THE URBAN HEAT ISLAND PILOT PROJECT:
A LOOK INTO CHICAGO’S PROGRESS

A THESIS
SUBMITTED TO THE GRADUATE SCHOOL
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE
MASTER OF SCIENCE
IN THE DEPARTMENT OF GEOGRAPHY

BY
LAURA A. GIBOO
(FACULTY ADVISOR: DR. PETRA ZIMMERMANN)

BALL STATE UNIVERSITY
MUNCIE, INDIANA
MAY 2011
THE URBAN HEAT ISLAND PILOT PROJECT:
A LOOK INTO CHICAGO’S PROGRESS

A THESIS
SUBMITTED TO THE GRADUATE SCHOOL
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE
MASTER OF SCIENCE
IN THE DEPARTMENT OF GEOGRAPHY

BY
LAURA A. GIBOO

Approved By:

______________________________________________  ________________
Committee Chairperson                                   Date

______________________________________________  ________________
Committee Member                                         Date

______________________________________________  ________________
Committee Member                                         Date

Departmental Approval:

______________________________________________  ________________
Departmental Chairperson                                  Date

__________________________________________  ________________
Dean of Graduate School                                    Date

BALL STATE UNIVERSITY
MUNCIE, INDIANA
MAY 2011
ABSTRACT

THESIS: The Urban Heat Island Pilot Project: A Look into Chicago’s Progress

STUDENT: Laura A. Giboo

DEGREE: Master of Science

COLLEGE: Sciences and Humanities

DATE: May, 2011

PAGES: 77

Urban heat islands (UHIs) are unique phenomena that occur when urban areas experience higher temperatures than surrounding areas. The primary cause of urban heat islands is the absorption of insolation by urban structures that is nocturnally released. UHIs can cause many problems both environmentally and physically (in terms of human health). In 1998, Chicago joined the EPA’s Urban Heat Island Pilot Project (UHIPP), which aims to mitigate the UHI effect in pilot cities throughout the country. Exactly how effective has UHIPP been in reducing Chicago’s UHI effect? This research examines Chicago’s heat island effect from 1997 (pre-UHIPP) to 2007. Observations of surface temperatures, along with hourly historical air temperature data, and population data provide the information needed to investigate Chicago’s UHI effect. Relationships between temperature and land cover as well as temperature and population will give further indication of the influences of the UHI effect. More specifically, hot spot and
cool spot analysis, will give Chicago and other cities an idea of the effectiveness of EPA’s UHIPP in reducing urban heat islands.
ACKNOWLEDGMENTS

I would like to thank my thesis advisor, Dr. Petra Zimmermann, for her time, support, enthusiasm, and guidance in the completion of this research. I would also like to thank my committee members, Dr. Jason Yang and Dr. Matthew Wilson, for their time and assistance. This thesis could not have been completed without their guidance and efforts.
# TABLE OF CONTENTS

ABSTRACT .................................................................................................................. ii

ACKNOWLEDGMENTS ............................................................................................... iv

LIST OF FIGURES ..................................................................................................... viii

LIST OF TABLES ........................................................................................................ xii

I. INTRODUCTION ...................................................................................................... 1

II. LITERATURE REVIEW .......................................................................................... 5

2.1 URBAN HEAT ISLANDS ..................................................................................... 6

2.1.1 URBAN-RURAL DIFFERENCES .................................................................... 8

2.1.2 URBAN HEAT ISLAND MAGNITUDE ............................................................. 10

2.1.3 URBAN HEAT ISLAND MITIGATION ............................................................. 10

2.2 URBAN HEAT ISLAND PATTERNS BASED ON POPULATION ANALYSIS ...
.................................................................................................................................. 11

2.3 REMOTE SENSING AS A DETECTION TOOL ...................................................... 12

2.3.1 UHI DETECTION USING LAND COVER/LAND USE APPROACHES ............. 13

2.3.2 UHI DETECTION USING THERMAL INFRARED IMAGERY AND IN SITU DATA ................................................................................................................. 16

2.3.3 UHI DETECTION USING MULTIPLE APPROACHES ..................................... 18
2.4 LIMITATIONS AND GAPS IN CURRENT UHI STUDIES  

III. DATA AND METHODOLOGY

3.1 DATA

3.1.1 THERMAL INFRARED DATA

3.1.2 IN SITU DATA

3.1.3 CENSUS BLOCK GROUP DATA

3.2 METHODOLOGY

3.2.1 DATA PREPROCESSING

3.2.2 LAND COVER AND UHI METHODOLOGY

3.2.3 ADDITIONAL DATA PROCESSING

3.3 SUMMARY OF DATA AND METHODS

IV. DATA ANALYSIS

4.1 STUDY AREA CHANGE 1997-2007

4.2 THERMAL SATELLITE DATA

4.3 CENSUS DATA

4.3.1 AIR AND SURFACE TEMPERATURE DATA IN COMPARISON TO CENSUS POPULATION DENSITY

4.4 AIR AND SURFACE TEMPERATURE DATA IN COMPARISON TO DIFFERENT LAND COVERS

4.5 UHI HOT SPOT AND COOL SPOT ANALYSIS

V. SUMMARY AND CONCLUSIONS
5.1 LIMITATIONS .......................................................... 71
5.2 CONCLUSION ......................................................... 72
REFERENCES ............................................................. 74
LIST OF FIGURES

FIGURE 1.1 STUDY AREA ________________________________________ 4

FIGURE 2.1 RURAL-URBAN TEMPERATURE CONTRAST _____________ 8

FIGURE 3.1 URBAN HEAT ISLAND STUDY: GROUND WEATHER STATIONS___
______________________________________________________________ 25

FIGURE 3.2 MODEL BUILDER WORK FLOW OF SURFACE TEMPERATURE
RAS TER TO STUDY AREA POLYGONS ________________________________ 27

FIGURE 3.3 LAND COVER CLASSIFICATION- OCTOBER 1997 ___________ 29

FIGURE 3.4 LAND COVER CLASSIFICATION- SEPTEMBER 2007 _________ 30

FIGURE 3.5 BUFFERED CLASSIFIED IMAGE- OCTOBER 1997 ____________ 32

FIGURE 3.6 BUFFERED CLASSIFIED IMAGE- SEPTEMBER 2007 __________ 33

FIGURE 3.7 MODEL BUILDER WORK FLOW OF LAND COVER ANALYSIS __ 34

FIGURE 3.8 RASTER TO POLYGON SETTINGS __________________________ 34

FIGURE 4.1 LANDSAT TM IMAGE OF CHICAGO ________________________ 37

FIGURE 4.2 LAYER STACK CHANGE IN THE CHICAGO VICINITY 1997-2007 __
_______________________________ ________________________________ 38

FIGURE 4.3 IMAGE ALGEBRA CHANGE DETECTION 1997-2007 _________ 39
FIGURE 4.4 LAND SURFACE TEMPERATURES IN 1997: DERIVED FROM LANDSAT TM IMAGE  

FIGURE 4.5 LAND SURFACE TEMPERATURES IN 2007: DERIVED FROM LANDSAT TM IMAGE  

FIGURE 4.6 FEBRUARY 1997 AIR TEMPERATURES  

FIGURE 4.7 FEBRUARY 1997 SURFACE TEMPERATURES  

FIGURE 4.8 APRIL 1997 AIR TEMPERATURES  

FIGURE 4.9 APRIL 1997 SURFACE TEMPERATURES  

FIGURE 4.10 JULY 1997 AIR TEMPERATURES  

FIGURE 4.11 JULY 1997 SURFACE TEMPERATURES  

FIGURE 4.12 OCTOBER 1997 AIR TEMPERATURES  

FIGURE 4.13 OCTOBER 1997 SURFACE TEMPERATURES  

FIGURE 4.14 FEBRUARY 2007 AIR TEMPERATURES  

FIGURE 4.15 FEBRUARY 2007 SURFACE TEMPERATURES  

FIGURE 4.16 APRIL 2007 AIR TEMPERATURES  

FIGURE 4.17 APRIL 2007 SURFACE TEMPERATURES  

FIGURE 4.18 JULY 2007 AIR TEMPERATURES  

FIGURE 4.19 JULY 2007 SURFACE TEMPERATURES  

FIGURE 4.20 SEPTEMBER 2007 AIR TEMPERATURES  

FIGURE 4.21 SEPTEMBER 2007 SURFACE TEMPERATURES
FIGURE 4.22 REGRESSION ANALYSIS OF POPULATION DENSITY AND TEMPERATURE- FEBRUARY 1997

FIGURE 4.23 REGRESSION ANALYSIS OF POPULATION DENSITY AND TEMPERATURE- FEBRUARY 2007

FIGURE 4.24 REGRESSION ANALYSIS OF POPULATION DENSITY AND TEMPERATURE- APRIL 1997

FIGURE 4.25 REGRESSION ANALYSIS OF POPULATION DENSITY AND TEMPERATURE- APRIL 2007

FIGURE 4.26 REGRESSION ANALYSIS OF POPULATION DENSITY AND TEMPERATURE- JULY 1997

FIGURE 4.27 REGRESSION ANALYSIS OF POPULATION DENSITY AND TEMPERATURE- JULY 2007

FIGURE 4.28 REGRESSION ANALYSIS OF POPULATION DENSITY AND TEMPERATURE- OCTOBER 1997

FIGURE 4.29 REGRESSION ANALYSIS OF POPULATION DENSITY AND TEMPERATURE- SEPTEMBER 2007

FIGURE 4.30 URBAN LAND COVER 1997

FIGURE 4.31 URBAN LAND COVER 2007

FIGURE 4.32 FOREST LAND COVER 1997

FIGURE 4.33 FOREST LAND COVER 2007

FIGURE 4.34 AGRICULTURAL LAND COVER 1997

x
FIGURE 4.35 AGRICULTURAL LAND COVER 2007 62
FIGURE 4.36 FALLOW LAND COVER 1997 63
FIGURE 4.37 FALLOW LAND COVER 2007 63
FIGURE 4.38 WATER LAND COVER 1997 64
FIGURE 4.39 WATER LAND COVER 2007 64
FIGURE 4.40 HOT SPOT AREAS 1997-2007 67
FIGURE 4.41 COOL SPOT AREAS 1997-2007 68
LIST OF TABLES

