University of North Carolina Asheville
Journal of Undergraduate Research
Asheville, North Carolina
December 2023

Developing a Heat Vulnerability Index for Buncombe County, NC

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Abstract

Between 2008 and 2018, urban development in Asheville, NC, led to a 6.4% decline in the tree canopy that protects communities from extreme heat, which can lead to higher levels of air pollution and negative health effects. In 2019, the City of Asheville City partnered with the NASA DEVELOP program to publish a heat risk index of Asheville using geospatial and census data. This project builds on their efforts by creating a Heat Vulnerability Index (HVI) for Buncombe County to identify which communities are most vulnerable to heat exposure. The HVI was created utilizing ArcGIS Pro and it compares surface temperatures, vegetation, and social vulnerability criteria on a scale of 0–3, with 3 being the highest vulnerability. Land surface temperatures and a normalized difference vegetation index were developed with Landsat 8 satellite imagery. Additionally, recent census tract data on age, chronic illnesses, and income inequality was utilized to determine social vulnerability. The study found that the most heat vulnerable areas are the South Slope area and River Arts District, Barnardsville, as well as areas between Swannanoa and Black Mountain, which fall within the index range of 2.0–2.5. The study also found that developed areas with a higher percentage of people of color than the county average experience temperatures that are 1–2°F hotter. The HVI determined that installing green infrastructure through tree planting in South Slope and the areas between Swannanoa and Black Mountain are critical to mitigating heat vulnerability, while Barnardsville may be benefited more by social programs to increase medical care.

Keywords: *Urban Heat Islands, Heat Vulnerability, Environmental Justice, Climate Resilience, Public Health, Asheville, Buncombe County, North Carolina, Urban Forests, Green Infrastructure*

1. Introduction

1.1 Effects of Urban Heat

Many cities experience Urban Heat Islands (UHI), which are urban and suburban areas that have elevated temperatures compared to their rural surroundings. UHIs are often considered a public health threat as they contribute to communities experiencing extreme heat events, thermal discomfort, and air pollution that can exacerbate health conditions and increase hospital attendance in sensitive populations (Ebi et al., 2021). They have also been linked to increased mortality rates in people over 65 years of age, people confined to bed or who live alone, and people with chronic diseases such as heart disease, lung disease, and depression (Ebi et al., 2021; Hsu et al., 2021). Hsu et al. (2021) explains that UHIs have led to an increase in non-fatal health outcomes including “heat strokes, dehydration, loss of labor productivity, and decreased learning” (p.2). Additionally, those at most risk for nonfatal injuries include the elderly, students, and workers with outdoor occupations such as farmers and firefighters (Arbuthnott & Hajat, 2017).

While there are many factors contributing to the formation of UHIs, urban development is a significant cause due to the use of pavement (Cheela et al., 2021). Pavements are often dark-surfaced with direct, unshaded exposure to the sun, making them prime candidates for absorbing and retaining heat for long periods of time. This heat is slowly released throughout the day and night, leading to elevated air and surface temperatures (Cheela et al., 2021). Other factors include humid geographical locations, limited tree cover, vehicle emissions, and heat loss from buildings.

Communities with historically high percentages of low-income workers and people of color may be more likely to be exposed to UHIs (Ebi et al., 2021; Fihlo et al., 202; Hsu et al., 2021). Studies are showing that low-income, Black, Hispanic, and communities who were historically denied home loans and insurance due to their racial makeup (redlining) are more likely to experience UHIs when compared to wealthy, non-Hispanic White communities. Hsu et al. (2021) looked at 175 of the largest urban areas in the United States and determined that, on average, a person of color experiences higher heat intensity than a White person living below the poverty line. This result occurred “despite the fact that, on average, only 10% of people of color live below the poverty line” (Hsu et al., 2021, p.2).

Due to the differing sizes, population densities, and layouts of cities, UHIs affect each city uniquely, which makes it a complex, but necessary, problem to tackle (Fihlo et al., 2021). Possible solutions include the implementation of green-infrastructure and the restoration of urban tree cover, which would not only reduce events of extreme heat, but also decrease CO_2 emissions, mortality rates, and energy and road maintenance costs (Cheela et al., 2021; Fihlo et al., 2021). These suggestions come from the observation that areas with over 40% tree cover are less likely to experience the UHI effect (Cheela et al., 2021). Trees offer cooling through shading and evapotranspiration, and can mitigate heat in various amounts depending on factors such as a tree's species and leaf density. Suburban areas without trees are on average 2-3°C hotter than suburbs with mature trees, and shaded pavements can be between 5–25°C cooler than unshaded pavements (Cheela et al., 2021). Additionally, for every 0.6°C increase in temperature, electricity demand increases by 1.5–2% (Cheela et al., 2021). This cooling effect of vegetation may provide further incentive to tackle the problem of UHIs by indirectly translating into lower CO_2 emissions and energy costs by decreasing the power demand for indoor cooling and heating (Fihlo et al., 2021). With more cities and counties acknowledging the need for climate resilience, it is important to think of solutions that nonprofits and city developers can implement that will be good for the environment and the community, such as in the case of Buncombe County, North Carolina.

