models a constant term in the data and is associated with the \(i=0\) cosine term, \(w\) is the fundamental frequency of the signal (\(w=2*\pi/n\)), and \(n\) is the number of months, in this case 7 ("Fourier Series - MATLAB & Simulink" n.d.).
2.3. Results

2.3.1 Seasonal and diurnal anthropogenic influence of rural areas on SUHII quantification

Seasonal LST response of cultivated and natural vegetation in the determination of daytime SUHII in the Chicago domain: Anthropogenic management of vegetation in the rural reference area modifies the daytime LST response, affecting SUHII seasonally. The largest impact is observed in spring (April, May, and June). In May, the daytime LST for corn is 32.6 °C, soybeans is 32.9 °C, and natural vegetation is 26.8 °C (Figure 2.5), resulting in a SUHII(NV-CV) of 6.0 °C (Figure 2.6) and indicating a large underestimation of SUHII caused by anthropogenic modification of the rural area. The smallest impact of anthropogenic management is observed in summer (July, August). In August, the LST for corn is 27.2 °C, soybeans is 27.3 °C and natural vegetation is 27.2 °C, resulting with SUHII(NV-CV) approximately 0 °C, indicating neither an over nor under-estimation of SUHII caused by anthropogenic modification of the rural area. The impact of anthropogenic management increases again in the fall (September, October), as observed in October when LST for corn is 21.1 °C; soybeans is 21.9 °C; and natural vegetation is 19.1 °C, corresponding to a SUHII(NV-CV) of 2.0 °C, indicating a slight under-estimation of SUHII caused by anthropogenic modification of the rural area.
Figure 2.5: Monthly variations in daytime LST in the Chicago domain.

Figure 2.6: Monthly variations in daytime SUHII in the Chicago domain.
Daytime LST response is driven by changes in NDVI: The daytime LST response can be attributed partially to regional background climate and partially to the changes in NDVI. The negative spring SUHII(CV) results from management practice of plowing the cultivated areas, leaving them devoid of noticeable vegetative activity as evidenced by the low NDVI for cultivated areas in April (Figure 2.7). The bare black soil readily absorbs solar energy, allowing cultivated areas to heat up substantially more than areas with natural vegetation. Cultivated areas exhibit rapid vegetation growth in May and June as corn and soybean plants emerge and begin to grow. During summer, cultivated and natural vegetation exhibit similar daytime LST responses resulting from the full canopies of both cultivated and natural vegetation as demonstrated by their similar summer NDVI, increasing evapotranspiration, cooling the local area. In September, daytime LST essentially remains stable over cultivated vegetation while it decreases 1.7 °C over natural vegetation. At the same time, NDVI decreases quicker and more substantially for cultivated areas than natural vegetation because of senescence and harvest. In September, the increase in daytime LST over cultivated vegetation and decrease in daytime LST over natural vegetation correlates with the larger decrease in NDVI(CV) with an increase in SUHII(CV) that is not present in SUHII(NV). The difference in LST response between cultivated and natural vegetation is presumably because the life-cycle of natural vegetation, unlike cultivated vegetation, has not reached senescence. In October, vegetation is removed from the cultivated areas via harvesting and NDVI(CV) decreases significantly more than NDVI(NV). Interestingly, daytime LST decreases a similar amount for both cultivated and natural vegetation despite the difference in NDVI change. This decrease in LST is presumably the result of regional fall cooling.
Figure 2.7: Monthly variations in NDVI in the Chicago domain.

*Impact of crop species on SUHII:* The specific crop species does not make a significant difference in the daytime LST response (Figure 2.6). Comparing cultivated species, a similar seasonal pattern during the growing season was found. Notably, soybeans have higher daytime LST throughout the growing season than corn, but the resulting SUHII difference is < 1 °C. The largest difference between cultivated species occurred in June when SUHII(soybeans) was 0.9 °C lower than SUHII(corn).

*Diurnal LST response of cultivated and natural vegetation in the determination of SUHII in the Chicago domain:* In contrast to the daytime response, cultivated vegetation exhibits a cooler nighttime LST when compared to natural vegetation throughout the growing season (Figure 2.8), resulting in a general over-estimation of SUHII (Figure 2.9). The largest difference between cultivated (4.4 °C) and natural vegetation (6.1 °C) nighttime LST is observed in October, resulting in SUHII(NV-CV) of 1.5 °C.
Figure 2.8: Monthly variations in nighttime LST in the Chicago domain.

Figure 2.9: Monthly variations in nighttime SUHII in the Chicago domain.
One notable outlier occurs in June when nighttime SUHII(CV) decreases slightly (1.5 °C) coinciding with the peak daytime LST (33.8 °C) for cultivated areas, while the nighttime SUHII(NV) increases. A potential explanation arises from the still immature canopy of cultivars allowing a larger amount of bare soil to be exposed to incoming solar radiation. Incoming solar energy is naturally higher in June than it is in May due to the position of the sun (summer solstice) because more joules of energy are available to be absorbed by the soil. The bare soil then absorbs the incoming solar energy, releasing it during the night, increasing nighttime LST and decreasing nighttime SUHII for cultivated land. However, natural vegetation, with mature canopies in June, does not contain a comparable amount of visible bare soil as cultivated areas, minimizing the amount of solar energy that is absorbed into the soil. Additionally, any bare soil that does exist in a forest area is expected to have extensive shading from the forest canopy, further reducing absorption of solar energy during the daytime.

*Regional LST response of cultivated and natural vegetation in the determination of SUHII:* In general, the Atlanta domain shows correlation to the Chicago domain. The largest impact on SUHII occurs in May when daytime LST is 33.8 °C for cultivated areas and 27.3 °C for natural vegetation (Figure 2.10), resulting in a SUHII(NV-NC) of 6.6 °C (Figure 2.11). The Atlanta domain exhibits a 0.6 °C higher SUHII(NV-CV) than the Chicago domain. NDVI values are higher for cultivated vegetation in the Atlanta domain (Figure 2.12), resulting in less difference in the NDVI values for cultivated and natural vegetation in the Atlanta domain, indicating that the bare soil/LST relationship is not a large contributor to SUHII(NV-CV). In summer, increasing NDVI coincides with decreased daytime LST as seen in the Chicago domain. A notable difference is that daytime LST(CV)
does not intersect with daytime LST(NV) as occurs in Chicago, possibly due to higher vegetative activity in natural vegetation leading to increased ET induced cooling. Elevation could also contribute to lower LST(NV) in the Atlanta domain. The August SUHII(NV-CV) is 3.4 °C, the lowest of the season, aligning with the Chicago domain. In the fall SUHII(NV-CV) (4.5 °C in October) for cultivated and natural vegetation in the Atlanta domain did not decrease to the same extent as in the Chicago domain, possibly because of the longer growing season and generally warmer regional background climate present at the lower latitude.