TABLE 2.1 URBAN-RURAL CONSTRAINTS ________________________________________ 9

TABLE 3.1 IMAGERY COLLECTION _____________________________________________ 23

TABLE 3.2 CHARACTERISTICS OF LANDSAT TM DATA ____________________________ 23

TABLE 3.3 GROUND WEATHER STATION DATA ____________________________________ 24

TABLE 3.4 ACCURACY ASSESSMENT-1997 ______________________________________ 31

TABLE 3.5 ACCURACY ASSESSMENT-2007 ______________________________________ 31

TABLE 4.1 TEMPERATURE DATA COMPARISON ___________________________________ 43

TABLE 4.2 CHANGE IN LAND COVER AREA 1997-2007 (ACRES) ______________________ 65

TABLE 4.3 HOT SPOT ANALYSIS 1997-2007 _____________________________________ 67

TABLE 4.4 COOL SPOT ANALYSIS 1997-2007 ____________________________________ 68
I. INTRODUCTION

An urban heat island (UHI) is a phenomenon in which cities experience increased temperatures compared to that of the surrounding rural areas. Among its causes are trapped insolation in the urban structure and anthropogenic activities. However, to fully understand the urban heat island effect, it is important to first acknowledge that city areas are primarily made up of concrete and asphalt materials (buildings and streets) with minimal amounts of natural vegetation. The absorption of incoming solar radiation (insolation) by the Earth’s surface and urban structures is the primary cause of urban heat islands (Gartland, 2008). While 30% of insolation is reflected back into the atmosphere, over 50% is absorbed by the Earth’s surface. Given that urban structures are typically made up of low-reflective materials, these structures absorb much insolation. This in turn creates a storage box for heat in urban areas in which the heat absorbed during the day is nocturnally released (Gartland, 2008).

While UHIs have been observed since the 1800s (Montagna, 1981), research on them remained relatively sparse until a study on Atlanta’s UHI was completed in 1997 (Quattrochi et al., 1997). The Atlanta study found a difference in temperature up to 15°F between the urban area and the surrounding rural periphery (Quattrochi et al., 1997). Today, researchers are analyzing the UHI patterns of larger cities, such as Hong Kong and Cleveland (Nichol et al., 2009; Harwood, 2008). UHIs are an important topic to
examine because the affect both the environment and human health. Pollutants are more likely to be trapped in urban area when a heat island is present, which can consequently lead to smog and increased asthma cases (EPA, 2003). Heat islands can also intensify heat waves, as seen in the devastating heat wave of 1995. During a two-week period, the death toll in the city of Chicago exceeded 500 people (EPA, 2003). Each day, the temperature in Chicago was 10-12°F warmer than the suburban areas (Changnon et al., 1996).

In today’s society, global climate change is a major concern for governmental officials and environmental scientists as well as the general populace. Furthermore, these groups of individuals are working on solutions to reduce the near-surface temperatures of city areas (EPA, 2003). If the heat island effect can be reduced, it could potentially help decrease the warming effect throughout the world. This is especially important, because as population and cities continue to grow in the United States, the warming effect felt throughout the country will also continue to amplify (Viterito, 1991).

According to the U.S. Environmental Protection Agency (EPA), the amplification of summer heat waves caused by heat islands result in heat stroke, organ damage and even death, as well as environmental effects such as an increase in ozone levels and even smog. In 1997, the EPA established an Urban Heat Island Pilot Project (UHIPP) partly due to concerns about health and environmental issues. Five cities were chosen to be a part of the UHIPP in 1998: Baton Rouge, Sacramento, Salt Lake City, Houston, and Chicago. Each city was chosen based on its air quality prior to the start of this project as well as the willingness of the city and community to reduce the UHI effects (EPA, 2009).
With the establishment of the UHIP, each city has been working with the EPA to implement a plan to mitigate the UHI effect (EPA, 2002).

Chicago is one of the largest cities in the United States with a population over 2.8 million within the city limits. It has the third largest population in the U.S., after New York City and Los Angeles (Census Bureau, 2011). Located along the coast of Lake Michigan, Chicago experiences seasonal variations year round in its weather patterns. Although the lake typically moderates the temperatures in Chicago, there is a clear and present UHI effect in the city with a profound difference in temperature between the central business district (CBD) and the surrounding areas (Magnuson, 1982).

The goal of this research is to examine Chicago’s UHI effect from 1997 to 2007 using remote sensing, historical ground weather station data, and census block group data. This city was chosen due to the lack of prior research completed on Chicago’s UHI effect since the start of the UHIPP. Since Chicago is a large metropolitan area, it is anticipated that the UHI will affect not only the CBD, but the surrounding suburbs as well. Therefore, the study area examined in this research includes Chicago’s CBD, along with the outlying suburban/rural areas (Figure 1.1). A seasonal approach is used to determine any changes in the UHI effect during the study period. Ultimately, 1997 and 2007 will be compared to determine the overall change in the heat island effect. The question to be answered is: Has Chicago’s urban heat island effect changed since the start of the EPA’s UHIPP? If so, how has it changed? Systematic analysis of air and surface temperatures and their relation to population density and land cover are also completed as they likely contribute to the UHI effect through anthropogenic activities and influences.
These results should give a better understanding on the changes in Chicago’s heat island effect from 1997 to 2007.

Figure 1.1- Study Area
II. LITERATURE REVIEW

Urban heat islands (UHIs) are unique phenomena that occur when urban temperatures exceed those of the surrounding rural area. These were first noticed in London in the 1800s when temperatures in London were noticeably warmer than the countryside (Harwood, 2008). Today, two types of UHIs are proven to exist. Atmospheric heat islands are “the layer of the urban atmosphere extending upwards from the surface to approximately mean building height” whereas surface heat islands are “the upwelling thermal radiance received by the remote sensor” (Voogt et al., 2003). In essence, atmospheric heat islands are measured using weather station air temperature data while surface heat islands are those measured with thermal infrared data of the ground.

The relationship between urban areas and its temperature (both air and surface) have proven to be of particular interest to environmental scientists and geographers within academia and the government. Environmental scientists are primarily concerned with how the UHI affects the state of the environment and is affected by the environment (Gartland, 2008), while many geographers are concerned how humans impact the environment (Viterito, 1991). When a 1997 UHI study of Atlanta, Georgia showed the higher temperatures in the city area due to urban growth and changes in land cover/land use (Lo et al., 1997), the EPA in the United States became increasingly interested in the mitigation of UHIs across the United States, largely due to the potential health and

This review of literature will examine the evolution of UHIs and their relationship to anthropogenic activities, urban and rural contrasts, and UHI magnitude and mitigation. UHI detection using remote sensing techniques will also be examined. Lastly, once current and past studies are examined, gaps in the literature will be addressed.

2.1 Urban Heat Islands

When UHIs were first noticed in the 1800s, more developed countries were going through a rural to urban transformation. Factories and industries also started to form in urban areas resulting in the Industrial Revolution (Montagna, 1981). There is no secret that the Industrial Revolution had great environmental impacts on the world. Heavy smoke from industries clouded many large cities in the world creating smog and health problems for urban dwellers (McNeill, 2000). London suffered through the Great Smog of 1952 that resulted in the creation of its own Clean Air Act of 1956 (McNeill, 2000). It wasn’t until the Clean Air Act of 1970 that the United States began to regulate pollutants from industries (EPA, 2011). More recently, the Kyoto Protocol was adopted in 1997 that aims to reduce greenhouse gas emissions globally (Stone, 2009). The countries that are bound by this protocol are committed to reducing their greenhouse gas emissions 5% by 2012 and must follow the guidelines established by the protocol (UNFCC, 2011).

Although scientists first noticed the heat island effect in the 1800s and air pollution regulations have been in place for decades, the heat island is still present throughout the world. If government regulations have been in place to reduce air pollution, why does the heat island effect continue to impact the environment?
Today, the local climate in urban areas is heavily influenced by the built environment as well as anthropogenic activities that humans depend on for survival and day-to-day activities (Woodward, 2003). These two factors are what contribute directly to UHIs. High-density structures in urban areas are heat absorbers for insolation that in essence trap heat into the urban canopy during the day and nocturnally release it (EPA, 2003). Since many of the urban structures are built in proximity to one another (narrow streets), wind speed is greatly reduced in urban areas, thus restricting air flow that would typically moderate temperatures (Woodward, 2003).

Anthropogenic activities that contribute to the UHI effect include the use of vehicles, heating and cooling of homes, and the use of factories for economic gain and human demand of goods (EPA, 2003). The 2007 Intergovernmental Panel on Climate Change (IPCC) report showed a significant increase in carbon dioxide, methane, and nitrous oxide mainly caused by anthropogenic activities (IPCC, 2007).

Aside from anthropogenic structures and activities, the reduction and displacement of trees and vegetative cover in urban areas is also contributing greatly to the UHI effect (EPA, 2003). Vegetation often moderates temperatures, but without trees and vegetative cover in urban areas, there are more air pollutants present (nitrogen dioxide, sulfur dioxide, carbon monoxide, ozone) that become trapped in the urban canopy, further resulting in higher urban temperatures (World Resources, 2000). Essentially, since greenhouse gases prevent heat and sunlight from reflecting back into the atmosphere, urban areas act as incubators that when mixed with insolation and air pollution to create higher temperatures.
2.1.1 Urban-Rural Contrasts

Urban heat islands result in urban-rural contrasts. This contrast exists because rural areas have more vegetation, virtually no high density buildings, and less emittance of air pollutants.