1.2 Study Site Description

Buncombe County is located in the far-western Appalachian Mountains of North Carolina as shown in Figure 1. Between 1981 and 2010, Buncombe County had summer air temperatures averaging in the 62°F–82°F range (National Weather Service, n.d.). The county has a population of 273,589 people over six municipalities in which 21.6% are above the age of 65, 17.3% are racial and ethnic minorities, and 11.7% are below the poverty line (U.S. Census Bureau, 2022). In 2017, 11.1 million tourists visited Buncombe County with Asheville, North Carolina as the primary destination due to its hiking trails and historic downtown area (Buncombe County Tourism Development Authority, 2017).

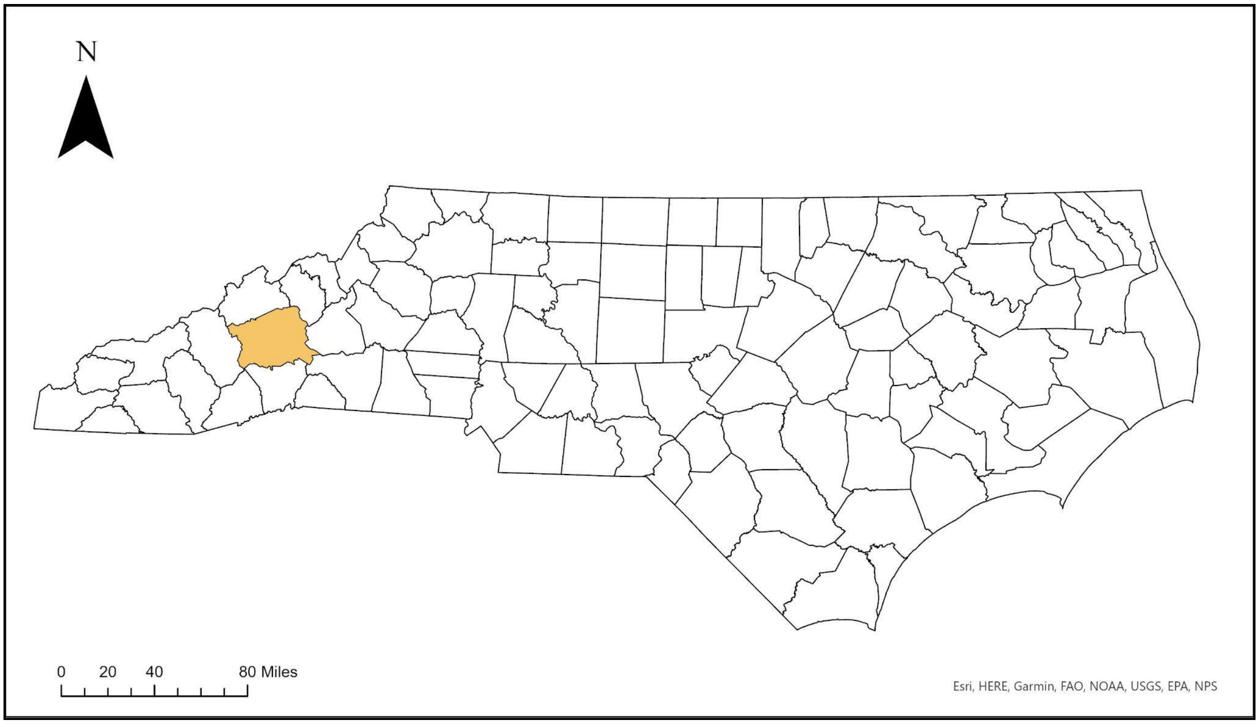

Figure 1. Study Site of Buncombe County, NC

The City of Asheville is located in the center of Buncombe County with a population of 93,776 people (U.S. Census Bureau, 2022). Summer air temperatures ranged from 73°F–84°F between 1981 and 2010 (National Weather Service, n.d.). According to a technical report published in 2019 by the NASA DEVELOP program, the city population increased by 10% and the percentage of urban tree cover decreased by 6.4% between 2008 and 2018. Land surface temperatures (LST) increased by as much as 31°F in some areas of the city during that same timeframe, with LST increasing an average of 4.4°F since the 1980s (Davey Resource Group, 2019; Gray et al., 2019). These high-heat areas were found to be primarily in developed areas including the South Slope neighborhood and near the airport (Gray et al., 2019).

With temperatures, urban development, and tourism increasing in Buncombe County, it is important to consider the effects this will have on the local communities and the county's abilities to adapt to the environmental impacts of climate change. To reduce the impact of extreme heat and protect the county's sensitive populations, nonprofits such as Asheville Greenworks are assessing effective ways to mobilize city planners and citizens to install green infrastructure and plant trees.

1.3 Project Partners and Objectives

Asheville GreenWorks (GreenWorks) is a nonprofit organization founded in 1973, originally under the name Quality '76, in an effort to "inspire, equip, and mobilize communities to create an equitable, climate-resilient future” (Asheville GreenWorks, n.d., para. 5). While their work started with cleaning up the polluted Swannanoa River, GreenWorks has since expanded to include multiple other roadside and river clean ups and hosted recycling events all throughout Asheville and the greater Buncombe County area.

