Inside the Urban Melting Pot: Exploring the Effects of Redlining and Greenspace on Heat Distribution in Providence, Rhode Island

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Introduction & Purpose

The “melting pot” was once synonymous with the idealistic concept of a post-racial society in America, centered on cultural acculturation and assimilation. In reality, America has yet to deal with much of its racist past as – for example – anti miscegenation laws existed until 1967 and Black people today continue to experience disproportionate police brutality (Hollinger 2003; Schwartz 2020). While the term “melting pot” has fallen out of vogue, it is perhaps a strikingly accurate description of city life during the summer heat.

The phenomena in which urban areas are considerably hotter than surrounding areas is more commonly known as the urban heat island (Santamouris 2013). Increasingly, assessments of the effect at the micro-climate scale are painting stark pictures of the intra-urban heat distribution that exists (Hoffman et al., 2020; Wilson 2020). Extreme heat is dangerous to an individual’s health as it can cause heat stress, heat cramps and heat stroke, which can even lead to organ failure and death (Kilbourne, 1997).

Research has shown hotter areas within a city are commonly predominantly inhabited by low-income, minority and other disenfranchised populations, who bear a double-edged sword of increased exposure to a hazard and lower adaptive capacity. Adequately addressing exposure to extreme heat is an important aspect of environmental justice.

US President Joe Biden has declared several priorities for his administration, including addressing climate change and racial equity (White House, 2021). These two issues are directly tied to the urban heat island effect as the climate warms and extreme heat events are projected to become more frequent. At the same time, we must demand policy makers recognize the inherent ties between heat, health and equity. Increasingly, attention is being paid to teasing out the effects of racist historical policies and this trend has been facilitated in part by the release of digitized Home Owners’ Loan Corporation redlining maps by the University of Richmond and partners (Nelson et al., 2021).

This project uses average ambient heat index data from an urban heat mapping campaign in Providence, Rhode Island to evaluate the relationship between the HOLC redlining maps, greenspace and exposure to extreme heat. The use of the average ambient heat index data is notable as it was calculated based on measurements of the ambient air temperature and relative humidity. Temperature and the urban heat island are often measured using land surface temperature because it can be easily calculated from satellite images across a large number of areas. The land surface temperature is a proxy and does not represent the actual temperature people in a community experience as ambient air temperature and heat index do. The heat index combines ambient air temperature and humidity (Anderson et al., 2013; National Weather Service, 2021). Because humidity can impede the body’s ability to cool itself, the heat index is a particularly important measure that more accurately captures the days when it is so hot and humid, it feels like you might be melting. While studies have utilized ambient heat index before and studies have evaluated land surface temperature and redlining, I have not seen any studies that utilize ambient air temperature or relative humidity to evaluate the micro-climate temperature effects of redlining policies.

Background & Lit Review

Understanding Extreme Heat, Health Effects & Climate-Driven Concerns

Heat is the leading weather-related cause of death in the US despite the fact that most of these deaths are avoidable with outreach, education and intervention, according to the EPA (2020). When the body is unable to properly cool itself, individuals are at risk for developing heat-related illness, such as heat exhaustion, heat cramps and heat stroke (Kilbourne, 1997). Severe heat stroke leads to organ dysfunction and rapid death, while survivors may have permanent organ damage and increased risk of early mortality (Kilbourne, 1997; Dematte et al., 1998; Dixit et al., 1997; Wallace et al., 2007). Estimates indicate that 600 people in the US die each year of heat-related illness (Sarofim et al., 2016). However, data have shown that extreme heat contributes to substantially more deaths than official death certificates indicate, and this figure is likely an underestimation of the true burden (Medina-Ramón, et al. 2017).

Certain populations are at increased risk. Adults over the age of 65 as well as young children are particularly vulnerable to heat-related illness and death as well as people certain pre-existing conditions like cardiovascular and respiratory illnesses Sarofim et al., 2016; Zanobetti et al., 2012; USGCRP, 2016; Kingsley et al., 2016; Gronlund, 2014). Additionally, studies have shown associations between being a minority, and particularly identifying as Black, as well as low-income and higher risk from extreme heat (Harlan et al., 2006; Mitchell and Chakraborty, 2014; Congressional Black Caucus, 2004).