![Figure 2.1: Rural-Urban Temperature Contrast (Source: U.S. EPA)](image)

As shown in Figure 2.1, rural areas, where great amounts of vegetation are found, have significantly lower temperatures than those of downtown areas. It can also be inferred that while the downtown areas may have the largest UHIs, smaller heat islands can exist in commercial areas as well as urban and suburban residential areas. Even smaller areas such as shopping centers have been shown to produce a small scale UHI effect (Viterito, 1991). Table 2.1 shows urban-rural constraints that amplify the UHI effect (Harwood, 2008, as cited in Robinson et al., 1986). Urban areas experience lower incoming radiation, wind speed, and relative humidity, while simultaneously experiencing higher temperatures, cloudiness, and precipitation.
Table 2.1: Urban-Rural Contrasts (Source: Harwood, 2008, as cited in Robinson et al., 1986)

<table>
<thead>
<tr>
<th>Element</th>
<th>Parameter</th>
<th>Urban Compared with Rural (- less; + more)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incoming Radiation</td>
<td>On Horizontal Surface</td>
<td>-15%</td>
</tr>
<tr>
<td></td>
<td>Ultraviolet</td>
<td>-30% (Winter)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-5% (Summer)</td>
</tr>
<tr>
<td>Temperature</td>
<td>Annual Mean</td>
<td>+0.7 C</td>
</tr>
<tr>
<td></td>
<td>Winter Maximum</td>
<td>+1.5 C</td>
</tr>
<tr>
<td></td>
<td>Length of freeze free season</td>
<td>+2 to 3 Weeks</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>Annual Mean</td>
<td>-20 to -30%</td>
</tr>
<tr>
<td></td>
<td>Extreme Gusts</td>
<td>-10 to – 20%</td>
</tr>
<tr>
<td></td>
<td>Frequency of Calms</td>
<td>+5 to +20%</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>Annual Mean</td>
<td>-6%</td>
</tr>
<tr>
<td></td>
<td>Season Mean</td>
<td>-2% (Winter)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-8% (Summer)</td>
</tr>
<tr>
<td>Cloudiness</td>
<td>Cloud Frequency and Amount</td>
<td>+5 to +10%</td>
</tr>
<tr>
<td></td>
<td>Fogs</td>
<td>+100% (Winter)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+30% (Summer)</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Amounts</td>
<td>+5 to +10%</td>
</tr>
<tr>
<td></td>
<td>Days (with &lt;5mm)</td>
<td>+10%</td>
</tr>
<tr>
<td></td>
<td>Snow Days</td>
<td>-14%</td>
</tr>
</tbody>
</table>

While the climatology of urban areas varies from place to place, most urban areas exhibit higher temperatures and more precipitation than the surrounding rural areas (Woodward, 2003). Wind speed is also altered in urban areas because the volume and size of buildings in the Central Business District (CBD) restrict wind from circulating
between buildings. Cloud cover and fog are more apparent in urban areas, but are due in part to air particulates and pollutants (Harwood, 2008).

### 2.1.2 Urban Heat Island Magnitude

While there is a clear difference in temperatures between urban and rural areas, it is still unclear exactly what that difference is. One researcher noted that urban areas have temperatures up to 18°F warmer (at nighttime) than the surrounding rural areas (Woodward, 2003), while another study claims the UHI effect contributes to daily overall temperatures up to 5.6°C warmer than the surrounding area at (EPA, 2003). Differences in these values can be attributed to population size, density, amount of vegetation, climate, and weather modifiers, such as large water bodies, of urban areas (Harwood, 2008). Although the magnitude of the UHI can vary from place to place and from day to day, most researchers agree that the daytime average mean temperature difference between large towns and rural areas is 0.6-1.5°C (Woodward, 2003; Robinson et al., 1999).

### 2.1.3 Urban Heat Island Mitigation

Urban heat islands have significant impacts on the biodiversity of the urban environment. The amplification of summer heat waves can lead to increased health problems and higher death tolls, especially among the poor and elderly. Higher temperatures create a larger demand for energy use to heat and cool buildings, resulting in smog and increased air pollutants (EPA, 2003). Because that the UHI effect is a serious problem that has both environmental and human impacts, its mitigation is crucial.
In 2003, the EPA released a guide that examines strategies to reduce UHIs in the U.S. Some of the strategies include the installment of cool roofs and green roofs in urban areas, the use of cool paving materials, and increased planting of vegetation and trees in urban areas. Cool roofs are made up of high reflectant materials that reduce the absorption of heat into buildings. Green roofs on the other hand are comprised of soil and vegetation cover over a waterproofed surface. Rooftop gardens or green roofs cool the air in urban areas through increased evapotranspiration. Benefits from cool roofs and green roofs include a reduction in energy use (air conditioning), aid in stormwater control, and a reduction in the UHI effect. Cool paving refers to paving materials that are made of permeable or lighter-colored material (i.e. a concrete rock based mixture). This type of pavement is shown to have a higher reflectance of insolation that will reduce the UHI. Lastly, the EPA calls for more green areas within urban regions. This includes more trees, vegetation, and increased park space. The EPA calls for deciduous trees to be planted to shade either the east or west of buildings to maximize cooling benefits. Shahmohamadi et al. (2010) also suggested using high albedo materials on urban buildings (not just the roof) as well as promote natural ventilation that will allow for air to circulate throughout the urban canopy.

2.2 Urban Heat Island Patterns Based on Population Analysis

Considering that urban heat islands are seen in urban areas with high density structures present, it is important to also note that these areas are where the majority of the population is centered. With this considered, UHIs will be concentrated where these people work/live as well where urban structures are most prominent (Viterito, 1991).
Fujibe (2010) examined how population can affect the UHI effect on different days of the week in Japan. In this study, he concluded diurnal variations in temperature existed during the mean weekly cycle likely due to people commuting in and out of the city for work. Holidays and Saturday evenings observed a decrease in air temperatures as people are likely not commuting into the city for work on these days. While these air temperature variations are certainly noticed in large scale cities, Viterito (1991) pointed out that they do exist in the smaller scale cities because the same influences are present (population and urban structures).

2.3 Remote Sensing as a Detection Tool

Remote sensing is a useful technique for analyzing the environment though recorded digital information of energy patterns from sensor systems on aircraft or satellites. While remote sensing is utilized for a wide range of activities including flood monitoring (Lacava et al., 2010), earthquake damage assessment (Pan et al., 2010), and the detection of hazardous volcanic clouds (Prata, 2009), UHI research has been (and continues to be) a major area of remote sensing work.

Thermal infrared imagery is capable of collecting surface temperatures crucial for UHI analysis. With thermal infrared imagery, models can be run to determine where the UHI effect will be most magnified (Henry et al., 1989). Aside from modeling UHI effects, thermal infrared imagery can be utilized to simply examine surface temperatures of the study area (Harwood, 2008). One problem with this method Shoshany et al., (1994) argue is that in order to determine a true surface temperature of an urban area, roof reflectance needs to be extracted from the imagery because it can increase the
radiance and temperature recorded on thermal infrared imagery due to the materials on the roof; this yields an inaccurate depiction of ground surface temperatures.

While these examples listed above give insight into methods of current UHI analysis, it should be noted that UHIs have been examined remotely from a multitude of perspectives over the years. The most common of these in current research include analyzing the relationships between UHIs and land use/land cover, using satellite thermal infrared imagery to detect the magnitude of the UHI effect, and employing \textit{in situ} data in conjunction with remotely sensed images (Lo et al., 1997; Nichol, 2005; Harwood, 2008).

\subsection{2.3.1 UHI Detection using Land Cover/ Land Use Approaches}

As the world continues to become increasingly urbanized, the earth’s surface continues to change. \textit{Land use} refers to what people do to the land surface (i.e. agriculture) while \textit{land cover} refers to the “type of material present on the landscape” (i.e. water, forest, asphalt) (Jensen, 2005). Although environmental scientists are concerned with the amount of land cover change happening on the Earth’s landscape (Mas, 1999), they are also concerned with the environmental effects of land use/land cover change (Chuvieco, 2008). One of those effects is the UHI (Viterito, 1991; Quattrochi et al., 1997; Harwood, 2008).

Typically urban land covers exhibit higher overall temperatures than vegetative land covers because urban structures trap heat in the urban canopy while vegetation helps to moderate the temperatures of the surrounding areas (EPA, 2003). Land use/land cover
UHI analysis can be completed from several different viewpoints. The relationship of different land uses can be compared to surface temperatures (Pease et al., 1976), temporal change in land cover can be examined with changes in UHI magnitudes (Lo et al., 1997), and seasonal analysis can also be examined with seasonal land cover patterns (Liu et al., 2008).

In a 1976 study, researchers examined the relationship between different land uses and the respective contributions of the UHI effect at Baltimore, Maryland (Pease et al., 1976). The authors gathered M-7\(^1\) multispectral data on May 11, 1972 from the Environmental Research Institute of Michigan (ERIM) and employed a modified land use classification scheme from the United States Geological Survey (USGS) that included the following land use classifications: residential (low, medium, and high density), the CBD, commercial, transportation, urban parks, institutional (schools), and water surfaces. The study found that transportation land use created the highest surface temperatures in the study area with a temperature of 40.3°C. High density residential areas were a close second at 37.2°C, while water surfaces yielded the lowest surface temperatures at 15°C. The total difference in surface temperature between transportation and water surfaces in the study area was 25.3°C. This large difference was due to the varying albedos present in the urban landscape (Pease et al., 1976).

Temporal analysis when coupled with land cover can also give insight into changes in UHI magnitude. Lo et al. (1997) examined how urban land covers exhibit higher temperatures during the daytime, while water land covers exhibited the lowest. At

\(^{1}\) M-7 is an airborne scanner that is capable of collecting multispectral data (Pease et al., 1976).
night however, water exhibited the highest temperatures due to its emissivity (absorption of heat during the day) while agricultural land covers exhibited the lower temperatures (as expected). Similar to this study, Chen et al. (2006) observed rapid urbanization in the Guangdong Province of Southern China from 1990 to 2000 by examining the changes in land cover. The authors found that with an increase in urban land cover there was a simultaneous increase in the UHI effect.