In 2019, Asheville City Council partnered with the NASA DEVELOP Program to create and publish a Heat Risk Index of the City of Asheville using NASA Earth observations, geospatial data, and census data. Since then, GreenWorks had ambitions to expand that study to the greater Buncombe County area to include all 6 municipalities, including Candler, Woodfin, and Weaverville. To do so, GreenWorks partnered with the University of North Carolina at Asheville and the McCullough Institute with the primary goal of creating a Heat Vulnerability Index (HVI) of Buncombe County using land surface temperature and vegetation cover in conjunction with socioeconomic and health data.

The HVI is used to pinpoint which communities in Buncombe County, NC, are exposed to dangerously high heat in the summer due to urban heat islands and social vulnerability. This project will ultimately result in publicly available maps that can be utilized to determine the best tree-planting locations to benefit those in heat vulnerable areas.

2. Methods

2.1 Overview

A Heat Vulnerability Index (HVI) shows how likely someone in a sensitive population will be exposed to high temperatures with little or no ability to adapt to it (Gray et al., 2019). To build an HVI three factors need to be considered: 1) which areas are exposed to high temperatures, 2) which populations are most sensitive to events of extreme heat, and 3) how much nearby vegetation is available to provide cooling relief. This study used Landsat 8 satellite images to acquire LST and the Normative Difference Vegetation Index (NDVI) needed to build the basework of the HVI. Demographic, socioeconomic, and chronic health data was taken from the U.S. Census Bureau at the census tract level to locate sensitive populations. The HVI was then developed in ArcGIS Pro using Esri’s Raster Calculator tool to create a raster file with 30 meter resolution that shows heat vulnerability data in Buncombe County scaled 0-3, with 0 being the lowest vulnerability and 3 being the highest. Finally, the completed map will be used by the project partner and the City of Asheville for analysis to determine where combined tree-planting efforts need to be targeted to protect sensitive populations.

2.2 Data Collection

2.2.1 Land Surface Temperature and Adaptive Capacity

Land surface temperatures are frequently used in the research of UHIs and are often easier to acquire than air temperatures (Gray et al., 2019; Sabrin et al., 2020). Since temperatures can vary within a city, LST can be also helpful in showing where that variation happens. To create the Heat Vulnerability Index, we used LST to find areas that are environmentally hotter and therefore more susceptible to events of extreme heat within a city.

There are multiple techniques used to calculate LST. The technique utilized in this study estimates LST from Landsat 8 satellite images and follows the methods used in Gray et al., 2019. The publicly available United States Geological Survey's (USGS) Earth Explorer allows users to download satellite imagery. This study uses Level 1 satellite imagery of Buncombe County taken from the Landsat 8 satellite equipped with the OLI and TIRS instruments on June 22, 2022 at 4:05pm. LST was calculated with bands 4 (red) and 5 (infrared) at 30-m resolution, and band 10 (thermal infrared) at 100-m resolution. Each band was clipped to the Buncombe County boundary prior to any calculations.

Adaptive capacity is a population's ability to lessen or adapt to extreme heat events which is necessary to pinpoint when creating a HVI, as neighborhoods with more ability to adapt to increasing temperatures are less likely to suffer negative effects (Gray et al., 2019). A prime category that contributes to the population's ability to adapt is the amount of vegetation in the area since all vegetation types lead to decreased land surface temperatures.

To determine the adaptive capacity of the residents in Buncombe County, a NDVI was developed using the bands 4 (red) and 5 (infrared) in Equation 1. NDVIs show all actively photosynthesizing vegetation in an area and are frequently used to study urban heat islands (Gray et al., 2019; Liu, 2011; Shah, 2015; Yang, 2017). These NDVI values are then used to calculate the proportion of vegetation in each pixel. Finally, LST (°F) was calculated using brightness temperature from band 10 and land surface emissivity derived from the NDVI and proportion of vegetation using Equation 2 (Gray et al, 2019; Sabrin et al., 2020) and converted from °C to °F.

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \tag{1}$$

$$LST = \frac{BT}{((1 + \lambda \times BT / \alpha) \times (Ln(Emissivity))} \tag{2}$$

2.2.2 Sensitivity

Sensitivity is defined as a combination of population characteristics that contribute to a population being vulnerable during events of extreme heat (Gray et al., 2019). Some people are more likely to experience adverse outcomes from events of extreme heat, including mortality (Arbuthnott, Hajat, 2017; Ebi et al., 2021; Hsu et al., 2021). The 2019 heat risk study of Asheville used a variety of socioeconomic, chronic health, and demographic data to develop a social vulnerability index which indicated which census tracts had the highest vulnerability. Our team utilized the same technique to determine sensitivity.

