The Legacy of Redlining and the Disproportionate Exposure to Extreme Heat in Seattle, Washington

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Abstract

The Legacy of Redlining and the Disproportionate Exposure to Extreme Heat in Seattle, Washington

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This paper examines disproportionate exposure to extreme heat in Seattle, Washington, in relation to the historical discriminatory lending practices known as redlining, to explain why such practices contribute to the variation in temperatures across the city. This paper aims to answer the following research questions: 1) are historically redlined census tracts disproportionately exposed to extreme heat compared to non-redlined census tracts in Seattle; 2) what census tracts were historically redlined and today experience higher relative land surface temperatures; 3) how does social vulnerability differ, based on a census tract's historic redlining grade and relative land surface temperature; and 4) what are the focus areas for resourcing against extreme heat?

The effects of redlining continue to disadvantage already marginalized people, both economically and environmentally. Climate change illuminates and exacerbates some of the environmental injustices that occur in historically redlined areas. Extreme heat is becoming an increasingly relevant natural hazard due to climate change. This paper contrasts extreme heat

exposure in historically redlined census tracts to that in non-redlined census tracts in Seattle. This will help inform how, where and to whom heat resilience efforts and resources should be targeted.

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I want to express my gratitude to both my biological and my chosen family for supporting me through this program. Navigating graduate school amidst a global pandemic was not easy, and I could not have done it without their care and support.

I also want to thank Art Lansing and Isaac Anzlovar for supporting a portion of the research used in this paper. Their expertise and skill in ArcGIS Pro were instrumental.

Lastly, I want to acknowledge my identity as a white settler on this land (Duwamish land now known as Seattle). My white ancestry kept my family from experiencing discriminatory practices such as redlining. I hope I was able to do this subject matter justice, but understand that my perception of the gravity of this topic is limited due to my own lived experience.

Chapter 1. INTRODUCTION

Intraurban heat variation disproportionately impacts low-income and communities of color in Seattle (Rights 2021). Research has found a correlation between areas that have been historically redlined and areas that are disproportionately exposed to higher temperatures (Hoffman, Shandas, and Pendleton 2021; Wilson 2020). This correlation is due to systemic disinvestment in historically redlined areas (e.g., more major roadways, less greenspace and vegetation) which then causes increased vulnerabilities to heat waves and other climate change induced disruptions (Hoffman, Shandas, and Pendleton 2021; Wilson 2020). Seattle has recently experienced more heat waves, and scientists expect their frequency and severity to only increase (Washington State Department of Ecology 2021).

Redlining refers to racist and discriminatory housing policies the federal government put in place in the wake of the Great Depression and during the New Deal Era. The Home Owner's Loan Corporation (HOLC) created color coded maps of hundreds of cities across the US to denote where mortgage lending would be "safe" and where it would be "hazardous," primarily based on the racial makeup of that neighborhood. This practice was enforced between the 1920s-1960s, but continues to have long lasting impacts.

A focus on redlining as a precursor to disproportionate heat exposure compels planners to recognize the disparate, systemic and racialized context that this phenomenon presents to communities. This context reveals compounding vulnerabilities to climate change. Most historically redlined neighborhoods are low-to-moderate income today (B. Mitchell et al. 2018), experience more social vulnerabilities (Nelson and Ayers n.d.), have less impervious land cover (Wilson 2020), and poorer air quality (Lane et al. 2022). This lower economic status, higher level

of social vulnerabilities, and lower environmental capacity, compounded by exposure to higher temperatures, poses threats to individual and community resilience in the face of future heat waves and other climate-induced disruptions.

A precursor to redlining is part of the USA's origin story: colonialism and slavery, which are both rooted in racism. Racism allowed white slave owners to enforce "otherness" which justified their "owning" black people and keeping them in extremely poor living conditions. Once slaves became "free" after the 244 (1619-1863) years of its practice, Black Americans continued to be excluded economically and socially. Their living conditions continued to be substantially poorer than their white counterparts. Urban planning policies were weaponized against black people to continue this trend: Black Codes, Jim Crow era segregation laws, restrictive covenants, exclusionary zoning, and of course redlining (King 2022). Redlining "severely limited the economic growth and ability to improve the built and natural environments of many inner-city areas, leading to poor-quality housing and unhealthy environments in addition to concentrated poverty and crime. Although many of these overtly racist housing practices were made illegal by the 1968 Fair Housing Act, their legacy persists in the form of neighborhood decay, devaluation, and disinvestment." (Botchwey, Dannenberg, and Frumkin 2022, pg 145).

Robert Bullard's Environmental Justice framework will be used throughout this research. He writes extensively about how the location where someone lives is the primary predictor of their health and well-being (Bullard 1993). It is people of color who disproportionately reside in areas that result in poor health outcomes, due to multiple systems of oppression (Bullard 1993). Intersectional oppressions lead to increased vulnerabilities in the face of extreme weather events (Bullard 1999), such as heat waves. This framework will be used in this research because it requires researchers to look at the root causes (e.g., racism) of current inequities.

The Environmental Justice framework is imperative to identifying solutions to extreme heat. Holistic solutions are those that mitigate or adapt to extreme heat, and mitigate the root causes of it. By solely addressing extreme heat in a vacuum, cities would be susceptible to harms such as green gentrification. Green gentrification "refers to the adoption of urban green agendas that lead or contribute to the displacement of the most socially marginalized residents despite being sold as providing universal benefits." (Botchwey, Dannenberg, and Frumkin 2022, pg 154).

Local research has been conducted to map temperature variations across King County, WA (King County and City of Seattle 2021). However, the data used in King County's heat mapping project uses temperature data from only one day, which was July 27, 2020 (King County and City of Seattle 2021). To increase reliability, the average temperature from multiple dates should be used. In recent years, there has been more research on the confluence of redlining and intraurban temperature heterogeneity (Hoffman, Shandas, and Pendleton 2021). However, this research is done on a national scale, and there is very little published on how this takes shape in the Seattle context. This research utilizes GIS mapping to identify which census tracts in Seattle are the hottest, experience social vulnerability, and to what extent these census tracts exist in areas that were historically redlined. Temperature data and social vulnerability data need to be used together to identify census tracts that are most vulnerable to future heat waves. With higher rates of social vulnerability, people have less individual capacity to shield themselves from the impacts of extreme heat. To understand the social vulnerability of populations living in these census tracts, the Center for Disease Control and Prevention's (CDC) social vulnerability index will be used. Integrating these two datasets will give researchers and public officials insight into which areas are most vulnerable to future heat waves. Heat waves are becoming an increasingly urgent

phenomenon in this region, making it imperative that local planners and government are aware of the underlying forces that cause vulnerabilities.

Seattle neighborhoods experience varying levels of vulnerability to heat waves, depending on a wide range of factors. The primary factors I examine in this research are census tract' HOLC grade, relative temperature, and social vulnerability index score. Temperature data and social vulnerability data are used to identify the census tracts most vulnerable to future heat waves. When identifying Focus Areas (areas I recommend investing in to build heat resilience), HOLC grade is also used as a factor. Redlining is important to consider, because its legacy has had profound and lasting impacts on marginalized communities and the built environment. It is not ethical for communities who already experience the disadvantages of historic racist lending practices to then bear a compounding and disproportionate impact to climate change. This is especially unjust when people of lower incomes contribute the least to climate change (Hubacek et al. 2017).

The purpose of this research is to understand where the highest level of vulnerability to extreme heat is in Seattle, and if historic redlining practices contribute to this vulnerability. It is important to understand the root causes of current day challenges to better devise solutions. This research will contribute to the body of knowledge related to the intersection of redlining and intraurban heat variation, as well as provide insight into where attention and resources should be invested to build heat resilience before future heat waves. I explore this topic by spatially analyzing historic HOLC grades on current maximum summertime temperatures and a current social vulnerability index. Using a quantitative approach through a GIS analysis, this thesis aims to answer the following research questions:

- Are historically redlined census tracts disproportionately exposed to extreme heat compared to non-redlined census tracts in Seattle?

- What census tracts were historically redlined and today experience higher relative land surface temperatures?
- How does social vulnerability differ, based on a census tract's historic HOLC grade and relative land surface temperature?
- What are the focus areas for resourcing against extreme heat?