Figure 2.10: Monthly variations in daytime LST in the Atlanta domain.
Figure 2.11: Monthly variations in daytime SUHII in the Atlanta domain.

Figure 2.12: Monthly variations in NDVI in the Atlanta domain.
In the Atlanta domain, cultivated areas are warmer than natural vegetation during the night, with the largest nighttime LST occurring in May when cultivated nighttime LST is 14.5 °C (Figure 2.13) and natural vegetation nighttime LST is 13.5 °C, resulting in a 1.0 °C SUHII(NV-CV) (Figure 2.14). This behavior is opposite to the nighttime LST behavior in the Chicago domain, indicating that nighttime LST in the Atlanta domain is less dependent on anthropogenic modification than the Chicago domain and more a consequence of regional background climate.

*Figure 2.13: Monthly variations in nighttime LST in the Atlanta domain.*
Figure 2.14: Monthly variations in nighttime SUHII in the Atlanta domain.

The similar SUHII (NV-CV) (Table 2.3) between cultivated and natural vegetation in the two domains indicate that anthropogenic modification plays a significant and relatively consistent role in modifying daytime LST, and thus daytime SUHII, in both domains.

<table>
<thead>
<tr>
<th></th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
<th>October</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chicago Corn</strong></td>
<td>2.6</td>
<td>5.9</td>
<td>4.8</td>
<td>0.4</td>
<td>0.0</td>
<td>1.7</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>Chicago Soybeans</strong></td>
<td>3.0</td>
<td>6.1</td>
<td>5.7</td>
<td>0.9</td>
<td>0.1</td>
<td>2.3</td>
<td>2.8</td>
</tr>
<tr>
<td><strong>Atlanta Cultivated</strong></td>
<td>3.8</td>
<td>6.6</td>
<td>5.9</td>
<td>4.6</td>
<td>3.4</td>
<td>4.0</td>
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<tr>
<th></th>
<th>April</th>
<th>May</th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Chicago Corn</strong></td>
<td>-1.5</td>
<td>-1.6</td>
<td>-0.7</td>
<td>-0.9</td>
<td>-1.1</td>
<td>-1.2</td>
<td>-1.7</td>
</tr>
<tr>
<td><strong>Chicago Soybeans</strong></td>
<td>-1.4</td>
<td>-1.4</td>
<td>-0.6</td>
<td>-0.8</td>
<td>-1.1</td>
<td>-1.2</td>
<td>-1.7</td>
</tr>
<tr>
<td><strong>Atlanta Cultivated</strong></td>
<td>0.7</td>
<td>1.0</td>
<td>1.2</td>
<td>1.1</td>
<td>0.9</td>
<td>0.8</td>
<td>0.5</td>
</tr>
</tbody>
</table>
2.3.2 Relationship between SUHII and ΔNDVI

Pearson's correlation analysis revealed daytime SUHII was significantly negatively correlated to ΔNDVI for both cultivated and natural vegetation during the growing season in the Chicago and Atlanta domains. No correlation was found between nighttime SUHII and ΔNDVI (see supplemental material in Appendix).

*Fourier approximation curves reveal the seasonal and regional differences in the SUHII/ΔNDVI relationship for cultivated and natural vegetation:* The Fourier approximation curves show that the range of SUHII and ΔNDVI is larger for both cultivars than it is for natural vegetation, indicating that there are larger changes in NDVI for cultivated areas resulting in larger changes for SUHII. All vegetation types within both domains exhibit similar high performance with respect to $R^2$ (0.96-0.99 in the Chicago domain and 0.86-0.99 in the Atlanta domain). Fourier approximation equations and $R^2$ statistics can be found in the Appendix. In the Chicago domain, corn and soybeans exhibit similar curves; however, the soybean curve is thinner, indicating the range of SUHII is smaller for soybeans even though the NDVI range is similar (Figure 2.15).

Although the Fourier approximation curves for cultivated vegetation are larger than for natural vegetation, the curve for natural vegetation lies within the curve for cultivated vegetation in the Chicago domain. In the Atlanta domain, there is no overlap between the cultivated and natural vegetation curves, showing that NDVI was always lower and LST was always higher for cultivated vegetation than for natural vegetation.
Comparing across domains, the cultivated and natural vegetation exhibits less change in both ΔNDVI and SUHII in the Atlanta domain than their counterparts in the Chicago domain. It is likely that this difference is due to the fact that the growing season in the Chicago domain is more time constrained than in the Atlanta domain, with greater variations in LST (Walker, de Beurs, and Henebry 2015a).

2.4 Discussion

Impact of anthropogenic management on daytime SUHII: The results of this study indicate that daytime SUHII varies substantially over the growing season from April through October and is highly dependent on the type of vegetation used as the rural reference area. Specifically, anthropogenic management has been shown to alter the phenology and subsequent LST response relative to natural vegetation. The differences in SUHII(NV) and SUHII(CV) result from the anthropogenic management of
the cultivated areas. These management practices include stripping the ground of essentially all vegetation when preparing for planting in early spring, tending throughout the summer, and harvesting in the fall.

The divergent seasonal response of LST to NDVI between cultivated and natural vegetation is most likely caused by the decisions humans make when managing their cultivated land. In preparation for planting in April, the fields used for cultivation are tilled, the soil is turned, existing vegetation is uprooted, and the former year’s crop residue is buried, leaving a uniformly dark surface. During the daytime, surface heat storage is a factor of both the thermal properties of the soil and solar energy absorption (Peng et al. 2012). The dark soil is able to absorb a substantial amount of heat from the incoming solar radiation, causing the springtime driver of daytime LST of cultivated land to be heat absorbing. After emerging in May, the seedlings begin to grow, comprising an increasing fraction of the surface and by July cultivated areas are dominated by vegetation rather than soil. Once there is sufficient vegetation biomass, and assuming sufficient moisture, the vegetation can absorb moisture from the soil and release it to the atmosphere via ET, reducing LST (X. Li et al. 2016). Therefore, during summer, the mechanisms driving LST over cultivated land change from heat absorption by the soil to ET induced cooling from the mature cultivar canopy. In September, senescence begins and the cultivars start to turn brown and vegetative activity decreases, ending ET induced cooling and allowing the newly exposed soil to again absorb incoming solar radiation, switching the LST driver back to heat absorption. In contrast, natural vegetation, although somewhat dormant in early spring, exhibits more vegetative activity than the black dirt of the newly tilled fields allowing for the mechanism of ET to be present. Natural vegetation quickly increases in
biomass, further increasing its ability to engage in ET and increasing the difference in LST between cultivated and natural vegetation.