Table 1 shows all data used as a marker of sensitivity on a census tract scale, which includes: adults 65 or older; the GINI-coefficient as a representation of income inequality; and people who experience diabetes, high blood pressure, depression, and chronic heart and lung diseases. These characteristics were chosen due to known increases in hospital attendance and mortality rates as association with heat events (Arbuthnott & Hajat, 2017; Ebi et al., 2021; Hsu et al., 2021). Due to a high elderly population in Buncombe County (21.6%) as shown by the Census Bureau, the GINI-coefficient was selected in place of individuals below the poverty line. The GINI-coefficient incorporates both income earned as well as savings and is an indicator of income inequality, which we believe will more accurately represent income levels in Buncombe County census tracts due to a substantial portion of the population obtaining low incomes from social security.

The sensitivity data is clipped to either 2010 or 2020 Buncombe County census tracts prior to download. While small geographic scales such as census block groups or census blocks would provide more accurate results, most of this data is unavailable at a smaller scale in order to preserve the medical privacy of individual households. This may provide a source of error in the resulting HVI, as smaller vulnerable neighborhoods may be overshadowed by larger, less-vulnerable neighborhoods within the same census tract.

Table 1. Demographic, socioeconomic, and chronic health conditions utilized as sensitivity criteria, alongside their source and year.

Data	Source	Year
Age > 65	Census	2017–2021
Age > 65 Living Alone	Census	2017–2021
Asthma	CDC	2021
Chronic Obstructive Pulmonary Disease (COPD)	CDC	2021
Coronary Heart Disease	CDC	2021
Depression	CDC	2021
Diabetes	CDC	2021
High Blood Pressure	CDC	2021
Medically Underserved Areas (MUA)	Health Resources and Services Administration	2023
GINI Index	Census	2017–2021

2.4 Processing, Normalization, and Aggregation of Vulnerability

The definition the study used for heat vulnerability follows the example used in NASA DEVELOP's study where it is a combination of exposure, sensitivity, and adaptive capacity (Equation 3).

$$HVI = Exposure + Sensitivity + Adaptive\ Capacity \qquad (3)$$

In order to develop an HVI, each variable needs to be normalized and aggregated in order to present an equal subjective view of heat vulnerability as a whole. First, all criteria are joined using a unique identifier present in both the census tract attribute table and the Census Bureau data's attribute table as the common value between tables. This unique identifier is called GeoID, which is a specific code used for each census tract in the U.S. After joining, the ArcGIS Pro Raster Calculator tool is used to apply Equation 4 to each individual criteria, where x is the numeric field hosting the percentages of each variable by census tract, the min is the minimum percentage experienced by Buncombe County as a whole, and the max is the maximum percentage experienced by Buncombe County as a whole. This normalizes each value to a scale between 0 and 1, with 1 being the highest vulnerability and 0 being the lowest.

$$(x - min) / (max - min) \tag{4}$$

To ensure that exposure, sensitivity, and adaptive capacity were weighted equally, sensitivity data was first normalized, aggregated together, and then normalized again to create a single social vulnerability index with a scale between 0 and 1.

This process, however, was reversed for the NDVI adaptive capacity criteria. NDVIs are already scaled between 0 and 1, with 0 being no vegetation and 1 being heavily forested, meaning that the scale needs to be flipped to ensure that lesser adaptive capacity increases a census tract's heat vulnerability. The NDVI scale was flipped using Equation 5.

$$(max - x) / (max - min) \tag{5}$$

Once this process was completed for each of the three HVI variables, each variable was converted from a shapefile to a raster file and aggregated together using Equation 3 to create the final HVI.

3. Results

3.1 Overview

The resulting maps of Buncombe County showed that on June 22, 2022, the county had a mean LST of 81.4°F, a mean sensitivity of 0.37 on a scale of 0-1, and a mean HVI of 0.89 on a scale of 0-3. The most heat-vulnerable area in Buncombe County is Census Tract 9, which is home to the South Slope neighborhood, a historically redlined and urban renewed community just south of Downtown Asheville. It is home to a percentage of the Black population over double the rate of Buncombe County as a whole (Census Reporter, 2021). The least heat-vulnerable areas in Buncombe County are along the Blue Ridge Parkway and Pisgah National Forest in between Barnardsville and Black Mountain, which are also home to the lowest LST.

3.2 Land Surface Temperature

Land Surface Temperatures in Buncombe County are shown in Figure 2. The coolest temperatures are primarily found in the Blue Ridge Parkway and Pisgah National Forest between Barnardsville and Black Mountain. These areas show temperatures between 68°F and 75°F. Conversely, the highest temperatures are found in central Asheville near the Asheville Mall, the Downtown area and the South Slope neighborhood. The highest temperature recorded on June 22, 2022 was 107°F near the Asheville Mall.