A regional study of 15 communities in New England, including Providence, Rhode Island, found an association between the maximum daily heat index and rates of emergency department visits and deaths (Wellenius et al., 2017). Importantly, these effects occurred on days where the maximum daily heat index was lower than ≥100°F, the threshold at which the National Weather Service issues a heat advisory in this area (Wellenius et al., 2017). Assuming a causal relationship, the researchers suggest that lowering the threshold to ≥95°F may prevent up to 550 emergency department admissions and 14 deaths per year in the study communities alone (Wellenius et al., 2017). At the state level, researchers found that in Rhode Island an increase in the maximum daily temperature from 75 to 85˚F was associated with a nearly 24% increase in the rate of heat-related emergency department visits between 2005 and 2012 and a 4% increase in all-cause mortality from 1999 to 2011 (Kingsley et al., 2016). This suggests people in Rhode Island are at increased risk of heat-related illness at temperatures as low as 85˚F and that the current population of Rhode Island would experience substantially increased morbidity and mortality if maximum daily temperatures increase – a pattern currently projected as a result of climate change (Kingsley et al., 2016).

Over the last few decades, hot summer temperature anomalies have become more common (Melillo et al., 2014). Extreme heat days are expected to increase in terms of frequency, intensity and duration as a result of climate change, resulting in a projected increase in heat-related mortality (Melillo et al., 2014; Gasparrini et al., 2105). This effect will be compounded in cities which are subject to the urban heat island effect.

The Heat Island Effect & Vulnerability

Many urban areas reach higher temperatures and stay hotter overnight compared to rural or suburban surroundings, a phenomena called the urban heat island (Santamouris, 2013). Heat islands effect increases electricity demand for air conditioning and pollutant emissions (Santamouris, 2013). Several characteristics of urban spaces contribute to the development of a heat island, including street canyons, thermal properties of building materials, anthropogenic heat, loss of green spaces and the urban greenhouse effect (Santamouris, 2013). Specifically, high density of urban infrastructure, including buildings and roads, absorb more incident solar radiation and emit more longwave radiation compared to organic materials, contributing to the increased temperature (Santamouris, 2013). Loss of green space compounds the issue as green space provides a cooling effect through both shade and evapotranspiration (Santamouris, 2013). The magnitude of the urban heat island intensity varies across the US based on regional and local characteristics (Kenward et al., 2014; Kim et al., 2018). Northern cities tend to have higher surface urban heat island than Southern cities, due in part to the contextual biome (Li et al., 2017). Regions with forested biomes have higher surface urban heat islands. (Li et al., 2017).

There are several determinants of heat-related mortality and morbidity, including age, housing characteristics, access to air conditioning, socioeconomic factors and location (Kovats and Hajat, 2007). These determinants support the idea that heat, health and equity are closely – and inextricably – tied. Living within a city, as described earlier, exposes a person to the urban heat island effect, but where they are within the city is also important. As the intensity of the heat island varies spatially within cities, location within a city may result in disproportionate exposure to extreme heat (Wilson, 2020; Hoffman et al., 2020).

Investigating the Persistent Impact of Redlining

Wilson (2020) argues that “the unevenly distributed heat exposure in cities observed today is due in part to past planning and investment decisions that shaped the location and character of urban development and, by extension, the distribution of ecological benefits.” Wilson is referring to the policies of the Home Owners’ Loan Corporation (HOLC), which originated to provide relief for households at risk of foreclosure or who had already lost their home and was later responsible for assessing the level of neighborhood risk for banks making loans (Hillier 2003). Working with real estate agents the HOLC assigned A to D grades to neighborhoods, ranking neighborhoods with less desirable characteristics with lower grades. The results were turned into color coded “residential security” or “mortgage security” maps, categorizing neighborhoods from “Best” (A, outlined in green), “Still Desirable” (B, outlined in blue), “Definitely Declining” (C, outlined in yellow), to “Hazardous” (D, outlined in red). They also directly influenced access to mortgage lending and at least partially influenced neighborhood demographics (Aaronsen et al., 2017; Mitchell and Franco, 2018). According to Hillier (2003), neighborhoods with Americans, as well as those with older housing and poorer households, were consistently given a fourth grade, or ‘hazardous,’ rating and colored red,” which contributed to the colloquial term ‘redlining’.

Several recent studies have explored whether racist historical housing policies and have impacts the spatial distribution of the urban heat island (Hoffman et al., 2020; Wilson, 2020). One study found that areas that were targeted for disinvestment through past housing practices, like redlining, had higher mean land surface temperatures than those that received more favorable ratings (Wilson, 2020). Hoffman et al. (2019) conducted spatial analysis on 108 urban areas in the US and found that in 94% of studied areas there were consistent, city-scale patterns of elevated land surface temperature in formerly redlined areas. In some areas, the difference was as much as 7°C and was 2.6°C warmer on average across the US. Hoffman et al., 2020). Today, poor and minority residents are disproportionately living in these areas in many cities (Wilson, 2020).