Lastly seasonal approaches can be utilized when observing UHIs and land cover. Liu et al. (2008) examined the seasonal variation in six different land cover classes for Indianapolis, Indiana, from 2000-2006. Four images obtained by NASA Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)\(^2\) were gathered for this study, one from each season (images were taken between October 2000 and February 2006). The researchers found urban areas to consistently have the highest temperature zones throughout each season, while vegetation and water were found to have the lowest temperature zones. The February image stood out to the researchers, because the urban and water/vegetation land cover had the largest change than any other season. The researchers attributed this to the vegetation being in a leaf-off season thus allowing more energy to be released from buildings. They also noted that the February image was from 2006 while the other images were from 2000, 2001, and 2004. Given that the February 2006 image was the most recent of the four images, when it was compared to the earliest image in 2000, urbanization in Indianapolis was observed that resulted in the increased land surface temperatures (LST) that were observed from 2000-2006.

\(^2\) ASTER is a satellite sensor that gathers information about emissivity, reflectance, elevation, and surface temperatures (Jensen, 2005).
Due to these past studies examining the different effects of land use/land cover on UHIs, a definite relationship between land surface temperatures (LST) and land use/land cover has been shown to exist (Weng, 2009; Lo et al., 1997; Chen et al., 2006). A linkage between land cover change and seasonal variation in the UHI has also been demonstrated whereby summer and winter months are linked to increased energy consumptions (Liu et al., 2008).

2.3.2 UHI Detection using Thermal Infrared Imagery and In Situ Data

Aside from analyzing the UHI effect from a land use/land cover perspective, other researchers are examining the UHI effect using thermal infrared imagery, sometimes compared with in situ air temperatures. Thermal infrared remote sensing is useful for determining thermal radiation, measuring evapotranspiration, evaporation, and soil moisture, as well as analyzing UHIs (Nichol, 2009). One study examining the seasonal heat island effect in Nagoya, Japan, using ASTER and Landsat ETM+ \(^3\) imagery along with meteorological data from approximately the same time the imagery was acquired (Kato et al., 2005). The researchers found that there was a higher heat flux in the summer and winter compared to spring. They also noted that this followed energy consumption and determined that anthropogenic behaviors were responsible for both higher nighttime heat flux and the lack of vegetation on the landscape.

Diurnal changes in UHIs are also examined with air and surface temperatures. Nichol investigated the diurnal change in the UHI effect in Hong Kong in 2005. This study used

---

\(^3\) Landsat ETM+ was launched in 1999 and gathers information in the visible, near-infrared, mid-infrared, and thermal infrared regions of the electromagnetic spectrum as well as panchromatic imagery. This sensor also has greater resolution than its predecessor scanners (Jensen, 2005).
ASTER imagery for nighttime analysis and Landsat ETM+ for daytime UHI analysis. The results showed a more pronounced microclimatic variation in the daytime imagery with both heat islands and cool islands shown (cool islands were vegetated urban areas). The cool areas were 8°C cooler than the surrounding urban surfaces. The areas described as “cool islands” in the morning imagery were only 2°C cooler than the surrounding urban structures in the nighttime imagery. Nichol (2005) attributed the morning phenomenon to the time at which the morning imagery was acquired. During the morning-time, there is still convective activity in urban areas. Since ASTER data was acquired close to the thermal crossover time (the point at which the UHI is magnified) the nighttime imagery did not yield the anticipated magnified heat island effect. In the same study, Nichol (2005) also noted that UHIs are more of a nighttime phenomenon, but studies in this field suffer because of the lack of adequate temporal coverage of areas at nighttime.

The combination of thermal infrared images to derive surface temperatures along with in situ weather data has been used in many UHI analyses (Nichol, 2005; Kato et al., 2005). Understanding the accuracy of data when the two methods are utilized in conjunction is imperative. A study by Rigo, et al., examined the validation of satellite derived temperatures with in situ measurements (Rigo, et al., 2005). The authors gathered images from the same time period and study area from NOAA-Advanced Very High Resolution Radiometer (AVHRR)\(^4\), Moderate Resolution Imaging Spectrometer

\(^4\) NOAA-AVHRR contains 5 bands that collect visible and infrared data in the electromagnetic spectrum. This sensor has a higher repeat time than Landsat (collects two images a day) and has a spatial resolution of 1.1km (Jensen, 2005).
(MODIS)\textsuperscript{5}, Landsat TM and Landsat ETM+ satellite sensors. In addition, they placed eight ground weather stations in the study area to observe daily temperatures, wind speed, and humidity. Once the data were collected, the \textit{in situ} ground station data was compared to the satellite-derived temperatures for accuracy assessment. The authors found that the mean absolute differences between the two temperature measurements (satellite-derived and \textit{in situ}) ranged from 0\% to 9.3\%. A positive correlation between the two temperature measurements was found. The positive relationship was attributed to high spatial resolution of the images.

\textbf{2.3.3 UHI Detection using Multiple Approaches}

Not all UHI studies are constrained to just one methodology. Zhang et al. (2010) examined the UHI effect in different global settlements using MODIS imagery and nighttime lights data. In this study, the authors gathered data from the 2001 National Land Cover Database (NLCD) to examine urban surface areas, LST data from MODIS, and nightlight-based data from the National Geophysical Data Center for thousands of settlements worldwide. Although the UHI effect varies based on settlement size, latitudinal zone, and the ecology of the area, the authors found that globally, the UHI is most prevalent during summer daytimes, followed by summer nighttime, winter daytime, and lastly winter nighttime respectively. They noted that “this research highlights significant positive relationships between UHI magnitude, impervious surface areas, and ecological setting” (Zhang et al., 2010).

\textsuperscript{5} MODIS contains 36 bands that collect data in the visible and infrared spectrums of the electromagnetic spectrum. MODIS has a repeat time of 2 days and collects data in 1km, 500km, and 250km spatial resolution (Jensen, 2005).
Similarly, Nichol (2009) utilized ASTER satellite-derived surface temperatures (Ts) and in situ air temperatures (Ta) in conjunction with land cover (one from January 31, 2007 and the other, February 1, 2007) to determine the heat island effect in Hong Kong over a winter evening. This study suggested a strong relationship between Ts and Ta in conjunction with different land cover types. Urban land covers held the highest irradiance while vegetation land covers yielded the lowest. This further indicates evidence supporting the population structure model of UHI causation, meaning the higher the population concentration, the greater the UHI magnitude (Nichol, 2009).

2.4 Limitations and Gaps in Current UHI Studies

While much progress has been made in the field of UHI detection, some issues still arise. First, many satellite sensors lack the ability to obtain nighttime imagery (Nichol, 2005). Since most heat islands are at their highest intensities a couple of hours after sunset, much of the UHI analysis is incomplete because nighttime data can be difficult to obtain for certain study areas. Second, most satellite sensors with a high spatial resolution lack high temporal repeat times necessary to obtain cloud-free images from the time frame needed (Harwood, 2008). Third, satellite sensors with high repeat times such as MODIS or NOAA-AVHRR lack the spatial resolution necessary for this microclimate analysis.

This research seeks to address gaps in current UHI research to include an analysis of hot spot and cool spot areas within the study area and an analysis of the UHIPP. Considering the heat island magnitude changes from day to day, it is impossible and inaccurate to declare a given temperature and higher on any day to be considered a hot
spot. In examining the top and bottom 10% of surface temperatures, this research aims to get rid of that biased and get an idea of how much area hot spots and cool spots occupy. The area of hot spots and cool spots will be examined from 1997 to 2007 to determine how these patterns have changed. Additionally, more research needs to be conducted on cities under the UHIPP to determine the effectiveness of the project. This is an area that surprisingly lacks research and is important to examine to determine whether this UHIPP is working and to what extent.
III. DATA AND METHODOLOGY

The methods of this thesis serve to meet the objectives of the study. These objectives are:

1. To examine what parameters influence the thermal patterns (population density and/or land use) and how those patterns have changed from 1997 to 2007, and
2. To determine whether or not Chicago has successfully worked towards mitigating its UHI effect.

Chicago’s UHI was examined over a 10-year period, commencing with the start of the EPA’s UHIPP (1997-2007), to determine what progress, if any, has been made in the reduction of the UHI effect (reduction will be measured in the area hot spots and cool spots occupy within the study area). While using satellite imagery and in situ data is sufficient to determine where the heat island effect will be most prominent, it is equally important to examine census block group data to assess where the highest population concentrations are within the study area. With census block group data it is possible to examine the change in population density between 2000 and 2005 and furthermore determine if it correlates with the changes in UHI magnitude. Lastly, land cover classification was completed and analyzed in conjunction with surface and atmospheric temperatures to determine if a correlation exists between different land covers and UHI magnitudes.
3.1 Data

Data used for this research include thermal infrared satellite imagery, *in situ* air temperature, and census block group data.

3.1.1 Thermal Infrared Data

Landsat TM\(^6\) imagery is the primary source of data for this UHI investigation because of its availability and temporal resolution. Landsat acquires imagery every sixteen days in the morning over the Chicagoland area which provides a sufficient number of images to choose from. In total, eight Landsat TM images (Path 23, Row 31) were gathered for this study. Four images were acquired from 1997 (one per season) and four images were acquired from 2007, again, during each season (Table 3.1). Seasonal images were obtained for the purpose of examining the heat island phenomena throughout the year, as Chicago likely experiences its strongest heat island effect in the summer and winter months due to the heating and cooling of homes and businesses. The thermal band of Landsat TM, or band 6, is of most interest for this study because of its ability to yield land surface temperatures (LST). Landsat TM has a spatial resolution of 120m for band 6 and 30m spatial resolution for multispectral data (Table 3.2). These images were acquired via the United States Geological Society (USGS) Earth Explorer, a free source that links to a large archive of satellite imagery dating as far back as 1972 for the United States and some parts of the world.