The relationship of higher NDVI leading to increased ET activity reducing local LST is well established (Qihao Weng, Lu, and Schubring 2004; Yao et al. 2019), leading to the theory that seasonal change of vegetation activity is the best predictor for daytime SUHII (D. Zhou et al. 2014; Yao et al. 2019; Peng et al. 2012; Y. Li, Wang, Zhang, et al. 2019; Sarkar, n.d.). The results of this study support those findings because the difference in NDVI (ΔNDVI) between developed and cultivated areas correlate negatively and strongly with daytime SUHII. However, most studies focus on summer only, rarely including spring or fall, and do not quantify the differences in cultivated and natural vegetation. This study demonstrates that there is a 6 °C difference between spring and summer SUHII(NV-CV) due to anthropogenic modification. The seasonal change in the difference in vegetative activity, i.e., NDVI, between developed and vegetation areas is considered the best predictor for the seasonal amplitude of daytime SUHII (D. Zhou, Zhao, Liu, Zhang, et al. 2014). The 6 °C difference in SUHII(NV-CV) between seasons indicates that SUHII studies should be expanded to include more frequent temporal periods.

The removal of vegetation in cultivated areas accounts for the difference in SUHII between cultivated and natural vegetation in the spring. In the summer, SUHII(NV-CV) is zero, indicating that cultivated and natural vegetation behaves similarly, i.e., that both areas have developed full canopies with high NDVI levels, and both are engaging in ET resulting in similar LST. In the fall, the cultivated species exhibit a decrease in NDVI quicker than natural vegetation. This decrease again shows that anthropogenic management dictates the amount of NDVI in an area and therefore affects LST. The
NDVI-LST relationship is driven by the phenology cycle which is controlled by anthropogenic modification. Controlling phenology ultimately has a large influence on LST and therefore on SUHII estimation.

In this study, the specific cultivated species was not found to make a significant difference on the LST-NDVI relationship, most likely because the anthropogenic modification was similar for both species in the Chicago domain. However, it is possible that other species would require different anthropogenic management which would ultimately change the timing of NDVI and subsequently change SUHII(NV-CV). Generally, corn has a larger biomass than soybeans, and therefore, is able to engage in higher levels of ET, causing the slightly lower LST for corn (< 1 °C) throughout the season.

This study found that daytime SUHII is larger for natural vegetation than for cultivated vegetation in agreement with other studies (Ellenburg, McNider, Cruise, and Christy 2016).

Impact of anthropogenic management on nighttime SUHII: Nighttime changes in SUHII due to anthropogenic modification are smaller than daytime changes and found to not be correlated to NDVI. Lack of SUHII-NDVI correlation indicate that nighttime SUHII is driven by regional background climate (L. Zhao et al. 2014a). Because ET does not occur during the nighttime, there is less influence on nighttime SUHII due to anthropogenic modification.

The difference between daytime and nighttime LST over cultivated areas is much larger than over natural vegetation in the early spring when the ground is essentially bare soil. Dry bare soil is able to capture and store incoming solar radiation and become a
hotspot (Shastri et al. 2017). At night, the bare soil, having low thermal capacity, is able to quickly emit absorbed heat back into the atmosphere, explaining the high daytime and low nighttime LST (Peng et al. 2012). The Aqua MODIS satellite daytime pass collects LST at approximately 1:30 pm local time, near the peak of the incoming solar radiation, and therefore, is near the hottest part of the day. The nighttime pass occurs at approximately 1:30 am local time, after much of the absorbed heat has been released, resulting in a lower LST (Wang et al. 2017).

In general, nighttime LST is related to the latent heat flux from the surface to the atmosphere. Cultivated areas, especially in the spring and fall when there is little vegetation and an abundance of bare soil, have low thermal capacity and inertia, releasing heat rapidly during nighttime, decreasing LST and increasing nighttime SUHII (Q. Weng 2001). Because cultivated crops are generally situated in open areas, long wave radiation from the ground can easily be scattered into the atmosphere, reducing LST (Chudnovsky, Ben-Dor, and Saaroni 2004).

*Regional differences in the anthropogenic management of SUHII:* Regional comparisons show only a 0.6 °C difference SUHII(NV-CV), a basically negligible amount (Imhoff et al. 2010b), between the Chicago and Atlanta domains, indicating the NDVI/LST relationship between cultivated and natural vegetation is similar in locations with diverse biomes, varied climatic regions, and different latitudes. It is hoped this relationship can be applied to UHIs in other regions and rural biomes.

Climatic conditions, as well as moisture availability, dictate the species of both cultivated and natural vegetation in a particular region (Walker, de Beurs, and Henebry 2015b); making regional variability in SUHII(NV-CV) due, in part, to the differences in the
phenological cycle of the species. The contrast in NDVI, and therefore SUHII, could result from differences in the growing season dictated by latitude. Peak NDVI timing is controlled by the amount of insolation received during the growing season, which is dependent on latitude (Walker, de Beurs, and Henebry 2015b); therefore, Chicago can be expected to have a more consistent and constrained peak NDVI. This study found greater magnitudes of seasonal SUHII at the higher latitude of the Chicago domain relative to the Atlanta domain (Peng et al. 2012). NDVI differences are larger in the Chicago domain than the Atlanta domain during May, implying less visible bare soil present in the Atlanta domain. The Atlanta domain displays a longer growing season than the Chicago domain, which allows changes in the peak NDVI depending on local climate conditions (Walker, de Beurs, and Henebry 2015b).

Relationship of SUHII and ΔNDVI: The seasonality of UHI and the way in which it varies between regions is not random, but instead stems from the local climate conditions as the same background temperatures result in different UHII in the spring and fall, depending on the location of the UHI (B. Zhou, Rybski, and Kropp 2013). This variation in UHI can be attributed in part to the seasonality of the UHI’s surroundings.

Fourier approximation curves can provide a clue to the relationship between SUHII and the vegetative activity surrounding the UHI. The shape of the Fourier approximation curves represents the dynamic relationship between SUHII and the phenology cycle of the vegetation in the surrounding rural area, revealing that very different SUHII can occur at a given ΔNDVI and indicating that each species of vegetation impacts SUHII in a unique way. The variations in the Fourier approximation curves result from the different phenological cycles of vegetation species influencing the local LST response, resulting in
a unique signature for each species in the region. The regional background climate is believed to be a contributing factor in the behavior of vegetation (L. Zhao et al. 2014a), resulting in different curve shapes in the two domains, i.e., a unique signature based on vegetation species and region.

The results of this study support the claim that UHI seasonality is not random and suggests that the rural reference area exhibits significant influence in the seasonality of SUHII as shown by Figure 2.15, in agreement with Imhoff (2010a). A clear contrast in the SUHII/ΔNDVI relationship can be seen between vegetation types when comparing the SUHII approximation curves, indicating anthropogenic management can modify the relationship between SUHII and the surrounding rural biome and impacting SUHII. This study confirmed that when calculating ΔNDVI, rural NDVI had the larger change and thus the larger impact on ΔNDVI (Yao et al. 2018).