1.1 METHODS

I conducted an analysis using ArcGIS Pro to determine if there is a correlation between HOLC grade, temperature and social vulnerability. This was conducted for the study area of Seattle, and at the 2010 census tract scale. Zonal statistics were used to determine the maximum summertime temperature and average redlining score for each census tract in Seattle. To determine the relationship between maximum temperature and average redlining grade, a Pearson-Linear Correlation test was used. This gives insight into whether a relationship exists, and if so, what the strength of that relationship is. These census tracts are compared to the social vulnerability index, which is already at the census tract scale. This provides information on the level of vulnerability a census tract has in face of an extreme heat event. Areas that experience a low HOLC grade, higher relative temperatures, and a higher social vulnerability score will be identified as "Focus Areas" that are recommended to be prioritized in investing in holistic, community-driven solutions to mitigate and adapt to extreme heat and the root causes that lead to it.

1.2 OUTLINE OF THESIS

This thesis is divided into six chapters: introduction, literature review, methods, results, discussion and conclusion. The following briefly describes the content of each chapter:

Chapter 2 consists of a literature review on heat and redlining. This includes a description of the Environmental Justice framework that is used throughout this research. Climate change is briefly described with consideration of how it contributes to extreme heat. Extreme heat has a disproportionate impact on certain communities, and here it is described what those communities are according to the literature. The historical context of and meaning of redlining is explained. The meaning of intraurban heat variation and the urban heat island effect is explained, as is how the built environment can contribute to this phenomenon. The public health connotations and impacts from extreme heat are described here. I conclude this section explaining what the literature suggests the field of planning should do to adapt to and/or mitigate extreme heat.

Chapter 3 describes the methods of the thesis analysis. This chapter explains how the data was gathered and what the data represents. I explain how the analysis tools within ArcGIS were used and why I used them to answer the specified research questions.

In Chapter 4 I present the findings of the ArcGIS analysis. Maps that were created through this analysis are displayed and described in this chapter, as well as the identification of focus areas.

The aforementioned results are discussed in Chapter 5. This chapter will explore possible reasons for these results and other contributing variables.

Finally, Chapter 6 will conclude the thesis. This chapter will explain the limitations of this research. Policy implications are described here: policies that are already in use, and future policy suggestions based on the findings of this research.

Chapter 2. LITERATURE REVIEW

The purpose of this literature review is to understand the existing research on extreme heat and the factors that contribute to the disproportionate exposure to it. The primary contributing factors to disproportionate heat exposure that I examine through this literature review are racism, redlining and systemic disinvestment, social and biological factors, elements in the built environment that create and retain heat, and climate change. The interconnection of the aforementioned factors is illustrated in Figure 2.1. This literature review includes how redlining could be a contributing factor to intraurban heat heterogeneity, which results in a disproportionate exposure to extreme heat. I also discuss how the fields of public health and urban planning assess the health impacts of extreme heat, and strategize on building heat resilience.

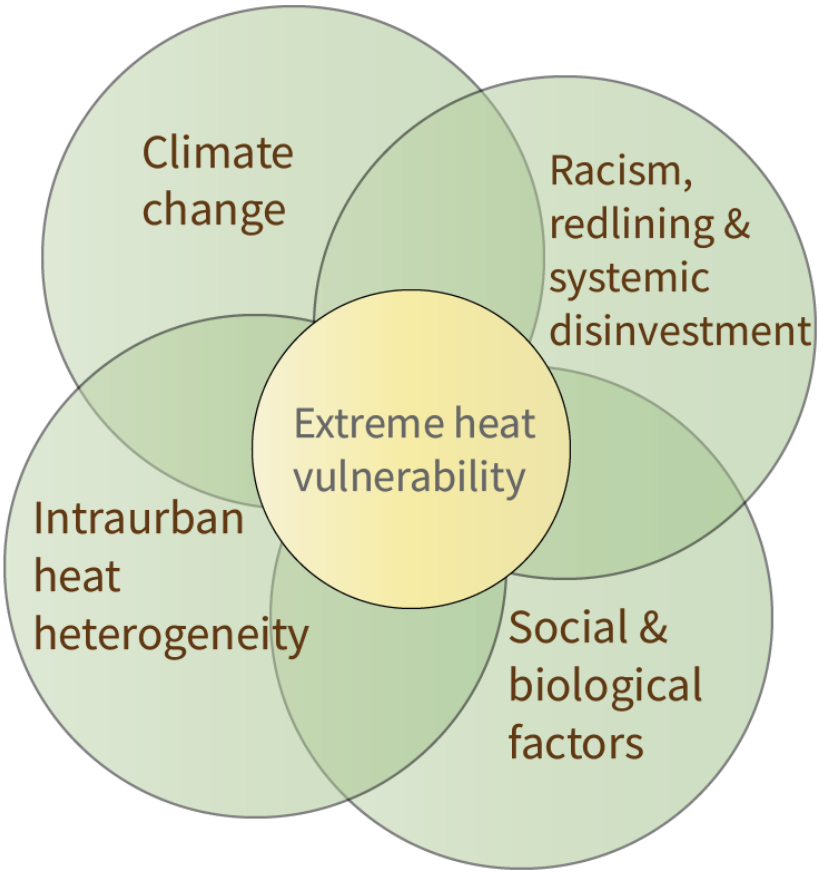

Figure 2.1: Literature map

2.1 Environmental Justice Framework

Bullard (1999) explains, using empirical evidence, that people of color and low-income communities experience more environmental and health threats in their neighborhoods, workplaces and playgrounds than their white counterparts. Botchwey et al (2022) explains that a person's "zip code is a bigger determinant of someone's health than their genetic code." This aligns with how people of color and low-income people are disproportionately exposed to higher temperatures based on where they live (Wilson 2020; Hoffman, Shandas, and Pendleton 2021). The HEAL Act established a definition of environmental justice for the State of Washington: "Environmental justice means the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development,

implementation, and enforcement of environmental laws, rules, and policies. Environmental justice includes addressing disproportionate environmental health impacts in all laws, rules, and policies with environmental impacts by prioritizing vulnerable populations and overburdened communities, the equitable distribution of resources and benefits, and eliminating harm." ("Environmental Justice | DOH" n.d.). This framework allows consideration of the existence and importance of root causes to current challenges. Using the environmental justice framework, this disproportionate exposure to heat should be remedied alongside the work to address the root causes that led to this issue. As the diagram below illustrates, racism is a root cause of disproportionate heat exposure.

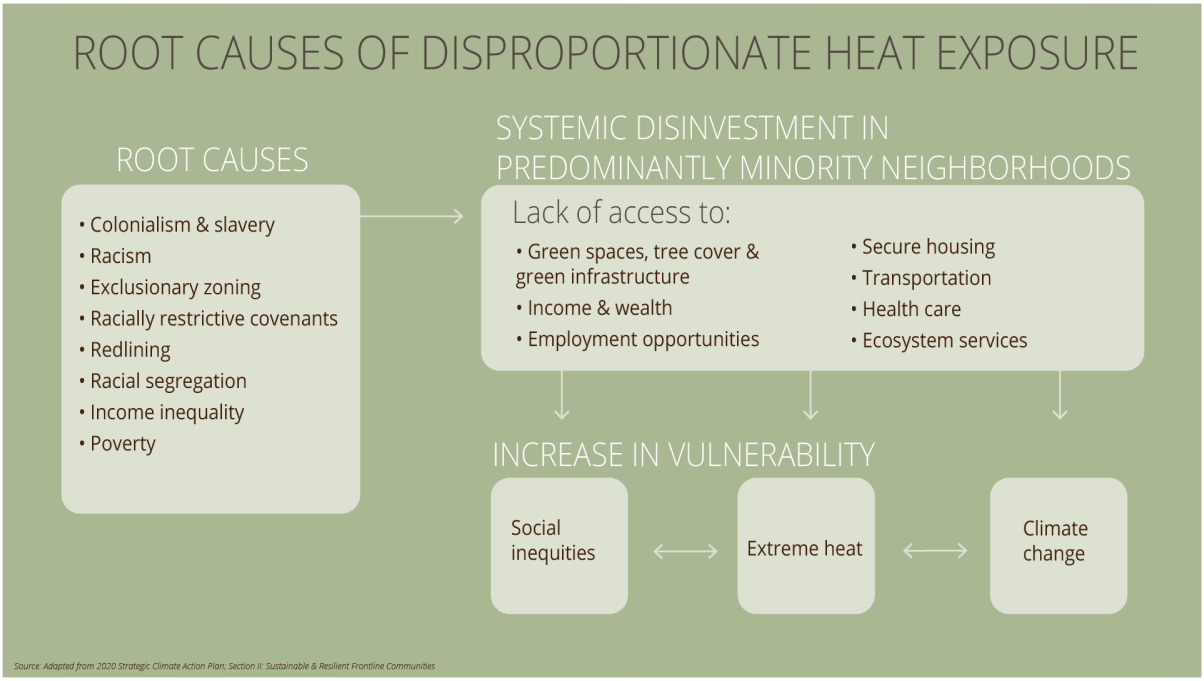

Figure 2.2: Root causes of disproportionate heat exposure

2.2 Racism, Redlining, and Systemic Disinvestment

Redlining refers to the practice of barring people from receiving home loans or insurance based on their neighborhood's racial composition. Mitchell, et al (2018) describes how the Home Owners Loan Corporation (HOLC) created maps for lenders to use to determine lending "risk" or

"mortgage security." This discriminatory practice blocked many people of color in Seattle and across the US from obtaining homes and building intergenerational wealth through homeownership equity.