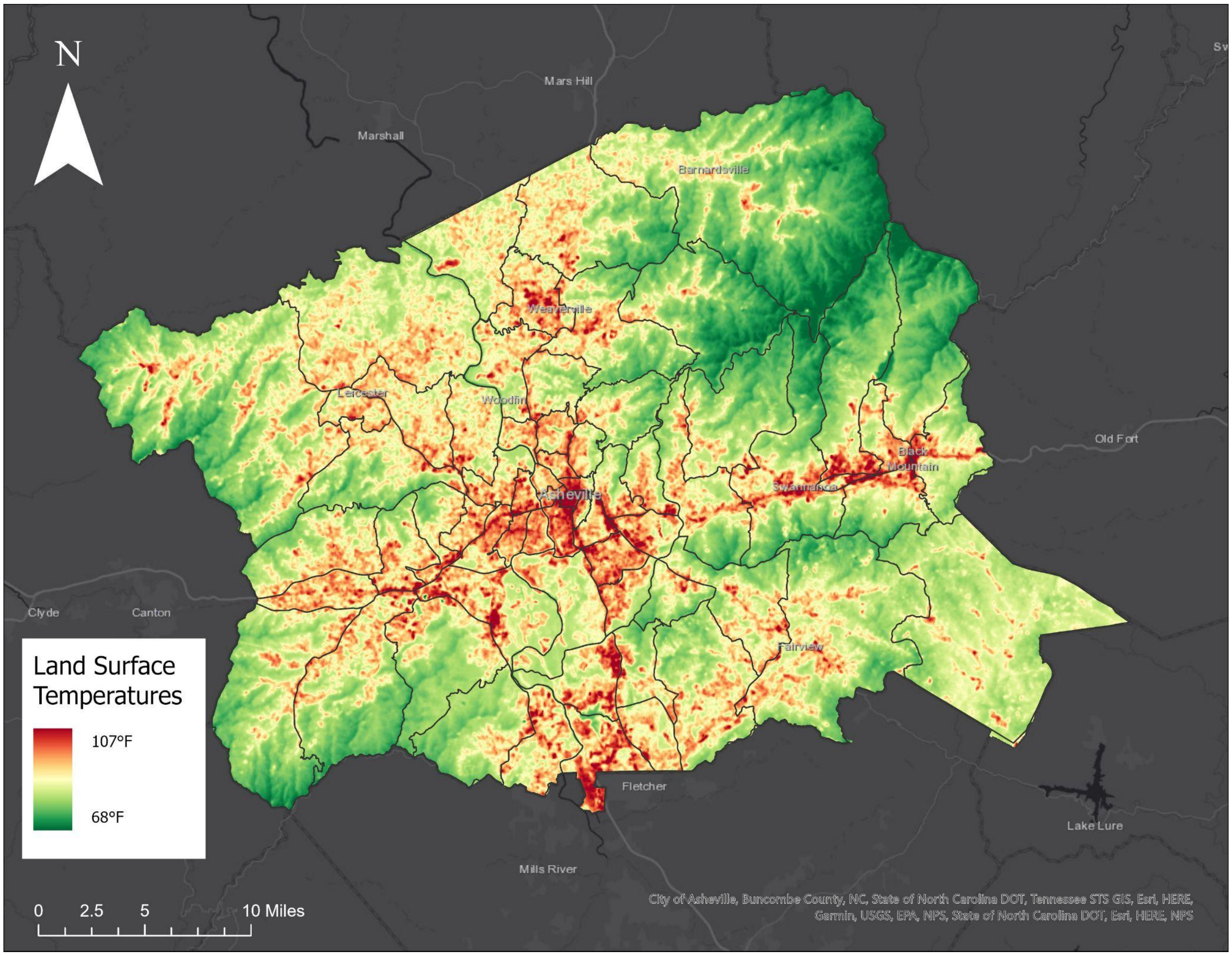

Figure 2. Land Surface Temperatures of Buncombe County, North Carolina on June 22, 2022 with Census Tracts.

3.4 Heat Vulnerability

The Heat Vulnerability Index roughly follows the patterns of temperature throughout each census tract as shown in Figure 3. Major visible changes occurred primarily in Census Tracts 29, 31.08, and 32.05, with Census Tract 29 containing Barnardsville being the most stark. Census Tract 29 has a population of 4,225 people with the median age being 45.6 years old and 27% of the population being 65 or older (Census Bureau, 2021). A primary contributor to the high HVI score is a high sensitivity score of 0.74, partially contributed to by the area being a Medically Underserved Area (MUA) and having a higher percentage of the elderly than the Buncombe County average.