---

\(^6\) Landsat TM was launched in 1982 and gathers multispectral information in visible, near-infrared, mid-infrared, and thermal infrared regions of the electromagnetic spectrum. Since this satellite sensor was launched previous to Landsat ETM+ it has lower spatial resolution in the thermal infrared band (Jensen, 2005).
Table 3.1- Imagery Collection

<table>
<thead>
<tr>
<th>Season</th>
<th>1997</th>
<th>2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>02-12-1997</td>
<td>02-08-2007</td>
</tr>
<tr>
<td>Spring</td>
<td>04-01-1997</td>
<td>04-29-2007</td>
</tr>
<tr>
<td>Summer</td>
<td>07-06-1997</td>
<td>07-02-2007</td>
</tr>
<tr>
<td>Fall</td>
<td>10-10-1997</td>
<td>09-04-2007</td>
</tr>
<tr>
<td>Total</td>
<td>4 images</td>
<td>4 images</td>
</tr>
</tbody>
</table>

Table 3.2- Characteristics of Landsat TM Data

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength (µm)</th>
<th>Band Spectrum</th>
<th>Resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.45-0.52</td>
<td>Blue</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>0.52-0.60</td>
<td>Green</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>0.63-0.69</td>
<td>Red</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>0.76-0.90</td>
<td>Near-Infrared</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>1.55-1.75</td>
<td>Mid-Infrared</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>10.40-12.5</td>
<td>Thermal Infrared</td>
<td>120</td>
</tr>
<tr>
<td>7</td>
<td>2.08-2.35</td>
<td>Mid-Infrared</td>
<td>30</td>
</tr>
</tbody>
</table>

Source: Jensen, 2005

3.1.2 In Situ Data

In addition to satellite imagery, meteorological data from proximate National Climatic Data Center (NCDC) ground weather stations were obtained for the study months in 1997 and 2007. NCDC ground weather stations utilized for this study are: Chicago-Midway, Chicago-O’Hare, Chicago-DuPage, Chicago-Meigs, Chicago-Palwaukee, Chicago-Waukegan, Calumet, and Aurora Municipal (Table 3.3 and Figure 3.1). These eight ground weather stations have hourly, daily and monthly air temperature data available from 1997 to 2007 from the same date/time the images were acquired. Although most of the NCDC ground weather stations fall outside of the Chicago city

---

7 Chicago-Meigs, Chicago-Palwaukee, and Calumet do not have data recorded for both 1997 and 2007.
limits, they still can be used to compare city temperatures to the surrounding suburban/rural areas.

Table 3.3- Ground Weather Station Data

<table>
<thead>
<tr>
<th>Weather Station</th>
<th>Hourly Weather Data Available</th>
<th>Latitude (North)</th>
<th>Longitude (West)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aurora Municipal</td>
<td>1997 and 2007</td>
<td>41.767</td>
<td>-88.467</td>
</tr>
<tr>
<td>Chicago-DuPage</td>
<td>1997 and 2007</td>
<td>41.917</td>
<td>-88.25</td>
</tr>
<tr>
<td>Chicago-Meigs</td>
<td>1997 Only</td>
<td>41.867</td>
<td>-87.6</td>
</tr>
<tr>
<td>Chicago-Midway</td>
<td>1997 and 2007</td>
<td>41.786</td>
<td>-87.752</td>
</tr>
<tr>
<td>Chicago-O'Hare</td>
<td>1997 and 2007</td>
<td>41.986</td>
<td>-87.914</td>
</tr>
<tr>
<td>Chicago-Palwaukee</td>
<td>2007 Only</td>
<td>42.121</td>
<td>-87.905</td>
</tr>
<tr>
<td>Chicago-Waukegan</td>
<td>1997 and 2007</td>
<td>42.417</td>
<td>-87.867</td>
</tr>
<tr>
<td>Calumet</td>
<td>2007 Only</td>
<td>41.733</td>
<td>-87.533</td>
</tr>
</tbody>
</table>
3.1.3 Census Block Group Data

Census block group data was used to examine relationships between population density and the heat island magnitude. Areas with concentrated populations as well as
highly industrial areas within the study area may have stronger heat island effects due to anthropogenic activities and the built environment surrounding urban areas. To test this, block-level Census data from 2000 and 2005 were used, as it is more detailed than tract or county-level data. Those data were closest temporally to the study’s time period. Lastly, the Census Tiger Line files of the Chicago area were obtained from the U.S. Census Bureau and used to help display the quantitative data in ArcGIS.

3.2 Methodology

3.2.1 Data Preprocessing

Prior to image processing, several data pre-processing steps were required. First, band 6 (thermal infrared band) from each image was converted from pixel brightness value to surface temperature in degrees Fahrenheit. To calculate surface temperatures, pixel brightness value was first converted to radiance (Chander et al., 2007) (Eqa. 1):

\[
L = \left( \frac{L_{\text{max}}(\lambda) - L_{\text{min}}(\lambda)}{Q_{\text{cal max}} - Q_{\text{cal min}}} \right) (Q_{\text{cal}} + L_{\text{min}}(\lambda)) \tag{Eqa. 1}
\]

where \(L_{\text{max}}(\lambda)\) is the maximum spectral radiance, \(L_{\text{min}}(\lambda)\) is the minimum spectral radiance, \(Q_{\text{cal max}}\) is the maximum digital number, and \(Q_{\text{cal min}}\) is the minimum digital number (Chander et al., 2007). Once radiance is determined, surface temperature can then be calculated using the Planck equation (Jackson et al., 2005) (Eqa.2):

\[
Tb = \frac{K^2}{\ln\left(\frac{K}{L} + 1\right)} \tag{Eqa. 2}
\]
where \( T_b \) is the surface temperature in Kelvin, \( K_1 \) is a constant \((607.76 \text{ Wm}^{-2} \text{ sr}^{-1} \mu\text{m}^{-1})\), \( K_2 \) is a constant \((1260.56 \text{ K})\), and \( L \) is the blackbody radiance for a temperature (Jackson et al., 2005). The results of the Planck equation return surface temperatures in Kelvin, which were then converted to degrees Fahrenheit (or °F). Pre-processing steps were undertaken with ERDAS Imagine software.

Following the conversion of pixel brightness values to surface temperature, subsets of each image were created by clipping the surface temperature raster to the study area counties in ArcGIS. The resulting rasters were further transformed to polygons for further analysis and editing (Figure 3.2).

**Figure 3.2: Model Builder Work Flow of Surface Temperature Raster to Study Area Polygons**

Multispectral images from Landsat TM were also pre-processed. Bands 1-5 and 7 from each date were stacked on top of one another to create a multispectral composite that can be used for change detection and classification. Methods of change detection chosen for this study include layer stack change detection and image algebra. For layer stack change detection, overall change was found from 1997-2007 using Eqa. 3.

\[
\text{Change} = \frac{\text{Band 4, October 1997}}{\text{Band 4, September 2007}}
\]

Eqa. 3
The September and October fall images were chosen for this layer stack because there were no clouds present in the imagery.

Image algebra was another method of change detection used in this study. Bands 4 from September and October multispectral images were used as the input. Next, Band 4 of the September 2007 image was subtracted from Band 4 of the October 1997 image to illustrate the overall change between the two study years. Each pixel was further assigned a 0, representing no change (shown in tan) or a 1, representing change (shown in purple) to make the changed areas more noticeable (binary image).

Image classification was the last pre-processing task performed on the imagery. Again, the September and October images were chosen because there was no cloud cover present in the images in the study area. Unsupervised Iterative Self-Organizing Data Analysis Technique (ISODATA) classification was used to classify the image into 40 classes with a maximum iteration of 25. Once ISODATA was run, the 40 spectral classes were then condensed and assigned to one of five broad land cover classes: water, urban, vegetation, agriculture, and fallow (Figures 3.3 and 3.4).
Figure 3.3: Land Cover Classification- October 1997
Following classification, a quantitative assessment was completed to determine the accuracy of classification. Illinois National Aerial Photography Program (NAPP) Digital Orthophotography quarter Quadrangle (DOQ) photos obtained from 1998 and 2005 (closest to the study time period) at 0.5m spatial resolution from the Illinois GIS Clearinghouse were used as the high resolution data to compare to the classified images. Each DOQ for my study counties was mosaicked together to form a single photo of the
entire study area for both years. Tables 3.4 and 3.5 illustrate the accuracy assessment of the classified land cover data.

**Table 3.4: 1997 Accuracy Assessment**

<table>
<thead>
<tr>
<th></th>
<th>Unclassified</th>
<th>Water</th>
<th>Developed</th>
<th>Vegetation</th>
<th>Agriculture</th>
<th>Fallow</th>
<th>Total</th>
<th>Users Accuracy</th>
<th>Commission Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unclassified</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>13</td>
<td>0.92</td>
<td>0.08</td>
</tr>
<tr>
<td>Water</td>
<td>0</td>
<td>8</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>9</td>
<td>0.89</td>
<td>0.11</td>
</tr>
<tr>
<td>Developed</td>
<td>0</td>
<td>0</td>
<td>11</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>13</td>
<td>0.83</td>
<td>0.15</td>
</tr>
<tr>
<td>Vegetation</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>24</td>
<td>3</td>
<td>0</td>
<td>28</td>
<td>0.86</td>
<td>0.14</td>
</tr>
<tr>
<td>Agriculture</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>31</td>
<td>21</td>
<td>0</td>
<td>25</td>
<td>0.94</td>
<td>0.10</td>
</tr>
<tr>
<td>Fallow</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>11</td>
<td>0</td>
<td>11</td>
<td>0.92</td>
<td>0.08</td>
</tr>
<tr>
<td>Total</td>
<td>12</td>
<td>8</td>
<td>13</td>
<td>31</td>
<td>25</td>
<td>0</td>
<td>51</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Producers Accuracy</th>
<th>Omission Error</th>
<th>Overall Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.00</td>
<td>0.00</td>
<td>0.84</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Kappa</th>
<th>DI</th>
<th>E(Xi * Xj)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.84</td>
<td>87</td>
<td>2022</td>
</tr>
</tbody>
</table>