It is believed that Fourier approximation curves can be used for the quantification of the relationship between the vegetation in rural and urban areas and SUHII, providing a signature for each species in the region. Further studies quantifying UHI in several regions could provide broader regional patterns, making city-to-city and region-to-region comparisons easier and more accurate.

2.5 Limitations

This study uses forested areas as a proxy for natural vegetation including forests at higher elevations (up to 1,676 m) which can have a lower LST than the majority of the domain. Most UHI studies mask elevations higher than 50m above the urban area’s
elevation to remove the influence of these expectedly cooler areas. Ignoring elevation and water bodies will generally result in an overestimation of SUHII (Yao et al. 2018). The inclusion of natural vegetation at higher elevations in the Atlanta domain could account for the SUHII(NV-CV) being larger in the Atlanta domain than in the Chicago domain. However, it is believed that to capture the true effects of changes in SUHII(NV_CV) it was necessary to include all available pixels and represent all conditions (Yao et al. 2018).

The Chicago domain contains a large portion of Lake Michigan, which although was masked along with other water bodies, still influences the overall temperature of the domain, especially the densely built up regions along the shore. In general, water bodies are not used as a rural reference area because they are known to bias SUHII, generally overestimating (Yao et al. 2018). Water has high thermal inertia relative to the atmosphere and the surface (Govind and Ramesh 2019), and can behave as a cooling force for the metro Chicago area as well as other areas along the shore.

Using the MYM can smooth out bias introduced by specific extreme years such as the heatwaves in 2012 (Borth, n.d.) or the abnormally cold and wet spring of 2019 (The Weather Channel" n.d.), especially for springtime vegetation activity. The regional temperature varies from year to year, resulting in an up to 3-week variation in start of season (SOS) of both cultivated and natural vegetation (Rippey 2015). This variation in SOS results with NDVI picking up signals for different stages of early season growth (Montgomery et al. 2020; Elmore et al. 2012).

Natural vegetation is under-represented in the Chicago domain and cultivated vegetation is under-represented in the Atlanta domain. In the Chicago domain, the cultivars studied were limited to corn and soybeans, while in the Atlanta domain, because
of the low amount of corn and soybeans, the cultivars included cotton and peanuts as well as corn and soybeans. The growing seasons of cotton and peanuts are similar to corn and soybeans with planting usually beginning in April and harvest usually beginning in September. The biomass of fully mature peanuts and cotton resemble that of soybeans. Therefore, it is believed that the cultivated classification in the Atlanta domain is comparable to the cultivars in the Chicago domain.

This study only covers the April – October because of the lack of adequate clear sky days during the rest of the year. This time period clearly covered the growing season in the Chicago domain, but the lack of early scenes means the study likely missed the beginning of the growing season in Atlanta. It would be beneficial to capture the full growing season for anthropogenically managed vegetation when studying different regions. However, because of the nature of remote sensing, clear sky days are a limiting requirement.

### 2.6 Conclusion

Most UHI studies fail to take into consideration the extent of anthropogenic modifications that occur in rural landscapes when determining SUHII. This makes it difficult to accurately compare SUHII city-to-city and region-to-region. In an effort to improve accuracy of regional SUHII comparisons, this study assessed the effect of anthropogenic modification of the rural reference point on the magnitude of SUHII.

Anthropogenic manipulation of the rural reference area can significantly alter the magnitude of SUHII, especially during the spring and fall, making site specific and time
specific measurements of the rural reference area vitally important. For example, in May in the Chicago domain, choosing cultivated or natural vegetation can make a difference in SUHII up to 6 °C whereas in July there is no difference.

SUHII is a dynamic value that changes throughout the year; therefore, studies that limit their SUHII data to only one or two time periods (annual, or summer/winter) might miss the temporal variability caused by the phenological cycle of vegetation, especially the variability caused by anthropogenic management (Yao et al. 2017).

Through the comparison of two different climate regions, this study suggests that temporal variability of SUHII is different in different climate regions and urges further investigations be undertaken into temporal variability, especially for anthropogenically modified rural areas which now have been shown to vary significantly.

This study investigated two UHI and it suggested that more UHI be studied to determine if the differences between cultivated and natural vegetation are indeed regional. Recommended future work includes expanding the temporal data set to include the full growing season of the Atlanta domain. Lastly, it is hoped that a global study would reveal a pattern in the Fourier approximation curves resulting in regional classification based on the relationship between SUHII and ΔNDVI.
Chapter 3

The impact of anthropogenically modified and natural vegetation responses to the 2012 heatwaves on SUHII

3.1 Introduction

*Human response to heatwaves:* Temperature extremes, such as heatwaves, can create unfavorable economic and social consequences by increasing energy and water demands (“Climate Impacts on Society | Climate Change Impacts | US EPA” n.d.), as well as raising the threat of heat stress and mortality via the spread of infectious diseases, heat stroke, heat exhaustion, and excessive dehydration (“Heat-Related Illnesses and Heat Waves | National Health Portal Of India” n.d.). Excessive heat kills more people than any other weather event in both developed and undeveloped countries (Atsdr 2016). As more people move into urban areas and are exposed to the extreme temperatures caused by urban heat islands (UHI), health risks to the population are expected to increase (Gabriel and Endlicher 2011). Heatwaves increase stress especially on vulnerable populations including the socioeconomically disadvantaged (Navarro-Estupiñan et al. 2020; Chakraborty et. al.2020). A more complete understanding of the true signal of surface urban heat island intensity (SUHII) will lead to improved heat mitigation in urban areas during heatwaves. Heatwaves are short-term events which occur within the greater background climate; however, their impacts on both natural and cultivated vegetation can linger after the heatwave itself is over.
**UHI changes as a result of heatwaves:** Urban areas are more predisposed to higher temperatures than the nearby rural areas (Ward et al. 2016). However, it has been found that in terms of UHI intensity, urban areas respond to heatwaves in decisively different ways. Some cities, such as New York City, NY, and Washington, D.C., exhibit increased UHI during a heat wave, while cities such as Philadelphia, PA, exhibit decreased UHI (Ramamurthy and Bou-Zeid 2017). In India, the majority of urban regions exhibit a surface urban cool island (SUCI) during extreme heat events, leading to the conclusion that the surrounding rural reference area experiences larger land surface temperature (LST) increases than the urban areas during a heat wave (“Climate Change Signals and Response: A Strategic Knowledge Compendium for India - Google Books” n.d.).

**Response of LST over vegetation to heatwaves:** Variation in vegetation species also contributes to the LST response of land covers. For example, the heating rate is initially faster over forests than over grass, but as the heat wave continues, evapotranspiration (ET) in grassy areas depletes the soil of moisture, causing the grassy areas to become the larger heat source (Zaitchik et al. 2006). However, specific investigation of the varied LST responses of cultivated and natural vegetation to heatwaves is lacking in the literature.