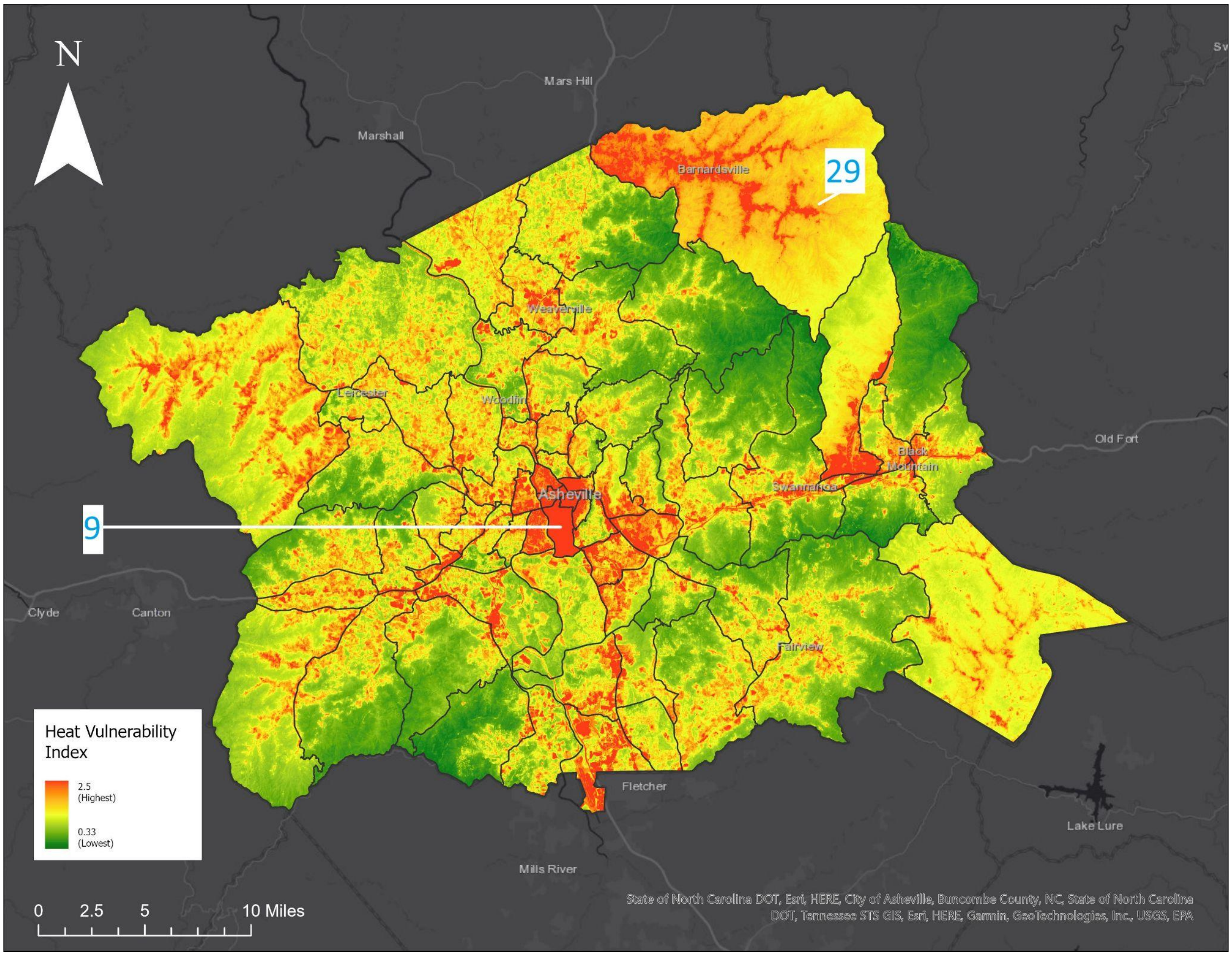

Figure 3. Heat Vulnerability Index of Buncombe County, North Carolina with Census Tracts 9 and 29 marked.

While Census Tract 29 is the most stark change from the LST map, it does not solely bear the highest HVI scores. Heat vulnerability index scores greater than 2 primarily show in Census Tract 9 as shown in Figure 4. Other areas include South Tunnel Road by the Asheville Mall and A.C. Moore, areas in between Swannanoa and Black Mountain, and parts of Barnardsville.

Figure 4. *HVI Values Above 2.0 (red) in Buncombe County, North Carolina.*

Census tract 9 includes the marginalized South Slope area, which is consistent with the findings of the NASA DEVELOP study in 2019. According to the Census Bureau, Census Tract 9 has a population of 3,037 people with the median age being 47.3 years old with 19.2% of the population being 65 and older, which is close to the county average. However, the Black population in this census tract is more than double the rate of Asheville city at 48%.

The lowest HVI scores in Buncombe County can be seen in Figure 5, where the blue highlighted parts show HVI scores below 0.5. These areas are primarily found along the Blue Ridge Parkway and Pisgah National Forest. West of Lake Julian, Beaten Branch, Bent Creek, and Long Branch all show scores below 0.5. Other areas include south of Swannanoa along Licklog Branch and Stepp Branch, south of Barnardsville by Sugarcamp Fork, Beetree Creek, Laurel Fork, and Wolf Branch, as well as southeast and southwest of Barnardsville near Glassmine, Stony Fork, and Flat Creek.