Redlining practices have had considerable long-lasting effects that also contribute to adaptive capacity. Because homeownership is a primary means of building wealth, over time redlining and other policies exacerbated the racial wealth (Krivo & Kaufman, 2004). Redlining has been associated with health effects such as late-stage cancer diagnosis and birth outcomes, such as preterm birth, small-forgestational age and perinatal mortality (Krieger et al., 2020; Nardone et al., 2020). Studies have shown that redlining resulted in sustained patterns of disinvestment, concentration of high-speed roadway construction and a paucity of green space in these areas (Rutan & Glass, 2018; Mohl, 20004; Heynen et al., 2006; Nardone et al., 2021). Evidence has also demonstrated an association between lack of green space as well as concentration of impervious surfaces and disadvantaged populations, such as those who are a minority or living in poverty (Jesdale et al., 2013; White-Newsome et al., 2009; Pearsall, 2017). Wilson (2020) argues that trees and vegetation contribute to adaptive capacity and are also an important conceptual linkage between hazard mitigation, urban heat management, and environmental equity.

Despite rising heat and significant vulnerability, regional access to important adaptation strategies like air conditioning are not accessible or affordable to everyone. According to the 2015 Residential Energy Consumption Survey (RECS), 25% of homes in New England do not use air-conditioning equipment compared to 13% nationally (US EIA, 2018a).[1] Among those who do have access to air conditioning equipment, 50% of households in New England use individual air-conditioning units compared to 27% of nationally (USA EIA, 2018). Conversely, only 27% of households have central air-conditioning, compared to 64% of households nationally. (USA EIA, 2018a).

Energy burden, the proportion of gross household income that is spent on energy, and energy security can exacerbate this issue as households that have a high energy burden or are energy insecure and have air conditioning equipment may struggle to afford the energy needed to use it. More than one-third of New England households report any household energy insecurity with 21% reporting they reduce or forego food or medicine to pay energy costs (USA EIA, 2018b). As many as 15% of households have left their home at an unhealthy temperature and 7% reporting being unable to use cooling equipment due to energy insecurity (USA EIA, 2018b). A study found specifically that Providence, RI is one of the five cities with the greatest difference between the city and state energy burden, and among cities with the highest median energy burden (4.7%) (Drehobl & Ross, 2016). In Providence, households who identified as Latino have one of the highest energy burdens in the country (6.3%) (Drehobl & Ross, 2016). Low-income households have a 9.5% energy burden, while low-income families in multifamily households have a 7.1% energy burden (Drehobl & Ross, 2016).

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[1] RECS percentages are crude estimates calculated from the high-level information provided by US EIA.

Methods

Data Sources & Preparation

Heat index data were provided by the Rhode Island Department of Health from the Heat Watch program. To collect the data, Heat Watch volunteers were outfitted with thermal sensors to collect ambient air temperature and humidity data as well as GPS location at one data point per second. Each volunteer was assigned a route to drive throughout East Providence, Providence, Pawtucket and Central Falls with the thermal sensor on their car at 6:00-7:00AM, 3:00-4:00PM, 7:00-8:00PM on July 29, 2020 and 12:00-1:00 AM on July 30, 2020. Program partner CAPA Strategies used the data to interpolate the ambient air temperature and heat index at each time point, provided as a raster file.

Given the role of infrastructure and green space in the development of an urban heat island, the most recent available (2016) data on urban imperviousness and tree canopy were downloaded from the Multi-Resolution Land Characteristics Consortium National Land Cover Database. The urban imperviousness data represents urban impervious surfaces as a percentage of developed surface over every 30-meter pixel in the US, identifying types of roads, core urban areas and energy production sites. The tree canopy data contains percent tree canopy estimates for each pixel and are derived from multi-spectral Landsat imagery and other information by the United States Forest Service (MRLC, 2021). The raster layer disc image files were opened in QGIS, each clipped by the Rhode Island state boundary and saved as GeoTiffs before reading into R using the raster function.

Census tract polygrams for Rhode Island were downloaded from the US Census Bureau using the tigris package in R. Using the extract function from the raster package, average and maximum heat index as well as tree canopy and urban imperviousness zonal statistics were calculated for each census tract at each time period.

As described in the literature, several researchers have established the link between racist historical housing policies and health as well as environmental exposure. Many studies have examined the relationship, specifically between the federal government's Home Owners' Loan Corporation area descriptions, created between 1935 and 1940 (Aaronson et al., 2021). The HOLC assigned residential neighborhoods with grades that indicated their "mortgage security", with "A" as the highest grade, representing the lowest risk for banks, and "D" as the lowest grade and highest risk for banks. The grades were used to create color-coded map and were highly influential in terms of who should receive loans and what areas of a city were deemed safe investments (Aaronson et al., 2021). Shapefiles of the HOLC maps from many US cities, including Providence, Woonsocket and Pawtucket/Central Falls, were digitized and made available by the *Mapping Inequality* project from the University of Richmond's Digital Scholarship Lab and partners (Nelson et al., 2021). The US shapefile was loaded into QGIS. HOLC neighborhoods in other states besides Rhode Island were removed. HOLC neighborhoods were superimposed over current census tracts. Tract-level HOLC-grades were calculated using areal apportionment HOLC polgyons did not line up exactly with census tracts (Nardone et al. 2020; NCRC, 2021). I used the Union function in QGIS join the layers and calculate the percent of overlapping polygons. I then assigned 1-4 weighting for the HOLC-sections, corresponding to grades A-D. The overlapping polygon area was calculated as was the percent it represented of the total census tract area. This data was saved as a Shapefile and read into R, where I calculated area-weighted census tract-level grades through a series of mutations.