These maps divided land into four categories, as shown in Figure 2.3 below. They were ranked from A "Best" to D "Hazardous." Hillier (2005) quotes the Federal Home Loan Bank Board's (FHLBB) appraisal manual in their descriptions of the four redlined grades:

- **Grade A** *(colored green and deemed "best"):* "Hot spots" and "homogenous" and in demand during "good times or bad."
- **Grade B** *(colored blue and deemed "still desirable"):* "They are like a 1935 automobile – still good, but not what the people are buying today who can afford a new one."
- **Grade C** *(colored yellow and deemed "definitely declining"):* "Expiring restrictions or lack of them" and "infiltration of a lower grade population." These areas contained poorly maintained homes and tended to lack racial homogeneity.
- **Grade D** *(colored red and deemed "hazardous"):* These areas "represent those neighborhoods in which the things that are now taking place in the C neighborhoods, have already happened." Housing conditions were poor and had "detrimental influences in a pronounced degree." There was an "undesirable population or an infiltration of it."

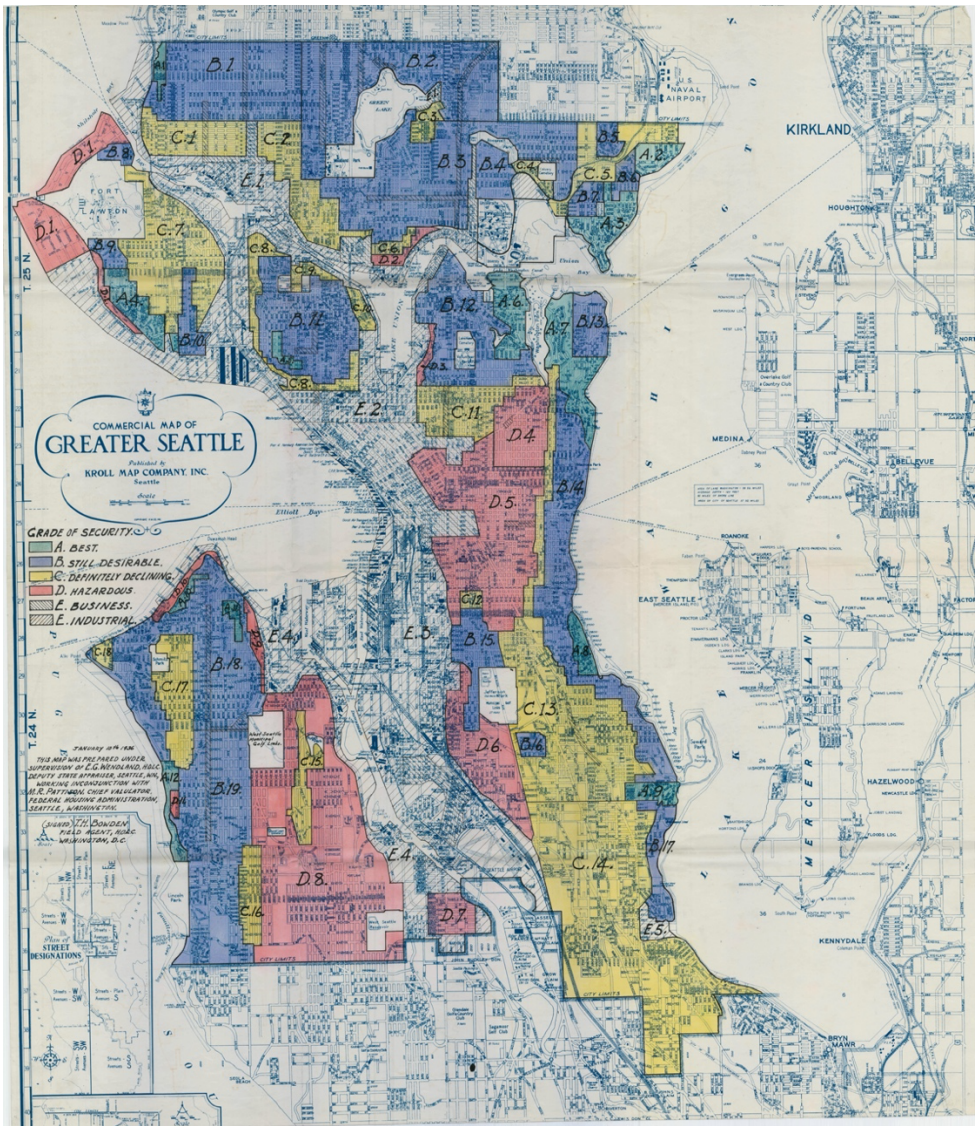

Figure 2.3: Seattle's 1937 redline map ("Mapping Inequality" n.d.)

While the use of these maps to determine lending risk legally ended in 1968, the impacts persist through the built environment, and in the communities that were excluded from generations of wealth building. Currently, 71% of neighborhoods across the country that were redlined are low-to-moderate income (LMI) today; and 64% are minority neighborhoods (Gutschow et al. 2021). There is greater economic inequality in cities that follow the pattern of historically redlined neighborhoods consisting of minority and LMI residents (B. Mitchell et al. 2018). This reveals that structural racism did what it was intended to do: use segregation as a tool to sustain white

economic superiority. The graph below compares the differences between White and Black Americans wealth building during the years redlining policies were in place.

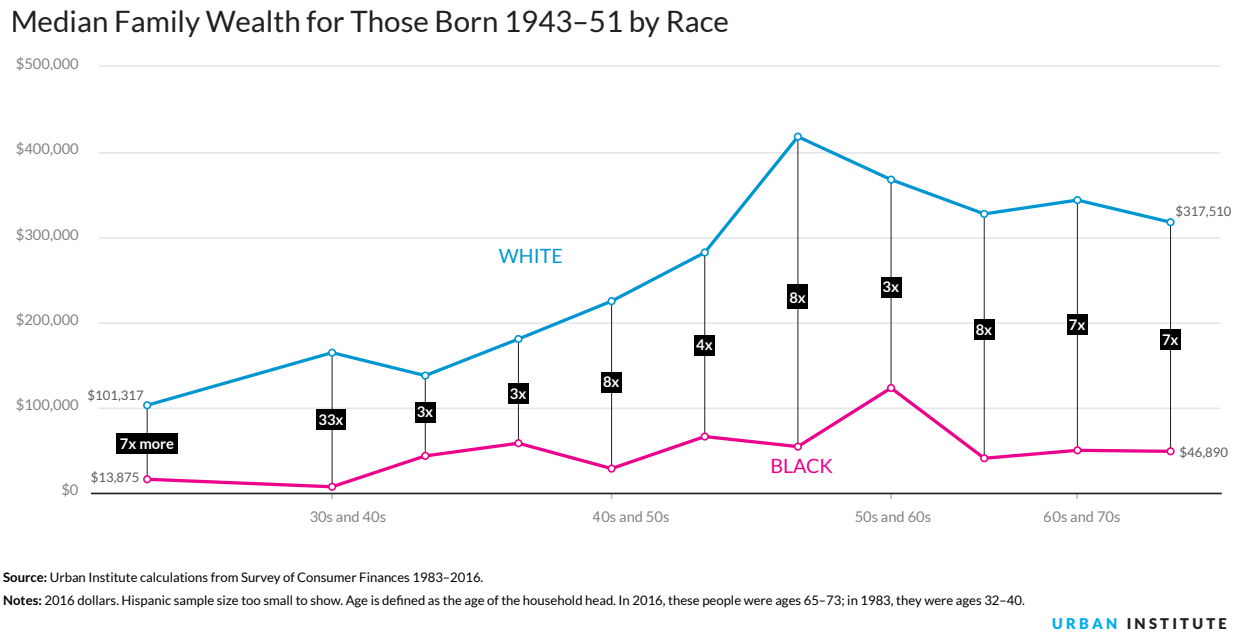

Figure 2.4: Median family wealth by race ("Nine Charts about Wealth Inequality in America (Updated)" n.d.)