**Response of vegetation to the timing of heatwaves:** Heatwaves can occur at different times of the year, producing different results in regard to vegetation health. Spring heatwaves have been found to increase vegetative activity and health to a larger degree than summer or fall heatwaves (Baumbach et al. 2017).
Objectives: Although the behavior of the rural reference area clearly influences the behavior of SUHII during extreme heat events, little is known about how anthropogenically managed and natural vegetation compare in their response to heatwaves or how that response will affect SUHII. The objective of this study is to characterize the way in which heatwaves impact SUHII due to the potential differences in the responses of cultivated and natural vegetation. Specifically, this study uses the 2012 heatwave as an example to quantify the changes in phenology and SUHII for both cultivated and natural vegetation and compares the SUHII, LST, and NDVI anomalies with the multi-year mean (MYM) from 2007–2018 in two urban domains: one predominantly surrounded by cultivated vegetation (Chicago) and the other predominantly surrounded by natural vegetation (Atlanta). Magnitude differences and temporal patterns during and post heatwave are explored.

The weather patterns in 2012 included an unusual spring heatwave March 12 - 22 followed by the most intense summer heatwave in USA’s modern history in late June through July. The March heatwave set records on multiple days in multiple states with temperatures reaching as high as 31 °C (88 °F), 22.8 °C above normal, in the Chicago area and 29 °C (84 °F), 12 °C above normal, in Georgia (US Department of Commerce). The summer heatwave, which resulted in 123 heat-related deaths across the US (“U.S. News”), was created by a high-pressure system over the US midsection from late June through July 2012, affecting both Chicago and Atlanta with temperatures reaching 40 °C (103 °F), 11 °C above normal in the metro Chicago area on both July 5 and 6, and 41 °C (106 °F), 14 °C above normal, an all-time high for the Atlanta metro area on June 30 (Weather Atlas).
3.2 Analysis

As shown in Chapter 2, the daytime SUHII changes seasonally, diurnally, and regionally when comparing cultivated and natural vegetation, making it essential to choose the rural reference area with care and intention. This study directly compares phenology changes and subsequent LST response that occur during extreme weather events, such as heatwaves, to assess potential overestimation or underestimation of SUHII when cultivated is used as the rural reference relative to natural vegetation.

Focusing on the variations introduced by climatic anomalies, changes in SUHII between cultivated and natural vegetation in 2012 are compared using natural vegetation as the reference. Using the same methodology as in Chapter 2, 1 km² pixels > 70% pure were identified and the spatially averaged LST and NDVI of these pixels were used to represent the developed, cultivated, and natural vegetation for later analysis. The differences in SUHII caused by diverse phenological responses to the heatwaves between cultivated and natural areas during and after the heatwaves were assessed. These differences are calculated using equation (3-1)

\[
SUHII(NV-CV) = SUHII(NV) - SUHII(CV)
\]  

(3-1)

where cultivated vegetation (CV) is represented by corn, the dominant rural land cover, in the Chicago domain and by multiple cultivars in the Atlanta domain. SUHII(CV) is SUHII as calculated using cultivated vegetation as the rural reference point. Natural vegetation (NV) is represented by forests in both domains. SUHII(NV) is SUHII as calculated using natural vegetation as the rural reference point. In this study SUHII(NV-CV) for 2012 is
compared to SUHII(NV-CV) for the multi-year mean (MYM) to determine what changes in SUHII, if any, are attributable to an extreme heat event.

3.3 Results

Regional differences in daytime SUHII response to the spring 2012 heatwave: In April the Atlanta domain exhibited more sensitivity of daytime SUHII(NV) to the spring heatwave (1.0 °C) than the Chicago domain (0.5 °C decrease) (Figure 3.1). However, the Chicago domain exhibited more sensitivity with a 0.5 °C increase in nighttime SUHII compared to the Atlanta domain (0.2 °C) (Figure 3.2). Daytime SUHII(NV) was more sensitive to the increased LST during the heatwave than nighttime SUHII(NV) for both domains. The higher sensitivity of the Atlanta domain is most likely due to the increased intensity of the heatwave in the Atlanta domain ("Weather Atlas").

Regional differences in daytime SUHII response to the summer 2012 heatwave: There is little difference in daytime SUHII(NV) in either domain at the beginning of the summer heatwave in June (Figure 3.1). However, in July daytime SUHII(NV) decreased 1.6 °C in the Chicago domain and increased 0.3 °C in the Atlanta domain, suggesting that the natural vegetation in the Chicago domain is more sensitive to increased temperatures than natural vegetation in the Atlanta domain. In August and September, following the heatwave, the 2012 daytime SUHII(NV) continued to be lower than the MYM daytime SUHII(NV) in the Chicago domain while the 2012 daytime SUHII(NV) in the Atlanta domain continued to be higher than the MYM daytime SUHII(NV). This difference in behavior between the domains appears to be the result of LST over natural vegetation
increasing more in the Chicago domain than the Atlanta domain. Nighttime SUHII(NV) is more sensitive to the summer heatwave in the Chicago domain with 1.0 °C and 0.7 °C increases in June and July, respectively, than it is in the Atlanta domain with 0.2 °C increase and 0.2 °C decrease in June and July, respectively (Figure 3.2). Following the heatwave, the Chicago domain continues to show more sensitivity than the Atlanta domain. As in the spring heatwave, daytime SUHII(NV) is more sensitive than nighttime SUHII(NV) in both domains.

Figure 3.1: Monthly variations in daytime SUHII for the 2012 heatwave and the MYM for both the Chicago and Atlanta domains.
Influence of anthropogenic management on daytime SUHII response to the 2012 heatwave in the Chicago domain: Following the March heatwave, the 2012 SUHII(NV-CV) underestimated daytime SUHII by 2.8 °C in April and 2.4 °C in May relative to the MYM (Figure 3.3). This difference in the behavior of SUHII during 2012 is most likely caused by an increase in the number of days of sunshine compared to the MYM (see Appendix for additional data), providing a higher than normal amount of incoming solar radiation which the bare soil absorbs, causing the local LST for cultivated areas to be 2.0 °C hotter than the MYM (Figure 3.4). Cultivated vegetation areas exhibited a smaller NDVI increase than natural vegetation (Figure 3.5). The natural vegetation was able to take advantage of the warmer spring temperature and start of season (SOS) to begin earlier than usual.
However, management of cultivated areas delayed SOS until after spring tilling, putting the growth of cultivars behind that of natural vegetation. It is possible that this increased vegetative activity in natural vegetation provided enough ET to offset the increased background temperature and effect the slight cooling observed.