To understand the relationship between the environmental exposure, historical housing policies and current social vulnerability, the most recent available data (2018) from the CDC Social Vulnerability Index were downloaded for the state of Rhode Island. Social vulnerability refers to factors, such as poverty, lack of transportation and crowded housing that can impede a community's ability to prepare, respond and adapt to disasters (CDC, 2019). The Social Vulnerability Index uses 15 census variables as a measure of the potential negative effects on communities caused by external stressors (CDC, 2019).

Exploratory Spatial Data Analysis & Statistical Analysis

Exploratory spatial data analysis was conducted to gain a deeper understanding of the heat index distribution within the study area. Based on summary statistics, the afternoon average heat index was selected for further exploration as it had the largest range of average and maximum temperatures.

A Moran's I test was used to evaluate the existence of spatial dependence within the afternoon average heat index data. First, "Max-Min" or maximum-minimum and range weights were developed and tested to identify the optimal weighting for measuring the spatial process. Standardized and lag versions of the afternoon average heat index variable were created. The linear relationship between the standardized and lag variables was overlayed over a smoothed scatterplot of the variables and indicated likely positive spatial autocorrelation. The moran.test function was used to test for spatial autocorrelation using both weights, and the Moran's I value was statistically significant ($p<0.001$) for both. As a result, we reject the null hypothesis that census tract level afternoon average temperature is spatially random. The Max-Min was selected as the Moran's I value was larger (0.12 vs 0.07). The Max-Min weight was used to create new variables for LISA clusters, based on the mean standardized and lag variables and statistical significance of the local Moran's I value.

Then, a fully realized linear regression model, including sociodemographic and environmental variables, was developed to diagnose the source of the spatial dependence. The linear regression model was run iteratively to remove variables with relationships to the afternoon heat index that were not statistically significant. The final model is included below.

lm([average afternoon heat index] ~ [percent poverty] + [census average weighed HOLC grade] + [percent minority] + [percent tree canopy], data=).

The LaGrange Multiplier test for spatial dependence returned no statistically significant results. For the sake of this project, the HOLC grade term was removed from the model. The LaGrange Multiplier test for spatial dependence indicated an error model should be run. None of the robust terms were statistically significant and the lag term was borderline statistically significant. The error term was statistically significant and smaller than the lag term. The error model indicated that spatial autocorrelation was addressed in the model. Results of a geographic weighted regression model are also included below.

Results

Exploratory analysis of Heat Index Distribution

Initial examination of heat index distribution at the census tract level indicated a high likelihood of spatial clustering at all times throughout the day for both average and maximum heat index. The afternoon time period had the largest difference between the hottest and coolest census tracts. Some census tracts in the study had a maximum afternoon heat index that was 13°F hotter than the coolest areas and afternoon average heat index that was 10°F hotter. Afternoon average heat index was used as the independent variable for the remainder of the project.