**Table 3.5: 2007 Accuracy Assessment**

<table>
<thead>
<tr>
<th></th>
<th>Unclassified</th>
<th>Water</th>
<th>Developed</th>
<th>Vegetation</th>
<th>Agriculture</th>
<th>Fallow</th>
<th>Total</th>
<th>Users Accuracy</th>
<th>Commission Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unclassified</td>
<td>17</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>18</td>
<td>0.94</td>
<td>0.06</td>
</tr>
<tr>
<td>Water</td>
<td>0</td>
<td>9</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>0.90</td>
<td>0.10</td>
</tr>
<tr>
<td>Developed</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>14</td>
<td>0.71</td>
<td>0.29</td>
</tr>
<tr>
<td>Vegetation</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>15</td>
<td>3</td>
<td>0</td>
<td>18</td>
<td>0.83</td>
<td>0.17</td>
</tr>
<tr>
<td>Agriculture</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>5</td>
<td>25</td>
<td>0</td>
<td>32</td>
<td>0.76</td>
<td>0.22</td>
</tr>
<tr>
<td>Fallow</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>5</td>
<td>8</td>
<td>0.65</td>
<td>0.35</td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
<td>9</td>
<td>14</td>
<td>25</td>
<td>30</td>
<td>5</td>
<td>100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Producers Accuracy</th>
<th>Omission Error</th>
<th>Overall Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.00</td>
<td>0.00</td>
<td>0.76</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Kappa</th>
<th>DI</th>
<th>E(Xi * Xj)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.76</td>
<td>81</td>
<td>2042</td>
</tr>
</tbody>
</table>

While several supervised and unsupervised classification attempts were applied with varying class sizes to improve accuracy, the unsupervised classification results in Figures 3.3 and 3.4 showed among the best of the classification trials because of its high accuracy.
3.2.2 Land Cover and UHI Methodology

One objective of this study is to examine how the thermal patterns are affected by different land covers. A 4.5 mile buffer was applied to each NCDC weather station (the greatest buffer that could be applied with no overlapping) that was further used to clip to the classified images from fall 1997 and 2007 (Figures 3.5 and 3.6). A buffer was applied so that the landscape around each NCDC weather station could be further examined as it may have an influence on the surrounding air and surface temperatures.

![Figure 3.5: Buffered Classified Image- October 1997](image_url)
Next, a land cover class field was created that assigned each record in the two classified images to a land cover class (water, urban, vegetation, agriculture, and fallow). The buffered classified images were then converted from a raster to a polygon using the land cover class field. While converting from raster to polygon, the new polygons were simplified. Lastly, an acreage field was created and populated to the classified buffered polygons to determine how much area each land cover class occupies in the 4.5 mile buffer. Figures 3.7 and 3.8 shows the workflow of this processesing.
The outcomes of this land cover processing make it possible to investigate if relationships exist between different land covers and air/surface temperatures. The change in land cover and thermal patterns can also be determined.

### 3.2.3 Additional Data Processing

Isotherm maps are useful for displaying temperature data of the study area. These maps were created using NCDC-obtained air temperatures and satellite-derived surface
temperatures in Adobe Illustrator. The weather stations that did not record data for a certain month were excluded from isotherm maps. Census population data at the block group level were also used for this analysis. Each block group was classified based on population density for 2000 and 2005 (available data closest to the study period). The NCDC and satellite derived isotherm maps were then overlaid on the census block group data to examine if any correlations exist. If a correlation exists, the highest temperatures will be found in the areas with higher population densities.

Hot spot analysis was completed by examining the top 10% of surface temperatures throughout the study area. Cool spot analysis was completed in a similar matter with the bottom 10% of surface temperatures being examined from the study area. Aside from examining the temperatures of hot spots and cool spots, the acreage of each were examined to determine what change, if any, has occurred. Considering the UHI magnitude varies from day to day, by analyzing the top and bottom 10% of surface temperatures in each image, it gets rid of the biased in determining exactly what temperature is considered a UHI. This provided a greater understanding of the UHI effect and mitigation within the Chicagoland area.

3.3 Summary of Data and Methods

With these data sets and methods, the magnitude of Chicago’s UHI effect can be measured from 1997 to 2007. While the majority of the methods listed are similar to those discussed in the literature review, this data analysis stands out from past research because it is examining how the UHI effect has changed over a decade in Chicago and
the surrounding areas as well as examining the effectiveness of the UHIPP since the start of the project.
IV. DATA ANALYSIS

4.1 Study Area Change 1997-2007

Examining the landscape of the Chicagoland area and surrounding suburbs is necessary before any UHI analysis. Changes observed in the landscape from 1997 to 2007 can give insight to UHI trends and patterns of the Chicago Metropolitan area (Figure 4.1).

Figure 4.1: Landsat TM Image of Chicago
The multispectral images in Figure 4.1 show noticeable changes in Chicago’s landscape due to city expansion and difference in agricultural growing seasons. The city area has expanded outwardly since 1997, encroaching on the rural fringes. A change in farm plots is also evident, but this is attributed to the difference in growing seasons. The September image (2007) was acquired during the growing season, while plants were still healthy and un-harvested, while the October image (1997) was acquired after fields were harvested, thus appearing fallow. Layer stack change detection is a method where two bands (i.e. Band 4) from two different images are stacked on top one another to show change. This method was performed on the two images from Figure 4.1 (Figure 4.2).

Figure 4.2: Layer Stack Change in the Chicago Vicinity 1997-2007
Changed areas in the landscape appear red in Figure 4.2 due to the band combination picked for this method of change detection. The amplitude of urban expansion can be seen in red as well as the difference in growing season on the rural fringes. The enlarged areas of Chicago in Figure 4.2 show finer details of land cover change in the city. O’Hare’s airport expansion, newly constructed roads, and additional buildings have appeared all in the 2007 image. Further change in the Chicago vicinity can be seen by completing image algebra change detection (Figure 4.3).

![Image Algebra Change Detection 1997-2007]

The binary image gives a clearer representation of those areas that have changed (purple) as opposed to those areas that haven’t changed (tan). Roads and airport expansion are
easily distinguished in the Chicago area and changes in agriculture are noticed in the far south and western suburbs due to differences in growing season between the two fall images (September and October).

4.2 Thermal Satellite Data

Landsat TM images were acquired for each study season in 1997 and 2007. Both February images have snow cover present, while the April and July images show cloud cover in the suburban fringes. With band 6 from Landsat TM, surface temperatures were extracted by converting pixel brightness value to temperature (Figures 4.4 and 4.5).

Figure 4.4: Land Surface Temperatures in 1997: Derived from Landsat TM Image
Recognizing that snow was present in the February images explains why the majority of the image is the same surface temperature. However, February 2007 had locally warmer temperatures in the area surrounding the city of Chicago. Both April images exhibit similar thermal patterns in that the warmer temperatures were concentrated in and around the city. One noticeable difference between the two April images was that the warmer areas in April 2007 extended further outward from the city than they did in April 1997. This could be attributed to the April 1997 image being acquired from the beginning of the month whereas the April 2007 image was acquired near the end of the month or this could be due to urban expansion. Cloud cover was present in McHenry, Kendall, and
Will counties on both July images. Clouds are easily distinguished because they are represented as some of the cooler temperatures in both figures. Similar to the April images, July images from each year closely resemble each other. However, there is a greater ‘warmer’ area in the 2007 image than 1997, likely due to urban expansion. Lastly, it is important to acknowledge that fall images were not acquired from the same months (the 1997 image is from October while the 2007 image is from September). With that said, it is expected to be warmer overall in September than October. The two fall images largely resemble one another closely in thermal patterns, however there is a small concentrated area in the western part of Chicago that is warmer than the surrounding area in the September 2007 image, again, likely due to urban growth over the ten year period.

4.3 Census Data

Census data at block group level was examined for the entire study area from 2000 and 2005 to determine what changes had occurred in population. The population of the entire study area was 8,655,298 in 2000 while the population grew to 9,065,014 in 2005. The city of Chicago had a population of 2,699,503 in 2000, but it decreased to 2,691,852 in 2005. Although the city itself observed a decrease in population from 2000 to 2005, Cook County saw a population growth from 5,248,379 in 2000 to 5,287,656 in 2005. The demographics and human settlement have clearly changed in Chicago. It appears more people moved outward from the Chicago city limits into the surrounding communities.
4.3.1 Air and Surface Temperature Data In Comparison to Census Population Density

A key aspect of this study is to determine if a relationship exists between population density (population per sq. mile) and air/surface temperature. Air temperatures were gathered from local NCDC ground weather stations that fall within the study area and surface temperatures were interpolated from the thermal infrared imagery. More specifically, surface temperatures were determined by examining the temperature on the thermal infrared imagery at the location of the NCDC weather stations. NCDC hourly air temperatures were then compared with surface temperatures obtained from the satellite thermal imagery (Table 4.1).