During the summer heatwave and through the remainder of the growing season, only negligible differences were found in SUHII(NV-CV) between 2012 and the MYM. This is most likely because both cultivated and natural vegetation responded to the heatwave with similar decreases in NDVI in June and July indicating that both cultivated and natural vegetation experience stress as a result of the extreme heat. The magnitude of LST was generally higher during the summer heatwave than during the spring heatwave. Extreme heat causes increased evaporation, leading the vegetation to extract more water from the soil. Once the water in the soil is depleted, the plants likely experience wilting, decreasing their vegetative activity and resulting in higher LST.

The spring heatwave increased the difference in LST response between cultivated and natural vegetation, resulting in a larger impact on SUHII daytime estimation relative to the MYM, while the summer heatwave decreased the difference in LST response between cultivated and natural vegetation, resulting in a smaller impact on daytime SUHII estimation.
Figure 3.3: Monthly variations in daytime SUHII plotted as a function of growing season (April – October) showing the changes in SUHII(NV-CV) during both the spring heatwave in March and the summer heatwave in June and July and the MYM in the Chicago domain.
Figure 3.4: Monthly variations in daytime LST for 2012 and the MYM during the growing season (April – October) in the Chicago domain.

Figure 3.5: NDVI plotted as a function of growing season (April – October) showing the changes in NDVI(\(NV-CV\)) during the 2012 heatwave and the MYM in the Chicago domain.
Influence of anthropogenic management on nighttime SUHII response to the 2012 heatwave in the Chicago domain: Similar to the daytime SUHI, the most significant deviation between 2012 and the MYM nighttime 2012 SUHII(NV-CV) occurred in April following the spring heatwave with SUHII exhibiting a 1.1 °C overestimation relative to the MYM (Figure 3.6). A likely explanation for the April anomaly is that the extra heat absorbed by the soil during the daytime was re-emitted during the night, causing a higher local LST (Figure 3.7). During and following the summer heatwave, 2012 SUHII(NV-CV) was higher than the MYM, but never more than 0.5 °C.

Figure 3.6: Nighttime SUHII plotted as a function of growing season (April – October) showing the changes in ΔSUHII(NV-CV) during the 2012 heatwave and the MYM in the Chicago domain.
Figure 3.7: Monthly variations in nighttime LST for 2012 and the MYM during the growing season (April – October) in the Chicago domain.

Influence of anthropogenic management on daytime SUHII response to the 2012 heatwave in the Atlanta domain: Similar to the Chicago domain, the largest variations in SUHII occurred following the spring heatwave with the 2012 SUHII(NV-CV) underestimating SUHII relative to the MYM by 2.7 °C in April and 1.3 °C in May (Figure 3.8). As in the Chicago domain, this can be attributed to the increased regional background temperature interacting with the bare soil and increasing the LST of the cultivated areas by 2 °C (Figure 3.9). Natural vegetation exhibited increased NDVI in the spring while cultivated vegetation remained essentially unchanged relative to the MYM (Figure 3.10).
There were no significant changes in 2012 SUHII(NV-CV) during the summer heatwave relative to the MYM in the Atlanta domain. Cultivated and natural vegetation behaved similarly in both domains, with decreases in NDVI for both vegetation types. However, unlike the Chicago domain, during August in the Atlanta domain 2012 SUHII(NV-CV) overestimated daytime SUHII relative to the MYM by 1.2 °C (Figure 3.8). This deviation is the result of local LST of the cultivated areas decreasing more than for either natural vegetation (Figure 3.10), mostly likely in response to increased NDVI of cultivated areas. This difference could be a result of the specific cultivar species present in each domain. It is also reasonable to believe that cultivated areas increased in vegetative activity due to water amendments (irrigation) resulting in induced ET cooling over the cultivated areas in the Atlanta domain.

Figure 3.8: Daytime SUHII plotted as a function of growing season (April – October) showing the changes in ΔSUHII(NV-CV) during the 2012 heatwave and the MYM in the Atlanta domain.
Figure 3.9: Monthly variations in daytime LST for 2012 and the MYM during the growing season (April – October) in the Atlanta domain.

Figure 3.10: NDVI plotted as a function of growing season (April – October) showing the changes in NDVI(NV-CV) during the 2012 heatwave and the MYM in the Atlanta domain.
Influence of anthropogenic management on nighttime SUHII response to the 2012 heatwave in the Atlanta domain: In the Atlanta domain, nighttime SUHII exhibits minimal variation in SUHII due to the heatwave (Figure 3.11), supported by the similar manner in which cultivated and natural vegetation change in response to the heatwave (Figure 3.12).

Figure 3.11: Nighttime SUHII plotted as a function of growing season (April – October) showing the changes in ΔSUHII(NV-CV) during the 2012 heatwave and the MYM in the Atlanta domain.
Figure 3.12: Monthly variations in nighttime LST for 2012 and the MYM during the growing season (April – October) in the Atlanta domain.

3.4 Discussion

Globally, the majority of heatwaves occur during the summer months; however, heatwaves can happen during all seasons (Smith, Zaitchik, and Gohlke 2013). Spring heatwaves appear to have a positive effect on vegetative activity as evidenced by the increased NDVI in April for both domains. The March 2012 heatwave caused an early growth response in natural vegetation that began before the start of the study period (April), indicating that their phenological cycle is driven by the regional background climate (Rathcke and Lacey 1985). However, the phenological cycle of cultivars is partially decoupled from the regional background climate because of anthropogenic management (Buyantuyev and Wu 2012). Anthropogenic management does take some
cues from the regional background climate, as shown by the 3-week early planting season (Rippey 2015). Cultivars always start their growing cycle with a similar NDVI because spring tilling ‘resets’ the ground cover to bare soil. This ‘resetting’ in 2012 caused the NDVI for cultivated land cover to be similar to the MYM, despite the increased regional temperatures. It is presumed that the increased solar radiation which accompanied the heatwave caused the increase in NDVI for both cultivated and natural vegetation. Natural vegetation experienced a lower LST via ET because the SOS began approximately 3 weeks early in 2012 (Rippey 2015) while the extra solar radiation heated the freshly tilled soil, warming the cultivated areas. The behavior difference between the cultivated and natural vegetation readily explains the contrasting results for SUHII.

Excessive heat causes increased ET; therefore, during periods of excessive heat, plants attempt to survive by pulling enough water out of the ground to replace the moisture lost by the increased ET (Chaves et al. 2002). The lack of water available in the soil puts stress on both cultivated and natural vegetation. Some species, such as soybeans (Rippey 2015) are more adaptable than others, resulting in better vegetative activity following the heatwave and causing differences in LST between various vegetative species. Cultivated species increasingly have the advantage of anthropogenic management practices that implement irrigation, providing a consistent water supply and averting the potential for irreversible damage to the cultivars (Rippey 2015). This management is in direct contrast to most natural vegetation areas that do not have the advantage of irrigation. Anthropogenic manipulation of the water cycle can account for the differences in SUHII between cultivated and natural vegetation both during and
following the heatwave in the Atlanta domain. However, this study did not take irrigation into account, suggesting further investigation is required.