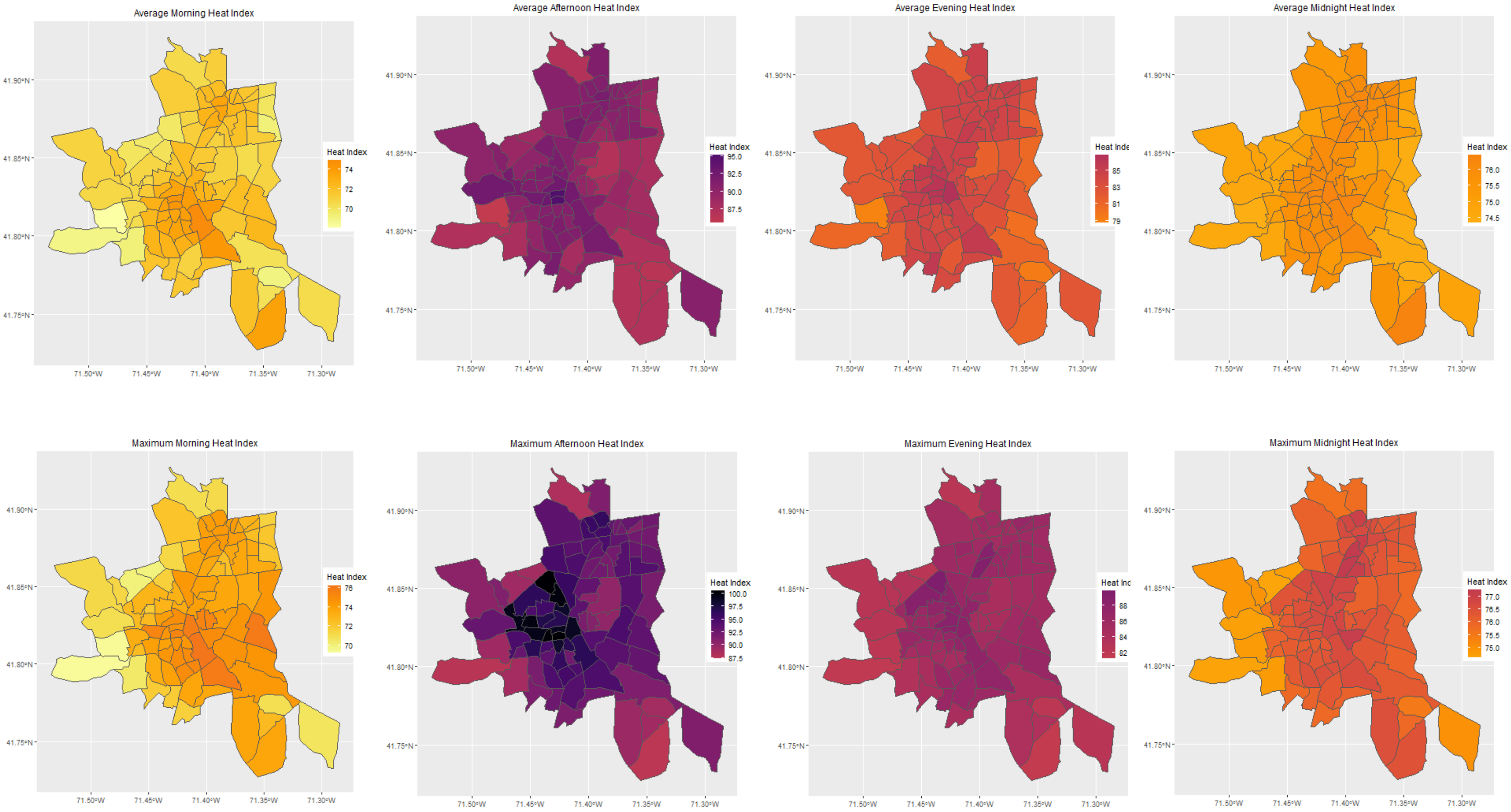


Figure 1. Distribution of average and maximum heat index at 6-7AM, 3-4PM, 7-8PM and 12-1AM (following day). Color for all images is set to the same, continuous scale.

Further analysis of the relationship between a standardized and lag afternoon average heat index variables indicated positive spatial clustering. Statistically significant LISA clusters were identified and approximately 20% of the study area was High-High clusters and 9% of the area was Low-Low, indicating spatial dependence is present.

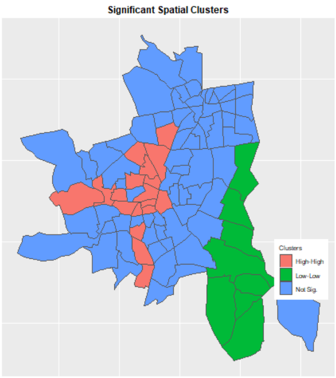


Figure 2. Distribution of High-High and Low-Low LISA clusters, indicating spatial dependence.

Exploratory Analysis of Select Dependent Variables

Visual examination of the distribution of HOLC grades, tree canopy and HOLC grades superimposed on top of an interpolated temperature map indicated similar patterns of spatial clustering, confirming further analysis of the relationships was warranted. Specifically, in the maps it is clear that areas targeted for disinvestment have less tree canopy and higher temperatures. When HOLC grades were calculated to create weighted scores for current census tracts, the mean and median grades were close to a C (2.588 and 2.744, respectively).