Rothstein (2018) explains how the government promoted racial segregation (de jure segregation). The Fair Housing Act of 1968 put an end to legal housing discrimination, but it did not invest in the reversal of the damage that over 30 years of housing discrimination caused. Homeownership is a primary method of wealth building that African Americans were left out of for decades. White families built equity during this time, whereas black families couldn't and today have lower levels of intergenerational wealth and lower rates of homeownership. Additionally, racial housing segregation led to less educational or employment opportunities.

Gentrification has led to decreased racial segregation in some historically redlined neighborhoods. Seattle is among the top cities that experienced gentrification in these neighborhoods (B. Mitchell et al. 2018). Fogel (2020) states that "gentrification is often the

outcome of decades of segregation, redlining, and urban renewal policies that exploit the large gap between existing and potential property values, which in turn encourages an influx of wealthier residents. Young professionals and more affluent people move back into the urban core, often into neighborhoods that have historically been home to people of color; this new wealth quickly changes the look and feel of the neighborhood, increases the cost of living, and displaces the original residents."

Historic redlining practices have caused segregation and systemic disinvestment in many historically redlined neighborhoods across the USA (Wilson 2020; Lewis 2021). This decreases access to greenspaces and parks that limit an area's vulnerability to extreme heat (Wilson 2020). Nardone, who conducted research on historically redlined areas experiencing poorer health outcomes today, explains that it comes down to how systemic disinvestment impacts the built environment: "In many of the historically redlined areas, the land was more often covered by impervious surfaces like asphalt and sidewalks, and the neighborhoods had a dearth of parks and trees." (Lewis 2021). When a neighborhood consists of low-income people as well as low canopy coverage, the adaptive capacity to extreme heat is lower because of economic barriers to cooling devices (A/C units) and ecological cooling barriers (low tree canopy) (Wilson 2020). Wesley et al. state that "redlining contributed to the geospatial isolation of and disinvestment in BIPOC communities" (Wesley et al. 2021).

Lane et al (2022) studied how redlining relates to intraurban air pollution disparities in 202 U.S. cities and found that areas that were historically redlined experience greater levels of air pollution today, compared to non-redlined areas. The two primary pollutants examined were nitrogen dioxide and PM 2.5. Nitrogen dioxide is associated with vehicle exhaust and industrial facilities. When describing this study, Zhong and Popovich explain that "…this is because some

areas graded “C” or “D” in the 1930s already hosted heavy industry and other sources of pollution. Over time, a lack of investment in these neighborhoods also made them attractive for new polluting projects, like interstate highways, that required cheap land” (2022).

Hoffman et al (2021) studied the relationship between redlining and anomalies in summertime intraurban land surface temperatures in 108 US cities, including Seattle. They found that 94% of their study areas showed consistent patterns of increased land surface temperatures in historically redlined areas, compared to more “desirable” neighborhoods. This study shows that historic redlining practices could be a primary cause for disproportionate exposure to heat in urban areas.

2.3 Communities Disproportionately Impacted by Extreme Heat

Extreme heat was identified by the 2018 National Climate Assessment as one of the most serious human health threats in urban areas (Wilson 2020). Each year, roughly 600 people die from extreme heat in the US, which is more deaths than from flooding and hurricanes combined (Wilson 2020; Hsu et al. 2021). Low-income and marginalized communities have been, and continue to be, the most affected by extreme heat (Wilson 2020).

Extreme heat is most likely to cause mortality and morbidity on the elderly, racial minorities, low-income groups and people with chronic illness (Wilson 2020). New research reveals that children and adolescents are also vulnerable to heat (Choi-Schagrin 2022). Children are more susceptible to extreme heat because, “compared to adults, children breath greater volumes of air and have immature immune systems, on-going brain and lung development, and higher metabolic rates” (Botchwey, Dannenberg, and Frumkin 2022, pp 260). In addition to these social factors, factors such as living alone, fear of crime, and linguistic isolation are also major contributors to heat vulnerability (Wilson 2020).

Voelkel et al studied vulnerability on the neighborhood scale, and found that neighborhoods with higher rates of racial diversity, extreme poverty and lower levels of formal education were more likely to be exposed to extreme heat (Voelkel et al. 2018).

Hsu et al (2021) found that in 169 of 175 studied cities, the average person of color resides in a census tract with a greater intensity of surface heat than non-Hispanic whites. This pattern persisted when they compared people below the poverty line to people over two times the poverty line.

2.4 The Urban Heat Island Effect and Intraurban Heat Variation

Urban areas tend to have higher ambient temperatures than suburban or rural areas in the same region for a number of reasons. A primary reason for this is that there is a higher concentration of built surfaces and less natural spaces with high vegetation. The UHI effect is widely studied and documented in over 400 cities across the globe (Santamouris 2020). Primary factors that cause/contribute to the UHI effect are described in the table below.

Table 2.1: UHI causes (Oke et al. 1991)

Primary causes of the Urban Heat Island effect	**Description of cause**
Canyon radiative geometry	"Decreased long-wave radiation loss from within street canyons due to the complex exchange between buildings and the screening of the skyline"
Thermal properties of materials used in cities	"Increased storage of sensible heat in the fabric of the city"

Release of anthropogenic heat	Heat released from human activities and the combustion of fuels (e.g., vehicle exhaust, industrial plants, HVAC systems, human metabolism) within street canyons
The urban "greenhouse" effect	"Increased incoming long-wave radiation from the polluted and warmer urban atmosphere"
Evapotranspiration	A biochemical process of plants releasing water vapor as they photosynthesize. Water vapor reduces heat. Areas that lack vegetation, lack the cooling effect of evapotranspiration

Temperatures can vary greatly within a singular city, which is a phenomenon that is referred to in this research as intraurban heat heterogeneity, variance, or difference. This temperature difference can vary up to 10 °C within a single city (Hoffman, Shandas, and Pendleton 2021). The Urban Heat Island Effect is a term that mainly refers to the temperature difference between cities and suburban or rural areas. This research focuses on the temperature variation *within* the city of Seattle. However, much of the research that went into the causes of UHI effect can be applied to answer questions around intraurban heat variation.

A primary indicator for land surface temperatures is total impervious surface area (ISA). According to the 2016 Seattle Tree Canopy Assessment, higher concentrations of inland tree canopies clearly help reduce surface temperature (O'Neil-Dunne 2016). Neighborhoods with a high concentration of concrete will likely be hotter than neighborhoods with more greenspace, canopy coverage and bodies of water (Hoffman, Shandas, and Pendleton 2021).

More research is emerging to prove that low-resource residents and communities of color are the primary inhabitants of many of the hottest urban areas in the US (Hoffman, Shandas, and Pendleton 2021). Who makes up these urban areas is important for many reasons, including that during heat waves the mortality rate in these areas is higher (Tan et al. 2010). Due to this same phenomenon, people living in urban areas are more susceptible to death during heat waves than rural or suburban residents.

The research on the UHI effect has historically been centered around what causes it and the magnitude it presents. More recently, researchers have pivoted to focus on heat waves and how the UHI effect is associated with them (Santamouris 2020).

2.5 Climate Change

The Earth's temperature has increased by 0.08°C per decade since 1880 (U.S. Global Change Research Program et al. 2017). This warming has sped up to 0.18°C per decade since 1981 (U.S. Global Change Research Program et al. 2017). Locally, it is estimated that average annual temperatures will increase by 1.5-5.2°F by the 2040s (Simmons et al. 2013). It is projected that summertime temperatures could increase up to 7.9°F by the 2040s (Simmons et al. 2013). These numbers are projected to almost double by the year 2100 (Simmons et al. 2013). According to Seattle's Climate Action Plan, "the frequency and duration of extreme heat events (days over 92°F) is projected to increase." Each UHI responds differently to each increase in degree due to geographical variations and the urban form (Moore 2017). According to the Pacific Northwest Climate Projection Tool, pictured below, warming is projected for all ten of their scenarios, with the greatest warming occurring during the summer months (Rogers and Mauger 2021).