The two domains exhibited different SUHII behavior in response to the summer heatwave. There are several possible reasons for this. Lake Michigan, which resides in the Chicago domain likely influences the overall domain by reducing daytime LST over developed areas especially during spring. This decrease in LST over developed areas would cause a decrease in daytime SUHII. The Chicago domain, being at a higher latitude, has a more constrained growing cycle, especially for cultivars (Walker, de Beurs, and Henebry 2015b). The cultivars in the Atlanta domain are a mixture of several different cultivated species resulting in mixed phenological signals which could account for differences in LST and SUHII(NV-CV) between the two domains.

3.5 Limitations

Because of the nature of the domains, natural vegetation is under-represented in the Chicago domain and cultivated vegetation is under-represented in the Atlanta domain. Disease and drought play a role in the overall health and resultant vegetative activity of both cultivated and natural vegetation. Reduction of vegetative activity in cultivated areas due to disease would likely occur in summer and increase LST due to decreased ET. The extent and spatial placement of irrigation was not taken into consideration in the analysis of this study. However, by providing additional water, irrigation can be expected to reduce LST for cultivated vegetation where it is used due to increased irrigation, causing an over-estimation of SUHII relative to natural vegetation.
This study used monthly means for both LST and NDVI, which although adequate to represent overall LST and NDVI trends, might be too gross in scale to capture the nuances involved in extreme weather events such as heatwaves. Heatwaves are generally short events and the full impact could get lost in the monthly data. It is believed that weekly means of LST and NDVI would provide a higher degree of understanding of the link between LST and NDVI and their response to extreme weather events.

3.6 Conclusion

This study analyzed the differences in the response of cultivated and natural vegetation activity to a heatwave and explored how the varied responses impact the measurement of SUHII. These results indicate that SUHII differs seasonally, diurnally, and regionally during a heatwave relative to the MYM. Specifically, this study concluded that in both domains, spring heatwaves affect SUHII to a larger degree than summer heatwaves, and that this is a direct result of anthropogenic management practices.

Differences in estimated SUHII due to varied vegetation is strongly influenced by anthropogenic management practices, such as species type, tilling, water and nutrient amendments, and weed and pest control. Additionally, the normal lifecycle of cultivated vegetation is more tightly controlled than that of natural vegetation; for example, earlier planting of cultivars will result in an earlier harvest. Natural vegetation also appears to be more resilient to extreme weather events such as heat than cultivated vegetation. The changes in phenology due to extreme heat directly impact local LST and therefore impact estimated SUHII.
Daytime SUHII was found to be impacted to a higher degree than nighttime SUHII. This is generally thought to be due to the greater effects of ET’s interaction with the atmosphere during daylight hours.

The phenology changes caused by the heatwave could be the result of regionally varied intensity of LST during the heatwave, a more constrained growing season in Chicago, the timing of the heatwave in regard to phenology stage, or different management practices within each region such as the use of irrigation. Water availability is an especially important consideration in the health of vegetation.

In this study, vegetation responded differently to the spring heatwave which occurred at the beginning of the phenology cycle than it did to the summer heatwave which occurred later in the phenology cycle. It appears that vegetation was able to tolerate and even thrive during the spring heatwave, while the summer heatwave caused lasting damage to both cultivated and natural vegetation.

The results of this investigation demonstrate that extreme weather events such as heatwaves impact the estimation of SUHII and that this change is multifaceted. Because the significant response of cultivated and natural vegetation phenology during heatwaves impacts local LST, an accurate measure of SUHII should include consideration of local climate conditions. To mitigate the impact of these variations on SUHII estimation, multi-year means could be used to provide a representative measure of SUHII.

Future work on this topic should include additional UHIs in a variety of regions across the globe. Estimated SUHII in relation to water management practices should also be investigated due to water’s importance in driving the phenological cycle and the cooling effects of ET.
Chapter 4

Conclusions

4.1 Summary of Findings

This research addressed two specific issues regarding the rural reference area used for the calculation of SUHII. Because the rural reference area of an UHI is often modified by human behavior, this research provides valuable information on assessing the impact of anthropogenic management on the LST of rural areas for both multi-year averages and during times of extreme heat.

4.1.1 Characterization of the impact of anthropogenically modified and natural vegetation LST response on SUHII

When estimating SUHII, natural vegetation is often considered to be the optimal reference area. However, anthropogenic practices, particularly cropland, can change the local LST, impacting SUHII estimation. Chapter 2 addresses how anthropogenic modification of rural areas influences the quantification of SUHII in the Chicago and Atlanta UHIs. Results that can be drawn from this study are as follows:

1. Cultivated vegetation underestimates SUHII in the spring and fall, but is neutral in the summer relative to natural vegetation.
2. Anthropogenic modification influences daytime SUHII to a larger degree than nighttime SUHII.

3. The Chicago UHI is influenced by anthropogenic modification to a larger degree than the Atlanta UHI.

4. A unique relationship was found to exist between SUHII and ΔNDVI for each vegetation species within a region which can be quantified using Fourier approximation, providing a unique species signature, leading to the possibility of developing regional vegetation signature patterns, enhancing city-to-city and region-to-region UHI comparisons.

SUHII(NV-CV) is dynamic, and consequently, studies that limit SUHII measurements to one or two times per year might miss the temporal variability caused by the phenological cycles of both cultivated and natural vegetation. This study also suggests that the temporal variability of SUHII is regional and dependent on the regional background climate as well as anthropogenic management. Accurate assessment of SUHII will be improved when taking the seasonal and regional particulars of anthropogenic modification of the rural reference area into consideration, therefore improving UHI mitigation studies and policies.

4.1.2 The impact of anthropogenically modified and natural vegetation responses to the 2012 heatwaves on SUHII

The behavior of the rural reference area clearly influences the behavior of SUHII during extreme heat events; however, little is known about how anthropogenically
managed and natural vegetation compare in their response to heatwaves and how that response will affect SUHII. Chapter 3 of this thesis addresses the impact of heatwave timing and intensity on the LST of cultivated and natural vegetation in the Chicago and Atlanta UHIs. Results that can be drawn from this study are as follows:

1. In both domains spring heatwaves affect SUHII to a larger degree than summer heatwaves. The larger impact in spring occurs over cultivated vegetation as a direct result of anthropogenic management practices.
2. Daytime SUHII was found to be impacted to a higher degree than nighttime SUHII.
3. Similar changes occurred in both domains during both spring and summer heatwaves.

Because extreme heat events can alter the estimation of SUHII, consideration of local climate conditions or use of multi-year means will provide increased accuracy.