Table 4.1: Temperature Data Comparison

<table>
<thead>
<tr>
<th>Date</th>
<th>Temperature (°F)</th>
<th>Aurora</th>
<th>Calumet</th>
<th>DuPage</th>
<th>Melga</th>
<th>Midway</th>
<th>O'Hare</th>
<th>Palwaukee</th>
<th>Waukegan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb-97</td>
<td>Surface Temperature</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Air Temperature</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td>Apr-97</td>
<td>Surface Temperature</td>
<td>41.6</td>
<td>41.5</td>
<td>40</td>
<td>40</td>
<td>46</td>
<td>48.4</td>
<td>47.1</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Air Temperature</td>
<td>28</td>
<td>37</td>
<td>32</td>
<td>28.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jul-97</td>
<td>Surface Temperature</td>
<td>55.3</td>
<td>48.7</td>
<td>53.5</td>
<td>52.3</td>
<td>53</td>
<td>50.3</td>
<td>52.2</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Air Temperature</td>
<td>61</td>
<td>60.3</td>
<td>64</td>
<td>63.7</td>
<td>61.7</td>
<td></td>
<td></td>
<td>63</td>
</tr>
<tr>
<td>Oct-97</td>
<td>Surface Temperature</td>
<td>41.6</td>
<td>41</td>
<td>40.8</td>
<td>43</td>
<td>49</td>
<td>43.3</td>
<td>44.6</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>Air Temperature</td>
<td>41.7</td>
<td>57</td>
<td>50</td>
<td>49.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feb-07</td>
<td>Surface Temperature</td>
<td>9</td>
<td>18</td>
<td>9</td>
<td>18</td>
<td>17</td>
<td>18.8</td>
<td>19</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Air Temperature</td>
<td>-11.3</td>
<td>1</td>
<td>-4.3</td>
<td>-0.6</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>Apr-07</td>
<td>Surface Temperature</td>
<td>56.2</td>
<td>44.3</td>
<td>55.7</td>
<td>50.5</td>
<td>51.7</td>
<td>55.8</td>
<td>53.1</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Air Temperature</td>
<td>46.3</td>
<td>50.3</td>
<td>45.3</td>
<td>52</td>
<td>48</td>
<td>46</td>
<td>48.7</td>
<td></td>
</tr>
<tr>
<td>Jul-07</td>
<td>Surface Temperature</td>
<td>42.7</td>
<td>51</td>
<td>54.1</td>
<td>54.2</td>
<td>57</td>
<td>59.2</td>
<td>57</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Air Temperature</td>
<td>54.3</td>
<td>63.3</td>
<td>54.3</td>
<td>61.3</td>
<td>57</td>
<td>55.7</td>
<td>57.7</td>
<td></td>
</tr>
<tr>
<td>Sept-07</td>
<td>Surface Temperature</td>
<td>51.2</td>
<td>60</td>
<td>56.2</td>
<td>57.7</td>
<td>61.7</td>
<td>61.7</td>
<td>61.2</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>Air Temperature</td>
<td>58.7</td>
<td>70</td>
<td>62.3</td>
<td>69</td>
<td>64.7</td>
<td>64</td>
<td>66</td>
<td></td>
</tr>
</tbody>
</table>

When comparing air and surface temperatures to one another, it can be inferred that five of the eight images had a higher air temperature observed than surface
temperatures. In some instances, the air temperature and surface temperature had a difference over 10˚F (i.e. O’Hare during July 1997). A possible explanation for the higher air temperatures in summer and fall of 1997 and 2007 is that during these times of the year, seasonal temperatures are heightened; coupled with the insolation becoming trapped into urban structures and little wind, it makes it hard for air temperatures to be moderated.

Bivariate maps were created to examine the relationship between air/surface temperatures and population density (Figures 4.6 through 4.21). Population density was broken into five classes based on natural breaks for 2000 and 2005, while air temperatures were gathered from NCDC weather stations. Surface temperatures were interpolated from the satellite thermal infrared imagery from each block group the NCDC weather stations fall.
Figure 4.6: February 1997 Air Temperatures

Figure 4.7: February 1997 Surface Temperatures
Figure 4.8: April 1997 Air Temperatures

Figure 4.9: April 1997 Surface Temperatures
Figure 4.10: July 1997 Air Temperatures

Figure 4.11: July 1997 Surface Temperatures
Figure 4.12: October 1997 Air Temperatures

Figure 4.13: October 1997 Surface Temperatures
Figure 4.14: February 2007 Air Temperatures

Figure 4.15: February 2007 Surface Temperatures
Figure 4.16: April 2007 Air Temperatures

Figure 4.17: April 2007 Surface Temperatures
Figure 4.18: July 2007 Air Temperatures

Figure 4.19: July 2007 Surface Temperatures
Figure 4.20: September 2007 Air Temperatures

Figure 4.21: September 2007 Surface Temperatures
As expected in observing the bivariate maps, warmer temperature were typically concentrated near the city of Chicago, while cooler temperatures were more focused in the outlying areas. More specifically, air temperatures were higher in and around the city than surface temperatures. There are, however, some anomalies. February 1997 and 2007 show higher surface temperatures compared to air temperatures, due to snow cover on the ground, which may have skewed the results. In April 1997, O’Hare airport and the surrounding area observed higher surface temperatures than air temperatures. The higher surface temperatures may be attributed to seasonality as well as time of day.

Atmospheric heat islands typically exist in summer and winter when anthropogenic energy consumption is at its highest. Since April is the beginning of seasonably moderate temperatures, the use of energy sources likely decreased during this time thus resulting in a higher surface heat island phenomenon. A similar outcome was seen in April 2007 when Aurora observed locally higher surface temperatures than the lakefront and CBD.

Based on the observations from Figures 4.6 through 4.21 and outlier/anomaly analysis, it seems as though the UHI effect appears to be more of an atmospheric phenomenon than surface within the densely populated areas. To further support this statement, scatter plots were constructed using population per square mile within a 4.5 mile radius of each NCDC weather station (taking into account the population density of the area surrounding each NCDC weather station is affecting the temperatures, not just at the NCDC station site). Regression analysis was also completed in conjunction with the
scatter plots to determined how much population density is influencing temperatures (Figures 4.22 through 4.29).

**Figure 4.22: Regression Analysis of Population Density and Temperature- February 1997**

**Figure 4.23: Regression Analysis of Population Density and Temperature- February 2007**
Figure 4.24: Regression Analysis of Population Density and Temperature- April 1997

Figure 4.25: Regression Analysis of Population Density and Temperature- April 2007
Figure 4.26: Regression Analysis of Population Density and Temperature - July 1997

Block Group Population in 4.5 Mile Radius: July 1997

Figure 4.27: Regression Analysis of Population Density and Temperature - July 2007

Block Group Population in 4.5 Mile Radius: July 2007
Air temperature exhibited a positive relationship to total population per square mile within the 4.5 mile radius of each NCDC weather station. In all the months from each study year, the regression analysis showed population density explained between
23-85% of the air temperature variance, meaning, the higher the population density, the higher the air temperature. Surface temperatures, on the other hand, did not exhibit positive relationships. Only 7-39% of the surface temperature variance for all the scatter plots can be explained by the population density. As previously stated, due to urban structures being built close together along with their absorption of insolation, heat does not escape the urban canopy easily nor does wind make it through. This in turn creates a greater relationship between population density and air temperature (compared to population density and surface temperatures) as examined in Figures 4.22 through 4.29. There isn’t as prominent of a relationship between population density and surface temperatures likely due to the time of day the satellite imagery was acquired (approximately 9:30am). Since insolation is absorbed by the ground and urban structures during the day, the surface UHI effect is often seen at nighttime. Therefore, since these images were acquired during the mid-morning for the study area, the amount of insolation absorbed by the ground is minimal leading to the less significant relationship observed.

4.4 Air and Surface Temperature Data in Comparison to Different Land Covers

Although the majority of this study area is occupied with urban land cover, other land cover types such as: forest, agricultural, fallow, and water exist. Land cover was obtained by classifying both fall images (October 1997 and September 2007). With classified images the relationship between different land cover classes and air/surface temperatures can be determined. This relationship is important to UHI analysis because it can give further explanation into why some areas have more hot spots or cool spots than others. Changes in land cover also provided further insight into the change in
thermal patterns observed during the study period. Since the UHIPP aims to mitigate the UHI effect by increasing cool spots, any increases in vegetation throughout the study area may be a result of the UHIPP.

As stated previously, buffers were placed around each NCDC weather station with a 4.5 mile radius (Figures 3.5 and 3.6). The land cover from the fall classified images was examined from each buffered NCDC weather station. Air temperatures were interpolated from the fall NCDC weather station data for 1997 and 2007 while surface temperatures were extracted from the fall Landsat imagery within each buffered NCDC weather station. Land cover was then plotted with air and surface temperatures to determine if any relationships exist (Figures 4.30 through 4.39).
Figure 4.30: Urban Land Cover 1997

Figure 4.31: Urban Land Cover 2007
Figure 4.32: Forest Land Cover 1997

Figure 4.33: Forest Land Cover 2007
Figure 4.34: Agricultural Land Cover 1997

Figure 4.35: Agricultural Land Cover 2007
Figure 4.36: Fallow Land Cover 1997

Figure 4.37: Fallow Land Cover 2007
Figure 4.38: Water Land Cover 1997

Figure 4.39: Water Land Cover 2007
Table 4.2: Change in Land Cover Area 1997-2007 (acres)

<table>
<thead>
<tr>
<th>Location</th>
<th>Water</th>
<th>Urban</th>
<th>Forest</th>
<th>Agriculture</th>
<th>Fallow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aurora Municipal</td>
<td>110</td>
<td>996</td>
<td>-3214</td>
<td>6501</td>
<td>4896</td>
</tr>
<tr>
<td>Chicago-DuPage</td>
<td>307</td>
<td>3215</td>
<td>-8373</td>
<td>3753</td>
<td>-363</td>
</tr>
<tr>
<td>Chicago-Meigs</td>
<td>-367</td>
<td>1519</td>
<td>-1152</td>
<td>8</td>
<td>-220</td>
</tr>
<tr>
<td>Chicago-Midway</td>
<td>-60</td>
<td>8975</td>
<td>-9392</td>
<td>35</td>
<td>-582</td>
</tr>
<tr>
<td>Chicago-O’Hare</td>
<td>229</td>
<td>7372</td>
<td>-10234</td>
<td>1256</td>
<td>-1221</td>
</tr>
<tr>
<td>Chicago-Palwaukee</td>
<td>203</td>
<td>5828</td>
<td>-9895</td>
<td>2433</td>
<td>-802</td>
</tr>
<tr>
<td>Chicago-Waukegan</td>
<td>243</td>
<td>3403</td>
<td>-5895</td>
<td>1653</td>
<td>-58</td>
</tr>
<tr>
<td>Calumet</td>
<td>-216</td>
<td>2571</td>
<td>-2161</td>
<td>-203</td>
<td>-213</td>
</tr>
</tbody>
</table>

Urban and water were the only two land cover classes that exhibited a positive relationship with air and surface temperatures. Considering air and surface temperatures were interpolated either from the NCDC weather station (air) or from the NCDC station buffer (surface) and acknowledging that Calumet and Meigs are situated in highly urban areas along the Lakefront, this likely explains why a positive relationship exists with air temperatures and water land cover.