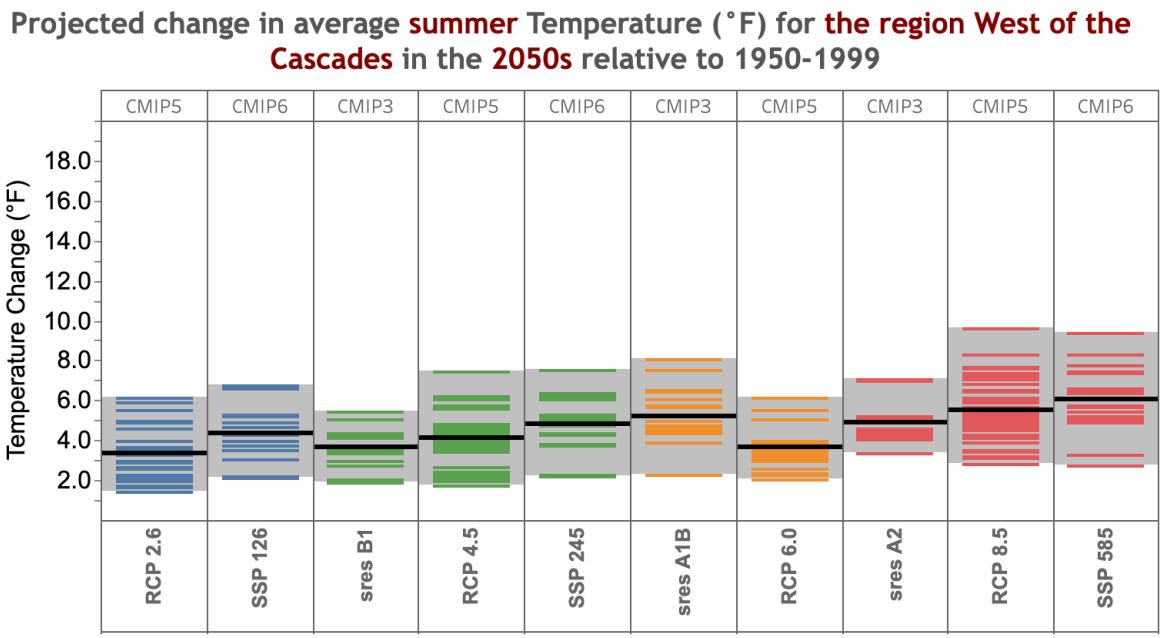

Figure 2.5: Pacific Northwest climate projection tool, (Rogers and Mauger 2021)

Climate change and the UHI effect has a somewhat interdependent relationship. A warming climate increases conditions for UHIs, and UHIs require energy that can contribute to climate change. Urban overheating causes a major increase in energy consumption (for cooling purposes) during a time where electricity demand is already at a peak (Santamouris 2020). Santamouris explains that for each degree of temperature increase, the corresponding increase of the peak electricity load varies between 0.45% and 4.6% (Santamouris 2020). The majority of assessments expect that future energy needs for cooling will far surpass the corresponding heating demand during the next 30-40 years (Santamouris 2020). Urban overheating also increases the concentration of harmful pollutants (Santamouris 2020).

High temperatures increase the rate of formation of ground-level ozone (Boswell, Greve, and Seale 2019). Ground-level ozone is deemed a “criteria air pollutant” under the Clean Air Act because it is among six common air pollutants found across the US that can be harmful to health and the environment (US EPA 2014). In order for ozone to be produced, a chemical reaction

needs to occur between nitrogen oxides, volatile organic compounds, and sunlight (Boswell, Greve, and Seale 2019). Nitrogen oxides and volatile organic compounds are created when "pollutants emitted by cars, power plants, industrial boilers, refineries, chemical plants and other sources chemically react in the presence of sunlight" (US EPA 2015). UHIs increase the concentration of ozone because it is formed in higher temperatures. Ozone is most susceptible to reaching harmful levels on "hot sunny days in urban environments" (US EPA 2015). Ozone is a public health issue, as well as an environmental issue because it is associated with a broad range of respiratory illness, and impacts vegetation and ecosystems.

2.6 Public Health

Extreme heat is a major issue within public health, and more specifically, within environmental health. Environmental health is a subfield of public health, and refers to the relationship between the health of people and their environment. Healthy environments promote healthy people. While traditionally this category of public health focused on issues such as sanitation, clean water, food safety, etc., now it very much addresses issues including climate change and the built environment. The most current version of "Healthy People 2030" includes an objective to "reduce diseases and deaths related to heat" within their environmental health section ("Reduce Diseases and Deaths Related to Heat — EH-D02 - Healthy People 2030 | Health.Gov" n.d.).

The increase in heat related mortality and morbidity is extremely alarming for people worldwide. Extreme heat has caused more fatalities than any other type of hazardous weather event (Wong, Paddon, and Jimenez 2013). Between 2000-2007, nearly 59,114 people died during 52 extreme heat events around the world (Santamouris 2020). Overheating in cities combined with increased levels of pollution contributes significantly to the rising number of heat-related deaths (Santamouris 2020).

The capacity for the human body to cool itself becomes more challenging during rising temperatures. Heart disease is a primary cause of death in the US, and people who have this condition are more vulnerable during a heat wave because high temperatures require the heart to beat faster in order to cool the body (Wilson 2020). Heat exhaustion, hyperthermia, heat stroke and the worsening of chronic conditions are other results from not being able to adequately regulate one's internal temperature due to extreme heat (Shindell et al. 2020). Heat exposure can lead to heat stroke, dehydration, loss of labor productivity and decreased learning (Hsu et al. 2021).

Air pollution is already a problem in urban areas, and the UHI effect can lead to increased air pollution, which has a compounding effect on people living with this phenomena (Wilson 2020). Ground-level ozone, which is an urban heat island "effect", is associated with a broad array of respiratory illnesses. People who have asthma are at higher risk of harm from breathing in ozone (US EPA 2015).

The CDC describes the social determinants of health as "the conditions in places where people are born, live, learn, work, play, worship, and age that affect a wide range of health risks and outcomes." ("Social Determinants of Health" 2021). The below figure illustrates the five key areas that determine someone's health: neighborhood and the built environment, social and community context, economic stability, education access and quality, healthcare access and quality.

Figure 2.6: Social determinants of health ("Social Determinants of Health, Health Equity, and Vision Loss | Subsection Title | Section Title | Site Title" 2021)

Extreme heat exposure touches almost every category within the social determinants of health. A person's neighborhood and built environment is a key determinant in their level of heat exposure, due to intraurban heat variation and the UHI effect. A person's social and community context plays a large role in their vulnerability to extreme heat events because people who live alone or who don't leave the house most days are almost twice as likely to die from extreme heat events (Klinenberg 2015, pp 46). Klinenberg found that people who had increased social contact (even just owning a pet or membership to a social club) was associated with a decreased risk of death in the 1995 Chicago heat wave (Klinenberg 2015, pp 46). This is something that public health professionals and planners need to pay close attention to because there is a major increase

in the number of people living alone worldwide (Klinenberg 2015, pp 43). A person's economic stability is another key determinant in someone's vulnerability to extreme heat. People of lower-incomes are less likely to own an air conditioner, which is the primary measure someone can take on the individual scale to protect themselves from extreme heat (Klinenberg 2015). Lower-income people are also more likely to live in areas that have relatively higher temperatures (Klinenberg 2015). They may also disproportionately experience pre-existing conditions that are worsened by extreme heat (Klinenberg 2015).

ChangeLab Solutions "identified five fundamental drivers of health inequity: 1) structural discrimination, 2) income inequality and poverty, 3) disparities in opportunity, 4) disparities in political power, and 5) governance that limits meaningful participation." (Wesley et al. 2021). Redlining is a critical factor in health equity because it touches all five of the drivers of health inequity.