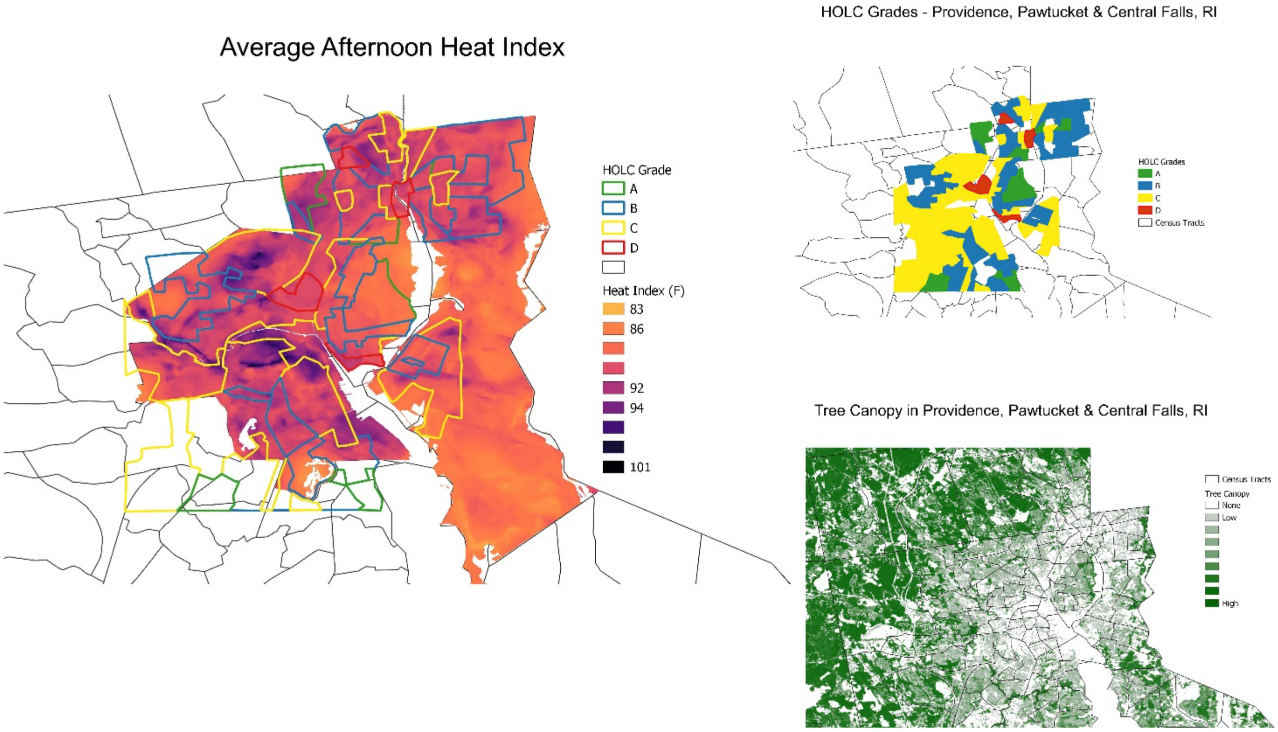


Figure 3. Left: spatial interpolation of average afternoon heat index with HOLC neighborhood grades superimposed on top; Top right: HOLC neighborhood grades in Providence, Pawtucket and Central Falls, Rhode Island, overlaid on top of current census tracts; Top bottom: spatial distribution of percent canopy with current census tracts.

Fully Realized Linear Regression

The fully realized linear regression demonstrated a statistically significant ($p<0.01$) association between increase in percent poverty, poorer HOLC grade and decreased percent tree canopy and higher temperatures, accounting for approximately 69% of the variation. As LaGrange Multiplier spatial dependence results indicated spatial autocorrelation was satisfactorily accounted for, a secondary model was developed to allow for continued analysis. This model contained the same variables with HOLC removed and confirmed a statistically significant ($p<0.01$) association between decrease in tree canopy and increase in afternoon average heat index, accounting 38% of the variation**.** For the second model, LaGrange Multiplier Spatial dependence results indicated a spatial error model should be developed and run to account for spatial autocorrelation, which addressed spatial autocorrelation adequately. Beta coefficients for all models are included in Table 1.