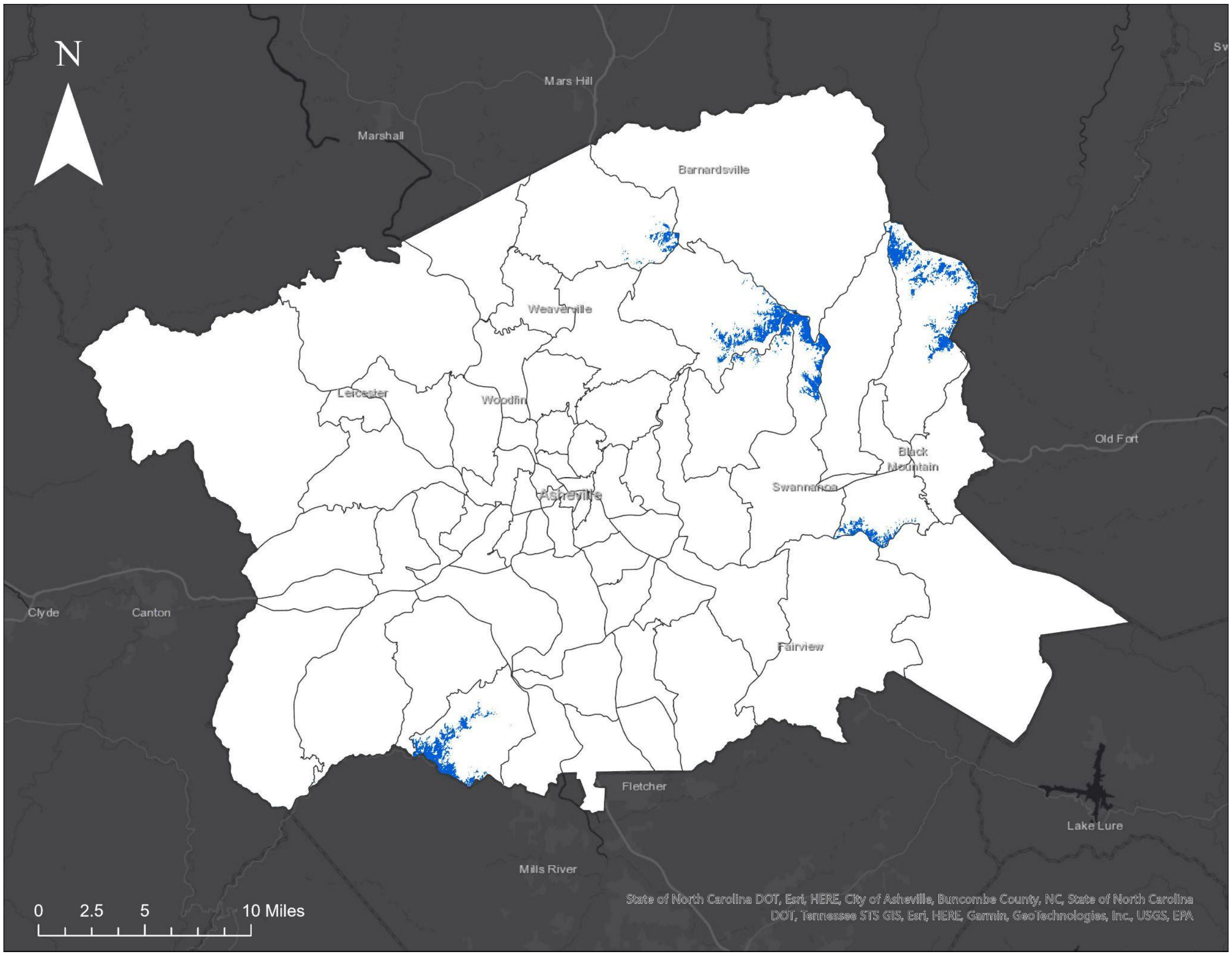

Figure 5. HVI Values Below 0.5 (blue) in Buncombe County, North Carolina.

4. Discussion

4.1 Beneficial Areas for Implementing Green Infrastructure

Through the development of the HVI, multiple locations have been identified to have high heat vulnerability and are in need of measures to protect against high temperatures and heat waves resulting from climate change and the urban heat island effect. The HVI suggests that community initiatives should prioritize tree-planting efforts in areas near South Slope, Downtown Asheville, and other communities within Census Tract 9, as well as areas near Swannanoa and Black Mountain. It also suggests that Census Tract 29 should focus more on tree canopy preservation measures and policy, rather than tree-planting efforts.

The city of Asheville contains the highest heat vulnerability scores in the county. This study found Downtown Asheville and the South Slope Neighborhood to be the most vulnerable areas in the city, with the hottest temperature occurring near the Asheville Mall. These findings are consistent with the Asheville heat-risk study completed by the NASA DEVELOP program (2019), which found the downtown area, South Slope, and the Asheville Airport to be the hottest in the city. It is clear these locations continue to be primary hotspots even when taking into consideration the greater county area. When analyzing the HVI, these areas show a need for more adaptive measures as they face high temperatures, high sensitivity scores, and low vegetation scores. Tree-planting efforts in these areas would provide homeowners and others in the community shaded places to recover from the heat.

In many cities around the United States, neighborhoods with high percentages of people of color have been seen to experience hotter land surface temperatures (Hsu et al., 2021). South Slope is in the most heat-vulnerable census tract in the county (Census Tract 9) and has a population of people of color that is higher than 17.1%—the county's average (U.S. Census Bureau, 2021). Further analysis into the HVI found that this area experiences high chronic illnesses, high income inequality, little vegetation, and high temperatures.