2.7 Urban Planning

The field of planning has identified heatwaves as natural hazards, and this field aims to mitigate and recover from natural hazards. With increased knowledge around climate change, the planning response to extreme heat has evolved. Rather than consolidating heat with all other natural hazards, a conceptual model, known as "urban heat management" has emerged (Wilson 2020). This concept includes a continuous governmental effort aimed at lessening the severity and duration of heat exposure, both during and outside of times of extreme heat (Wilson 2020).

Boswell, et al. defines climate action planning as "a strategic planning process for developing policies and programs for reducing (or mitigating) a community's GHG emissions and adapting to the impacts of climate change" (Boswell, Greve, and Seale 2019). Climate adaptation refers to the strategies people employ to build resilience in the face of the impacts of

climate change. Climate mitigation refers to the strategies used to reduce the amount of greenhouse gas (GHG) emissions into the atmosphere. Extreme heat events are an impact of climate change that will require both adaptation and mitigation efforts. Below is a diagram of adaptation and mitigation strategies relevant to extreme heat.

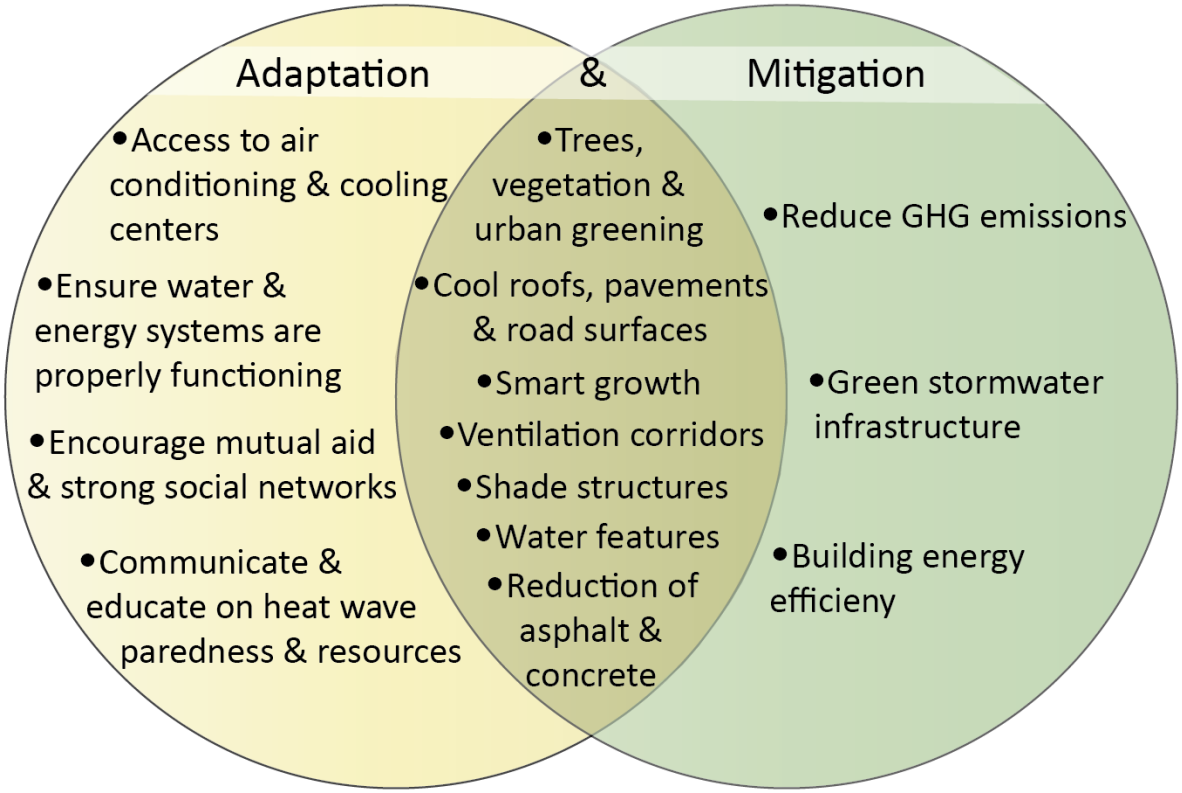

Figure 2.7: Adaptation and mitigation for extreme heat

An example of a planning strategy to reduce asphalt and concrete employed by the City of Minneapolis was to no longer require developers to accommodate parking requirements (Ladd and Meerow 2022). This allowed increased investment in infrastructure for non-motorized transport and reduced the amount of land surface covered in asphalt or concrete. Asphalt and concrete have high heat absorption capacities, and are one of the biggest contributors to the UHI effect (Ladd and Meerow 2022).

Boswell et al. explains that a guiding principle for adaptation is “maximizing mutual benefits” (Boswell, Greve, and Seale 2019). While increasing access to A/C units is an adaptation measure, it also releases GHG which in turn contributes to UHIs. Planting more trees, for example, has the co-benefit of sequestering carbon *and* alleviating impacts of extreme heat.

The UN Populations Reference Bureau expects about 68% (an increase from today’s 55%) of the world's population will be living in urban areas by the year 2050 (United Nations 2018). To accommodate this level of growth in cities, while remediating disproportionate heat exposure already faced within cities, multipronged work needs to be happening. Urban planners and local governments have a responsibility to drive this work. According to Botchwey et al., "government has a key role in ensuring healthy conditions, including a healthy built environment" and "eliminating socioeconomic inequities is fundamental to achieving public health" (Botchwey, Dannenberg, and Frumkin 2022). We need a healthy built environment to address today's public health issues, including heat. Due to systemic inequities, interventions from the government and other entities (as opposed to the responsibility falling on the individual) need to occur to increase the health of people via our built environments.

An environmental risk analysis, which can be applied to heat waves, typically includes the following components: hazard (spatial distribution of where extreme heat occurs), exposure (spatial distribution of where people intersect with the hazard), and vulnerability (extent of potential suffering when exposed to hazard) (Hsu et al. 2021).

Cities can employ a number of strategies (i.e., “smart surfaces”) to reduce urban heat. These tactics include the use of reflective roofs, green roofs, porous pavements, solar PV, trees, and combined solutions (Martin 2021). Reflective roofs can slow global warming by reflecting heat and light (Martin 2021). Green roofs reduce building energy consumption, provide shade,

and contribute to cleaner air and water (Martin 2021). Porous pavements allow rain to be absorbed into the ground and help replenish groundwater sources. They also reduce pollution, stormwater runoff and flood risk (Martin 2021). Solar PV converts sunshine into electricity, which is a sustainable source of energy. They also provide shade for buildings and sidewalks (Martin 2021). Trees reduce urban temperatures by providing shade. They also sequester carbon, clean the air, and mitigate flooding risk (Martin 2021). Combined solutions refer to using any of the above strategies in concert with others. For example, adding solar PV onto green roofs can manage the elements while reducing non-sustainable energy consumption (Martin 2021).

2.8 Conclusion

This thesis sets out to understand disproportionate exposure to extreme heat in Seattle, and what factors contribute to it. Research shows that heat waves disproportionately impact elderly people, communities of color, and low-income communities (Wilson 2020). People who live in areas with higher relative temperatures are more susceptible to extreme heat (Tan et al. 2010). Areas that have been historically redlined are more likely to experience higher relative temperatures today (Wilson 2020). This is important to understand because heat waves are expected to increase in frequency and severity (Tan et al. 2010). Heat waves are the biggest cause of death compared to all other extreme meteorological events combined (Klinenberg 2015). It is important to use an environmental justice lens to understand the structural variables at play that lead to disproportionate heat exposure.

Chapter 3. METHODS

3.1 STUDY AREA

Seattle, Washington is the study area for this research. Seattle has been steadily growing since the 1980s, with a sharper increase since 2010. According to the 2020 census, the population of Seattle is 737,015 (“About Seattle - OPCD | Seattle.Gov” 2022). Seattle was among just 14 other US cities that experienced a population gain of 100,000 or more between 2010-2020 (“About Seattle - OPCD | Seattle.Gov” 2022). According to the 2016 American Community Survey (ACS), Seattle’s median household income is $83,476 which is well above the national median household income of $57,617 (“About Seattle - OPCD | Seattle.Gov” 2022). However, 23% of Seattle residents of color live in poverty, as compared to only 9% of white residents (“About Seattle - OPCD | Seattle.Gov” 2022). According to the 2014-2018 ACS, about 35.5% of Seattle residents are people of color, as demonstrated in the pie graph below. The percent of people of color is growing in Seattle, although this growth is at a much slower pace than the rest of King County and the overall US. Since 2010, the growth of people of color in Seattle is mostly within groups identifying as multiracial and Asian, whereas Seattle’s Black population has remained somewhat stagnant (“About Seattle - OPCD | Seattle.Gov” 2022).