The overall land cover change (in acres) is presented in Table 4.2. Fallow appears to have decreased while agriculture has increased in area. It must be reiterated that the fall images were from different growing seasons, thus leading to the apparent change in these two land covers. As observed with the classified images, urban land cover increased over the ten years throughout the entire study area (with the buffered areas around O’Hare and Midway observing the highest increase). As a result of urban expansion, forest land cover has been lost. While the overall results were not unexpected, some interesting anomalies exist. Urban areas had a higher relationship to surface temperatures than air temperatures. Second, forest land cover and surface temperatures also produced an unexpected result. Typically in vegetative areas, the
temperature is lower, but in Figures 4.32 and 4.33 there was a slight positive relationship between forest land cover and surface temperatures. Although the regression analysis yielded for this results is rather insignificant, a possible explanation for this could be attributed to the low albedo forest land cover possess, thus resulting in the increased surface temperatures. These two anomalies could also be caused by small sample size thus resulting in the unexpected results.

4.5 UHI Hot Spot and Cool Spot Analysis

Additional analysis of Chicago’s UHI effect is conducted by examining hot spots and cool spots within the study area, Cook County, and the city of Chicago. For this analysis, the top 10% of temperatures were selected from each season of each year and same with the bottom 10%. From the top and bottom 10%, the average surface temperatures were found as well as total acreage each top and bottom 10% occupy in each image (Tables 4.3 and 4.4). Average surface temperatures were interpolated by examining the average surface temperature from the top and bottom 10% of each image. This data allows further examination into the magnitude and area of hot spots and cool spots.
### Table 4.3: Hot Spot Analysis 1997-2007

<table>
<thead>
<tr>
<th>Hot Spot Acreage</th>
<th>Study Area 1997</th>
<th>Study Area 2007</th>
<th>Cook County 1997</th>
<th>Cook County 2007</th>
<th>Chicago 1997</th>
<th>Chicago 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>8193</td>
<td>7795</td>
<td>112</td>
<td>8589</td>
<td>41</td>
<td>5760</td>
</tr>
<tr>
<td>Spring</td>
<td>31533</td>
<td>38605</td>
<td>5586</td>
<td>1867</td>
<td>26502</td>
<td>584</td>
</tr>
<tr>
<td>Summer</td>
<td>129344</td>
<td>11119</td>
<td>19563</td>
<td>2452</td>
<td>257</td>
<td>770</td>
</tr>
<tr>
<td>Fall</td>
<td>16848</td>
<td>36435</td>
<td>1583</td>
<td>5449</td>
<td>257</td>
<td>2365</td>
</tr>
<tr>
<td>Sum</td>
<td>185938</td>
<td>93954</td>
<td>26804</td>
<td>18357</td>
<td>27197</td>
<td>9429</td>
</tr>
<tr>
<td>Change 1997-2007 (acres)</td>
<td>-91984</td>
<td>-6447</td>
<td>-91984</td>
<td>-6447</td>
<td>-17718</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Average Temp (°F)</th>
<th>Study Area 1997</th>
<th>Study Area 2007</th>
<th>Cook County 1997</th>
<th>Cook County 2007</th>
<th>Chicago 1997</th>
<th>Chicago 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>29.8</td>
<td>23.0</td>
<td>32.3</td>
<td>21.5</td>
<td>35.3</td>
<td>21.5</td>
</tr>
<tr>
<td>Spring</td>
<td>50.1</td>
<td>59.8</td>
<td>50.9</td>
<td>64.3</td>
<td>51</td>
<td>64.5</td>
</tr>
<tr>
<td>Summer</td>
<td>58.4</td>
<td>64.3</td>
<td>61.3</td>
<td>64.8</td>
<td>64</td>
<td>65.2</td>
</tr>
<tr>
<td>Fall</td>
<td>54.3</td>
<td>66.1</td>
<td>57.3</td>
<td>66.1</td>
<td>57.7</td>
<td>66.2</td>
</tr>
<tr>
<td>Average for Year</td>
<td>48.1</td>
<td>53.075</td>
<td>50.45</td>
<td>54.175</td>
<td>52.05</td>
<td>54.35</td>
</tr>
<tr>
<td>Change in Average (°F)</td>
<td>4.975</td>
<td>3.725</td>
<td>2.3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Figure 4.40: Hot Spot Areas 1997-2007
While examining Figure 4.40, it can be inferred that the total area of hot spots has decreased in the study area, Cook County, and Chicago from 1997 to 2007. This overall decrease in hot spot area can be attributed to the UHIPP and new planning measures in the
study area. Chicago is, after all, aware of its heat island effect, which is why they chose to become part of the UHIPP. With the resources provided by the EPA, and UHI mitigation strategies (urban gardens, cool pavement, etc) the city appears to have made strides in reducing the total area of the hot spots.

Figure 4.41 shows an apparent increase in cool spot areas from 1997 to 2007 not only in Chicago, but Cook County and the study area as a whole, as well. Forest preserves, ‘cool’ pavement, and construction/increase of parks could all be contributed to the increase in cool spot areas.

While the total hot spot areas have decreased in the study area, the average surface temperatures have increased. A possible explanation for this is the trend of warmer temperatures throughout the world in the past couple of decades (IPCC, 2007). Similar surface temperature patterns were noticed with cool spots. As the area of cool spots has increased in the study area, surface temperatures have also increased with the exception of the study area as a whole (unexplainable results). Again, this could be due in part to warmer temperatures being observed world-wide in recent decades. A secondary explanation for this observed trend in higher temperatures could be due to time of day the image was acquired and the conditions present at that time. The fact that Chicago and the surrounding areas have decreased their hot spot areas while simultaneously increasing their cool spot areas shows some evidence that this study area is mitigating the UHI effect observed.
V. SUMMARY AND CONCLUSIONS

Urban sprawl is a direct result of population growth and development. Population in the Chicagoland area has not only increased, but has expanded outward from the city from 1997 to 2007. With the increase in population density, higher air and surface temperatures were shown to be more prominent near those higher concentrated areas. While analysis of air temperatures show a steady positive relationship with population densities, the surface temperatures were more erratic in findings when compared to population densities (not always a positive relationship). Regression analysis also provided a strong relationship to population density and air temperatures.

Reductions in forest, agricultural, and fallow land covers are a result in the increase of urban expansion from 1997 to 2007. The reduction of these vegetative land covers reduces the amount of carbon dioxide storage in the area as well as decreases the moderation of temperatures. Land cover analysis show that the more vegetative land cover in an area, the lower the temperatures. Furthermore, increases in urban land cover are linked to an increase in air and surface temperatures.

Although there was an increase in hot spot surface temperatures from 1997 to 2007, there was an overall decrease in the area of hot spots throughout the study area. Similar to hot spots, cool spots also saw an increase in surface temperature, but also
showed an increase in overall cool spot area for the entire study area from 1997 to 2007. Increases in surface temperature within the hot and cool spots are attributed to overall temperature increases noticed throughout the world (not just Chicago).

Since Chicago began its participation in the UHIPP in 2008, the city has been making strides to reduce the heat island effect (Daley, 2005). Chicago has created a landscape ordinance to allow for more trees planted in the city, new energy codes in buildings, and the implementation of roof top gardens (EPA, 2002). To date, Chicago has added more than 600,000 trees to the cities landscape since 1989 (City of Chicago, 2010). In 2003, Chicago updated their energy code to include reflective roof ordinances that required an ENERGY STAR approval on all new building roofs (EPA, 2002). Since the start of this project, Chicago has repaved 3,500 acres of alleyways with an impermeable (rock-based) surface to decrease runoff and absorption of insolation (PCA, 2011). Roof top gardens have also started to appear on downtown buildings, with the largest being located at Daley Center (Daley, 2005). The Daley plaza roof top garden consists of 20,000 plants over a 20,300 square foot space (City of Chicago, 2010). With the help of the EPA’s UHIPP and the enthusiasm of city governments in this project, Chicago is becoming a “greener” city.

5.1 Limitations

While completing this study, several limitations were imposed. First, image classification could have been more accurate with higher resolution imagery due to its greater detail. Second, the classified images for the entire study area could not be transformed to polygons in Arc Map because the file size was too large. The original
goal was to examine the change (in acres) of each land cover class for the entire study area from 1997-2007, but since the file was too large, ArcMap continuously crashed.

Third, nighttime imagery would have been useful for a complete UHI analysis, but due to lack of data availability it was left out of this research. Fourth, Census data only takes into account where people live, not where people work. Since six of the eight images were acquired during the weekday when people are presumably at work and away from home, it may have had some affect on this analysis. Lastly, not all NCDC weather stations had complete data sets for the study time frame. In addition to this limitation, the establishment of more NCDC weather stations may be beneficial for future UHI analysis to obtain a more complete analysis.

5.2 Conclusion

Chicago certainly has made strides in the UHI reduction, but a secondary program that may be beneficial to the Chicago metropolitan area that establishes a UHIPP-like program for the suburbs. Since the suburbs and outer fringes of the Chicago metropolitan area are the areas that are expanding at increasingly high rates, it is important that they too work to mitigate any UHIs that may appear in the future.

Considering this area has been influenced by urban sprawl from 1997 to 2007 and continues to expand, encroaching on the rural fringes, surface temperatures will also continue to increase along with an increase in urban land cover. While the analysis completed examined both of both air and surface temperatures with changes in population and land cover, the UHI effect appears to be more of an atmospheric phenomenon. Overall hotspots in the city and surrounding areas have decreased in area,
while cool spots have increased. The reduction in hot spots and increase in cool spots is exactly what the UHIPP aims to accomplish. If the city can continue to mitigate its UHI effect, they can make even more strides leading to further reductions in hot spots.

Overall, the UHIPP does appear to have been successful for Chicago thus far, but results could not have been noticed without the enthusiasm of city governments and the EPA in this project. Research should continue to examine Chicago as well as the suburbs to monitor the UHI effect and ensure mitigation continues.
REFERENCES