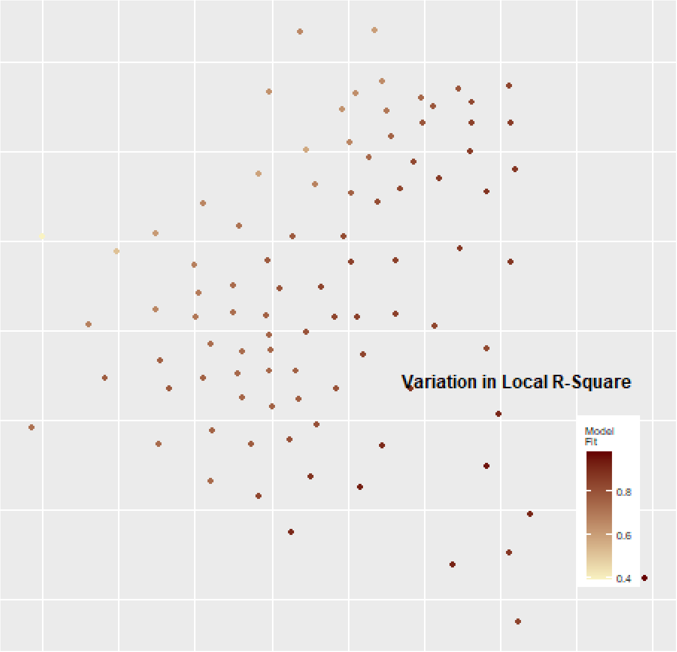
Table 1

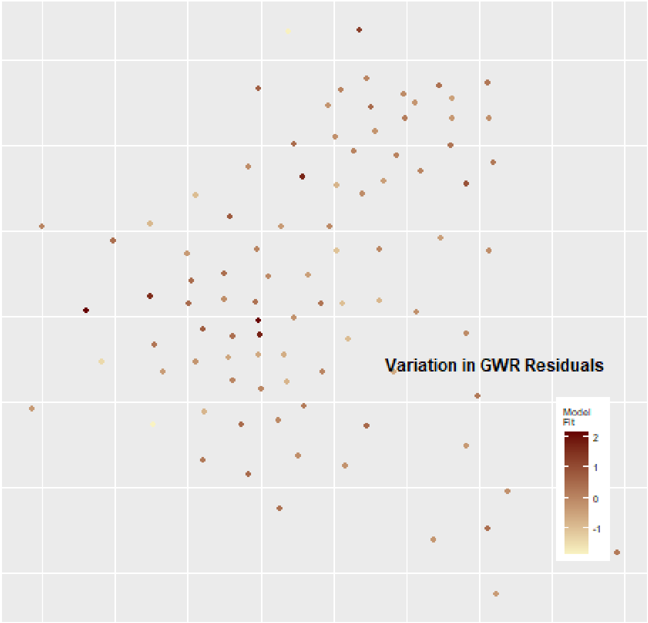
Fully Realized Linear Regression Model Results

Coefficient	Estimate	Standard Error	p-value
First model (R^2: 0.689)			
Intercept	90.004	0.55	$2*10^{-16}$*
Percent Poverty	-0.064	0.016	0.002*
HOLC Grade	0.953	0.0160	0.02*
Percent Minority	0.007	0.006	0.443
Percent Tree Canopy	-0.157	0;046	0.006*
Second Model (R^2: .3942)			
Intercept	90.004	0.55	$2*10^{-16}$*
Percent Poverty	0.026	0.550	.193
Percent Minority	0.012	0.020	.151
Percent Tree Canopy	-0.061	0.017	-001*
Spatial Error Model			
Intercept	90.411	0.614	$2.2*10^{-16}$*
Percent Poverty	0.026	0.0184	0.156
Percent Minority	0.007	0.008	0.408
Percent Tree Canopy	-0.07	0.0164	$2.219*10^{-5}$*
*indicates statistical significance			

Table 1. Fully realized linear regression model results are summarized.

Finally, geographic weighted regression with Gaussian distribution was conducted to understand the spatial distribution of the results. The results indicate slight spatial variation in the model fit, residuals and tree canopy with better fit and more effect in some census tract areas than others. There is little evidence of spatial variation and consistent effect in the poverty variable, which is expected as the variable was not statistically significant in this regression model. There is also little spatial variation in the minority variable.