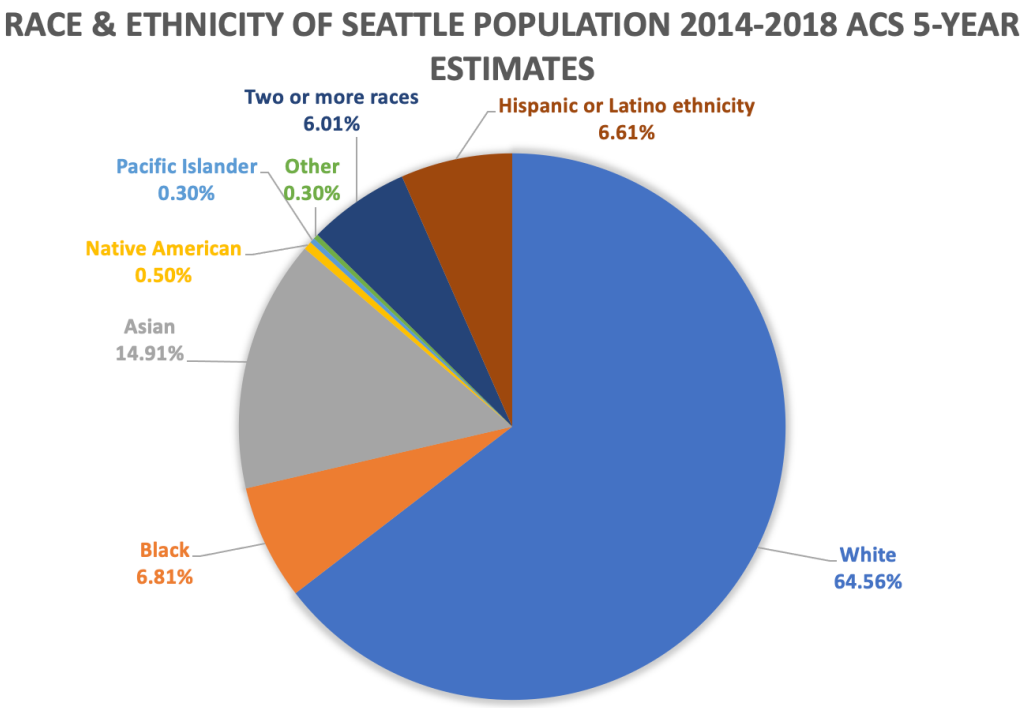

Figure 3.1: Race and Ethnicity of Seattle Population

Redlining policies were in effect and enforced in Seattle from the 1930s-1960s. It was not until 1976 that changed, as "Seattle City Council took a stand against redlining" ("Planning and Urban Development Committee Meeting" 1976).

Seattle has become increasingly warmer, as shown in the figure below. The frequency and severity of Seattle heat waves have also increased, and are projected to continue increasing (Rights 2021).

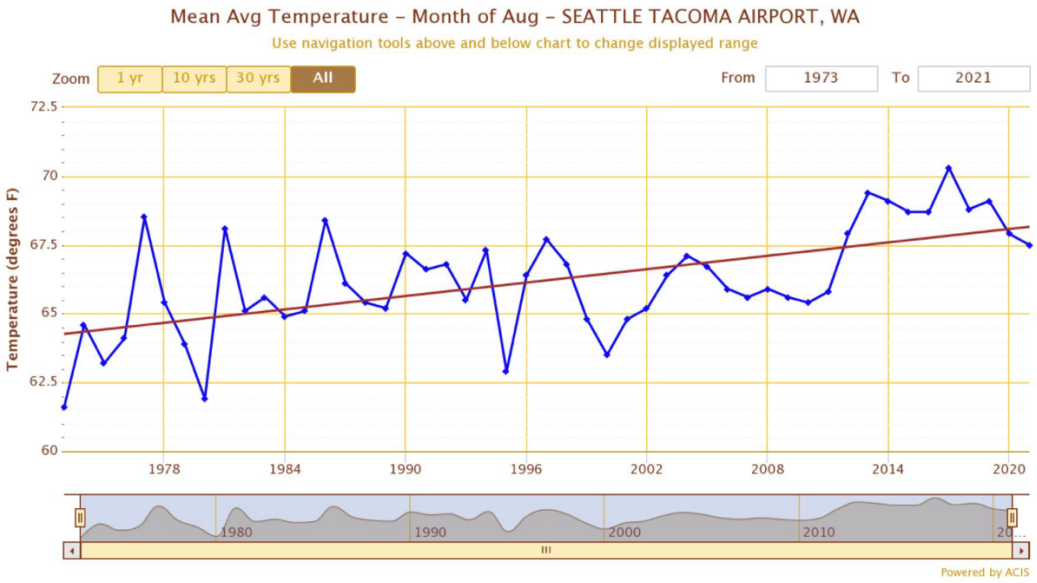

Figure 3.2: Mean average temperature 1973-2021 Seattle Tacoma Airport (Dunagan 2021)

The study area of this research is Seattle Washington and the unit of analysis is 2010 census tracts. This is shown below in Figure 3.3.

Figure 3.3: Study area map

3.2 Research Design and Data

To understand vulnerability to extreme heat in Seattle on the census tract scale, I ask the following research questions: 1) are historically redlined census tracts disproportionately

exposed to extreme heat compared to non-redlined census tracts in Seattle; 2) what census tracts were historically redlined and today experience higher relative land surface temperatures; 3) how does social vulnerability differ, based on a census tract's historic HOLC grade and relative land surface temperature; and 4) what are the focus areas for resourcing against extreme heat? Quantitative methods are used to answer these questions. The majority of this research was conducted by the author, in collaboration with Isaac Anzlovar and Art Lansing.

The first and second questions (*are historically redlined census tracts disproportionately exposed to extreme heat compared to non-redlined census tracts in Seattle*; and *what census tracts experienced historic redlining and have higher relative land surface temperatures?*) are designed to understand and clarify the spatial and quantitative relationship between historic redlining and intraurban heat variation. To answer them, a spatial analysis using ArcGIS Pro was conducted. Global Summer Land Surface Temperature (LST) data from 2013 was used for this analysis. The data represents daytime maximum temperature (1:30pm) during the summer months (July-August). Maximum temperature during the summer is the biggest threat to human health which is why this data is being used. The spatial resolution is of 30 arc-seconds, which is at the scale of about 1 km. This was the highest resolution data at this level of validity that I could access. However, the resolution was too small for the census tract scale, so it was resampled to 30 meters by 30 meters, using a bilinear technique. It would be difficult to see the nuance of temperature variation at the census tract scale if the resolution were much smaller than this. The temperature data is in the degree of Celsius.

To see where redlining occurred, we downloaded a digitized HOLC map as a shapefile from the University of Richmond's "Mapping Inequality" project. They created this by georeferencing historic HOLC maps and creating polygons, then transcribing area descriptions.

Additionally, this resource offers a shapefile download with census tract boundaries cut into the HOLC polygons. A limitation is that the boundaries of HOLC maps and census tracts do not align, and actually intersect one another. To navigate this, we gave each census tract an average HOLC grade. To do this, the City of Seattle HOLC shapefile was converted into a raster file so that each raster cell was given a HOLC grade (A-E). Then the created HOLC raster was reclassified so that A=1, B=2, C=3, D=4, and E=5. Next, using the reclassified HOLC raster, the raster input and the census tract shapefile as the zonal boundaries input, the "zonal statistics as a table" tool was used to determine the average redlining score for each census tract. In census tracts that had more than one HOLC grade within it, we took whichever HOLC grade took up the majority of space within that census tract. This map is shown below in Figure 3.4. In later steps I will explain how this map was used to identify maximum summertime temperature and social vulnerability by census tract.