4.2 Summary of Contributions

The excessive heat exposure associated with UHIs and heatwaves are considered to be a leading cause of weather-related mortality across the globe. A more complete understanding of the mechanisms contributing to UHI are expected to provide greater accuracy in estimation of SUHII, allowing for enhanced policy and mitigation strategies. In addressing the proposed hypothesis questions, this research extends the understanding of the spatial and temporal distribution of SUHII over 12 years during a
variety of weather conditions via remote sensing. This thesis contributes to the literature on UHI studies in several ways:

• This study provides a monthly and diurnal characterization of the impact of anthropogenic modification of rural reference area using composite LST data during the growing season.
• This study also provides a monthly and diurnal characterization of the variable impacts heatwaves have on cultivated and natural vegetation.
• This study suggests a new way to characterize SUHII/ΔNDVI relationships which may lead to better city-to-city and region-to-region comparisons.

This study expects to broaden applications of remote sensing in UHI research, improving accuracy during quantification of SUHII.

4.3 Future Direction

Future work will characterize additional UHIs in similar and different regions in an effort to decipher the broader impacts of anthropogenic modifications on SUHII and discover possible regional trends. Additional cultivated and natural species will be considered to further refine the impact of specific vegetation species. Irrigation is a growing anthropogenic modification of cultivated land, therefore, additional studies investigating the response of LST to irrigation and its subsequent impact on SUHII would enhance the current understanding of SUHII estimation. Further investigation and characterization of the unique Fourier approximation signatures are expected to lead to better city-to-city and region-to-region comparisons.
Appendix

Pearson’s Coefficients and p-values for SUHII and ΔNDVI

<table>
<thead>
<tr>
<th>Chicago Domain</th>
<th>Corn</th>
<th>Soybeans</th>
<th>Forest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson’s</td>
<td>-0.89</td>
<td>-0.88</td>
<td>-0.81</td>
</tr>
<tr>
<td>p-value</td>
<td>3.3e-30</td>
<td>9.2e-28</td>
<td>1.6e-20</td>
</tr>
<tr>
<td>equation</td>
<td>y=-17x+0.4</td>
<td>y=-17.4x+0.1</td>
<td>y=-22.7x+-0.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Atlanta Domain</th>
<th>Cultivated</th>
<th>Forest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson’s</td>
<td>0.62</td>
<td>0.58</td>
</tr>
<tr>
<td>p-value</td>
<td>1.4e-09</td>
<td>4.4e-08</td>
</tr>
<tr>
<td>equation</td>
<td>y=-15.7x+0.3</td>
<td>y=-22.5x+1.8</td>
</tr>
</tbody>
</table>

Fourier Approximation Curves, Statistics

Chicago MYM

Type: Soybeans

R^2_x 0.990953,R^2_y 0.994719

RMS_x 0.022542,RMS_y 0.440901

Fit_x = -0.075570 + -0.127376*cos(x*w) + -0.117977*sin(x*w) + -0.033162*cos(2*x*w) + -0.023708*sin(2*x*w)

Fit_y = 0.712058 + 3.162928*cos(y*w) + 2.781884*sin(y*w) + 1.226672*cos(2*y*w) + 1.294134*sin(2*y*w)
Type: Corn
\[ R^2_x \text{ 0.967101}, R^2_y \text{ 0.993369} \]
\[ \text{RMS}_x \text{ 0.057459}, \text{RMS}_y \text{ 0.484549} \]
\[ \text{Fit}_x = -0.048374 + -0.147998\cos(x\omega) + -0.169649\sin(x\omega) + \]
\[ -0.013442\cos(2x\omega) + -0.067785\sin(2x\omega) \]
\[ \text{Fit}_y = 1.235095 + 3.139884\cos(y\omega) + 2.758693\sin(y\omega) + \]
\[ 1.313373\cos(2y\omega) + 0.950983\sin(2y\omega) \]

Type: Forests
\[ R^2_x \text{ 0.988693}, R^2_y \text{ 0.992289} \]
\[ \text{RMS}_x \text{ 0.013015}, \text{RMS}_y \text{ 0.291662} \]
\[ \text{Fit}_x = -0.177952 + -0.074474\cos(x\omega) + -0.049712\sin(x\omega) + \]
\[ 0.013978\cos(2x\omega) + 0.015847\sin(2x\omega) \]
\[ \text{Fit}_y = 3.690117 + 2.445492\cos(y\omega) + 0.452107\sin(y\omega) + \]
\[ -0.019950\cos(2y\omega) + 0.264945\sin(2y\omega) \]

Atlanta Domain MYM

Type: Cultivated
\[ R^2_x \text{ 0.863983}, R^2_y \text{ 0.921925} \]
\[ \text{RMS}_x \text{ 0.029244}, \text{RMS}_y \text{ 0.709162} \]
\[ \text{Fit}_x = -0.065774 + -0.035063\cos(x\omega) + -0.033424\sin(x\omega) + \]
\[ -0.020165\cos(2x\omega) + -0.018738\sin(2x\omega) \]
\[ \text{Fit}_y = 1.977679 + 1.765761\cos(y\omega) + -0.196340\sin(y\omega) + \]
\[ 0.317956\cos(2y\omega) + 0.368559\sin(2y\omega) \]
Type: Natural

$R^2_x 0.905065, R^2_y 0.985779$

$RMS_x 0.016162, RMS_y 0.246476$

$Fit_x = -0.178382 + -0.028856*\cos(x*w) + -0.015291*\sin(x*w) + 0.010368*\cos(2*x*w) + 0.015782*\sin(2*x*w)$

$Fit_y = 5.778955 + 1.407792*\cos(y*w) + -0.510478*\sin(y*w) + -0.404825*\cos(2*y*w) + 0.003376*\sin(2*y*w)$

**Fourier Approximation Curves, Equation**

```matlab
function out = my_fourier(x,a0,a1,a2,b1,b2)
    w = 1/7*2*pi; % Frequency chosen 1/months*2pi
    P = 7;
    w = 2*pi/P;
    fprintf('Frequency = %f
',w);
    out = a0 + a1*cos(x*w) + b1*sin(x*w) + ...
        a2*cos(2*x*w) + b2*sin(2*x*w);
```
Figure A.1: Total number of days per month that had > 50% clear coverage for LST throughout the study period.

Figure A.2: Number of days per month that had > 50% clear coverage for LST data during 2012.
References


Boryan, Claire, Zhengwei Yang, Rick Mueller, and Mike Craig. 2011. “Monitoring US


Bureau, U.S. Census. n.d. “American FactFinder - Results.”


Richardson, Andrew D., Trevor F. Keenan, Mirco Migliavacca, Youngryel Ryu, Oliver


Sarkar, Rajib. n.d. “MEASUREMENT OF LAND SURFACE TEMPERATURE AND ITS RELATION TO VEGETATION COVER: A CASE STUDY OF KOLKATA MUNICIPAL CORPORATION.”