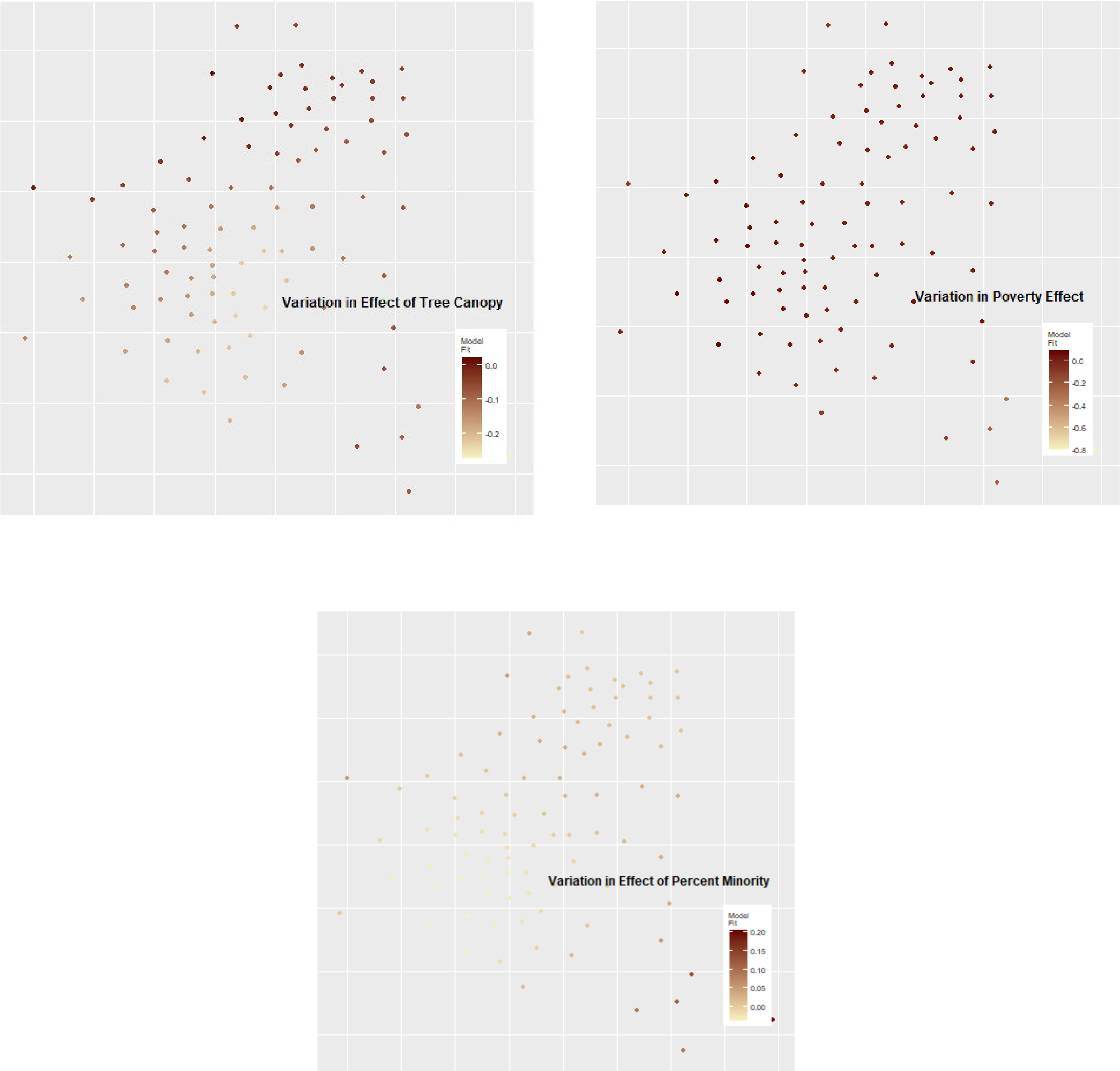


Figure 4. Graphed geographic weighted regression output for local R^2, residuals, percent tree canopy, percent poverty percent minority.

Discussion & Conclusions

These results demonstrate the persistent and harmful impact of reduced tree canopy on average afternoon heat index as well as the lasting effects of structural racism. They add to the growing body of evidence regarding the current effects of racist historical policy, like HOLC grades (Hoffman et al., 2020; Wilson 2020). Specifically, the are aligned with other findings that HOLC grades are associated with built environment characteristics, like tree canopy, and environmental conditions, like temperature or heat index (Hoffman et al., 2020; Jesdale et al. 2013; Nardone et al., 2021).

Calculation of area-weighted HOLC scores may have masked true relationships and a more accurate approach should be considered in the future. Further studies should evaluate heat index and related variables at the HOLC neighborhood level. The correlation between HOLC and SES variables was not evaluated and could explain why an association was not seen between minority status and temperature and why the relationship with poverty was attenuated. More careful and thorough analysis is warranted.

Afternoon average heat index was selected given the wide disparity in exposures. Given the even greater difference in maximum afternoon heat index, this relationship warrants further study. Additionally, given the scope of the project, I was not able to evaluate the differences in overnight temperatures. This relationship should be more fully evaluated and addressed as the overnight period is a critical time that allows the body to recover from the physiological stress if the environment has sufficiently cooled. These findings are rather limited and statistical significance may have been influenced by the relatively small sample size. Further analysis should evaluate wider areas for which interpolated heat index evidence is feasible based on the current data set.

As Kingsley et al., (2016) suggest Rhode Island residents are at risk of health events at a heat index of as low as 85F, these results sound the alarm that urban residents may be subject to regular, unhealthy temperatures without reprieve. They mandate that additional analysis be conducted and call for both structural and individual-level programmatic interventions. One such suggestion is to update the current National Weather Service criteria for issuing heat advisories in this region (Wellenius et al. 2017). These authors argue that lowering the guideline criteria could lead to substantially fewer deaths and emergency department visits in New England, and this is worth exploring at the regional, state and community levels.

These findings also suggest an urban tree canopy program for areas that have been targeted for disinvestment might make a substantial difference in the exposure to extreme heat in these areas. Green space has been associated with a multitude of other benefits and may help address persistent inequities.

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