To determine if Buncombe County's land surface temperatures correlate with racial disparity, further steps were taken to analyze the data. First, non-developed areas were removed from the LST to ensure temperature averages would not be influenced by uninhabited forest areas. Second, temperatures were averaged for each census tract. Lastly, census tracts were split into two groups: above and below the county's percentage of people of color. Temperatures in developed areas were found to be 1–2°F hotter in census tracts above the average, with an average temperature of 87.6°F. Developed areas in census tracts with fewer people of color had an average temperature of 86.4°F. This can be compared to the county's average temperature of 86.8°F, showing that there may be a correlation between heat and race experienced in Buncombe County. This is consistent with the findings written by Hsu et al. (2021) that neighborhoods with a high percentage of the Black population experience hotter temperatures. Therefore, it is important to note that South Slope would likely benefit from additional collaborative mitigation efforts due to historic racist practices likely correlating to their high scores.

Another area found at risk is Census Tract 29, which contains Barnardsville. Census Tract 29 is a Medically Underserved Area, has a population with a high percentage of adults above the age of 65 and adults with chronic illnesses, and is seen to have high levels of income inequality. However, few areas in the census tract show high temperatures. Additionally, the census tract is home to some of the highest percentages of forested areas in the county. Therefore, sensitivity is the primary contributor to Census Tract 29's high HVI scores. This demonstrates that additional green infrastructure would be less effective in this area. Instead, communities in and near

Barnardsville should place emphasis on urban tree cover preservation in order to protect high percentages of heat-sensitive populations from being exposed to high temperatures should the areas continue to be developed and thus warmed through the urban heat island effect.

Parts of Swannanoa and Black Mountain are also found to have high heat vulnerability scores. Similarly to Census Tract 9 and the Asheville city center, this area's HVI is composed relatively equally of all three criteria. Due to high temperatures, sensitive populations, and low levels of vegetation, this area would benefit from tree planting initiatives and installation of green infrastructure.

4.2 Limitations

The primary goal of the study was to identify key areas in need of green infrastructure to mitigate the negative effects resulting from rising temperatures in developed areas. However, the study has limitations that may contribute to error in the results.

First, it is important to note that sensitivity variables used in the HVI were on a large scale and do not adequately represent the sensitivity of every neighborhood in the county. Some neighborhoods in need of environmental protections for sensitive populations may be overshadowed by larger, less-sensitive ones within the same census tract. To look at vulnerability on a smaller scale, census blocks or census block groups would be preferred. However, most sensitivity information is not available at a smaller scale to ensure medical privacy for individual residents. While this is important for the privacy of our communities, it makes providing neighborhood-by-neighborhood recommendations on green infrastructure implementation challenging in a time-restrained study.

The second limitation comes from the usage of land surface temperatures. Land surface temperatures are easy to acquire from satellite imagery, which makes them prime candidates for the study of urban heat and UHIs; however, they may not represent what the average civilian actively feels when walking about their city. Air temperature, humidity, and air quality all contribute to the feeling of heat as one goes about their day. These variables often need large-scale movements of volunteers and paid resources to obtain, which makes it inaccessible to most studies. Asheville GreenWorks acknowledges these factors and is currently taking the extra steps to complete a study of air quality and temperature within Asheville City and major areas of Buncombe County such as parts of Candler and Weaverville.

A third limitation of this study was obtaining vegetation information from satellite imagery. Knowing the percentage and type of vegetation in a city provides difficulties in that it requires time, resources, volunteers, and money to provide, which this study did not have access to. To make the HVI more accurate, a county-wide tree survey would be incredibly helpful. This study utilized a NDVI as they are free to create using summertime satellite data accessed online. Asheville GreenWorks intends to work with the county to get a tree survey completed, however results from that will be in the distant future.

5. Conclusion

With temperatures increasing throughout Buncombe County due to urban development and its resulting tree canopy loss, it is important to ensure that there are protections in place for the community's most vulnerable citizens. The urban tree canopy is an essential component of the county's ability to adapt to the rising temperatures and ensure those with chronic health conditions such as heart disease and those who live in marginalized communities have the protection they need to stay safe and healthy during heat waves. This study developed a Heat Vulnerability Index that the public can use to identify where the most vulnerable populations live within Buncombe County. The most vulnerable areas in Buncombe County were Census Tracts 9 and 29, downtown Asheville and the South Slope area, along South Tunnel Road by the Asheville Mall, and in parts of Swannanoa and Black Mountain. By identifying the most vulnerable areas, Asheville GreenWorks and the Asheville City Urban Foresters can target tree-planting campaigns and preservation efforts to protect the citizens from high temperatures known to exacerbate health risks in many individuals.

6. Acknowledgements

This project could only be completed with the funding and support from the McCullough Institute at UNC Asheville through the McCullough Fellowship. I also thank Nicole McNeill from Asheville GreenWorks and Dr. Jackie Langille from the Environmental Studies department at UNC Asheville for the guidance, help, and support to make this research happen. Dr. Catherine King from the Environmental Studies department at UNC Asheville, Greg Dobson and Ian Johnson, and the other McCullough Fellows also deserve thanks for their feedback and encouragement throughout the research process. Lastly, I want to thank Cassandra Normand for her intensive feedback during the revision process.

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