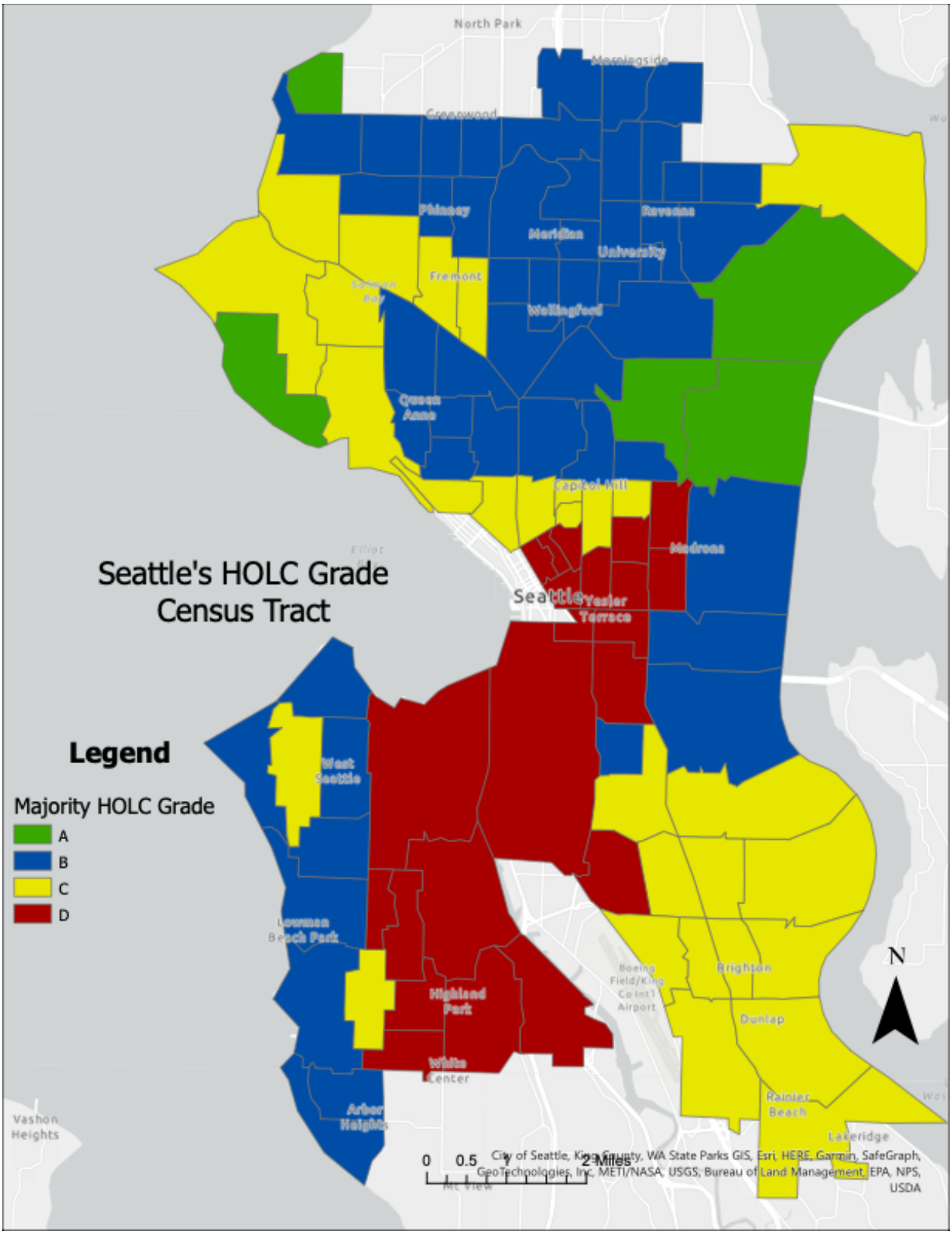

Figure 3.4: Seattle HOLC grade census tract, created by the author, Art Lansing, and Isaac Anzlovar

To measure if there is a correlation with HOLC grade and maximum summertime temperature, we used zonal statistics. The resampled Global Summer LST raster was used as the raster input and the 2010 census tracts were used as the zonal boundaries input for the "zonal statistics as a table" tool. This allowed us to determine the maximum temperature for each census tract. The output tables were then saved. We then exported the census tract data to an excel file so it could be used in a regression model. To do this, we joined the created census HOLC grade table, the created census tract temperature table, and the social vulnerability shapefile (which is discussed below) to the census tract shapefile. To ensure that the join was saved, the shapefile was exported to a new shapefile. Next the "feature to table" tool was used to export the attribute table of the new census tract shapefile to an excel file so that the relationship between the census tract's HOLC grade, maximum summertime temperature and social vulnerability score could be compared in a regression model. This regression model allowed us to answer the first question (*are historically redlined census tracts disproportionately exposed to extreme heat compared to non-redlined census tracts, in Seattle).* A map was created to show this relationship spatially, which answers the second question (*what census tracts experienced historic redlining and have higher relative land surface temperatures).*

The third question (*how does social vulnerability differ, based on a census tract's historic HOLC grade and relative land surface temperature?*) aims to understand the socioeconomic capacity a population has to withstand environmental disruptions, such as heat waves. This is important because if an area is relatively hotter, *and* is home to people with less adaptive capacity, the threat and impact of heat waves increases. To answer this, we downloaded the shapefile from the CDC. This shapefile was joined with the aforementioned census tract

shapefile. As described above, we then used the "feature to table" tool to export the attribute table of the joined census tract shapefile to an excel file so that the relationship between the census tract's HOLC grade, maximum summertime temperature and social vulnerability score could be compared in a regression model.

The CDC's social vulnerability index was created to "help emergency response planners and public health officials identify and map communities that will most likely need support before, during, and after a hazardous event."("CDC/ATSDR SVI Fact Sheet | Place and Health | ATSDR" 2021). They obtain their data from the U.S. Census. This index includes the following categories: socioeconomic status, household composition and disability, minority status and language, and housing and transportation. The National Integrated Heat Health Information System (NIHHIS) uses this same index to understand social vulnerability to extreme heat.

The social vulnerability index data is derived at the 2010 census tract scale, for the year 2018. Below are the variables used to create the social vulnerability index.

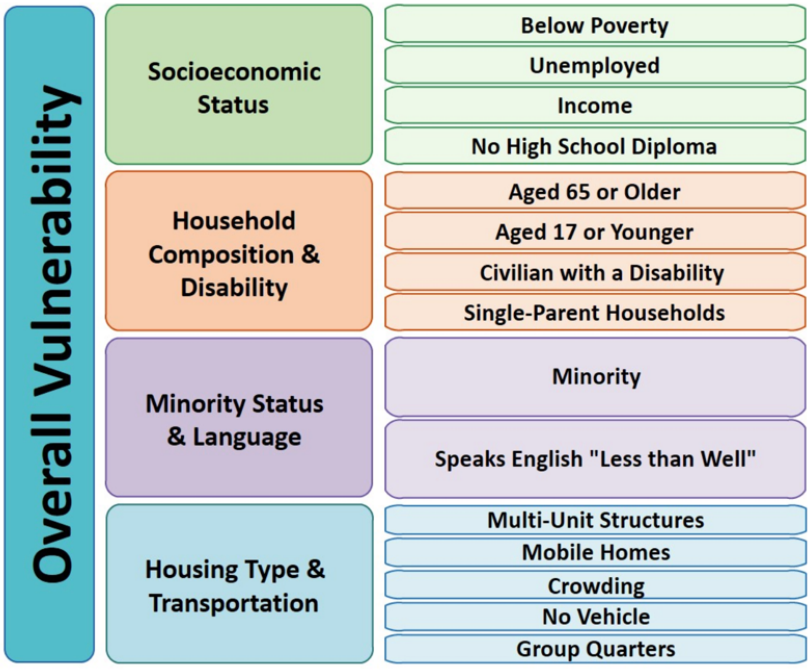

Figure 3.5: CDC social vulnerability index ("CDC/ATSDR SVI Fact Sheet | Place and Health | ATSDR" 2021)

3.3 Development of Focus Areas

The final question asks: *what are the focus areas for resourcing against extreme heat?* Focus areas are areas that have poor adaptive capacity, high exposure to extreme heat and a history of redlining. The CDC's social vulnerability index is used to identify "adaptive capacity." The 2013 Global Summer LST data is used to identify "exposure," and the HOLC maps are used to identify the "history of redlining". Focus areas are identified through this research as disproportionately vulnerable to extreme heat. These areas should be prioritized in resourcing for adapting to extreme heat and mitigating the contributing factors to it. The framework used here is illustrated in Figure 3.6 below.

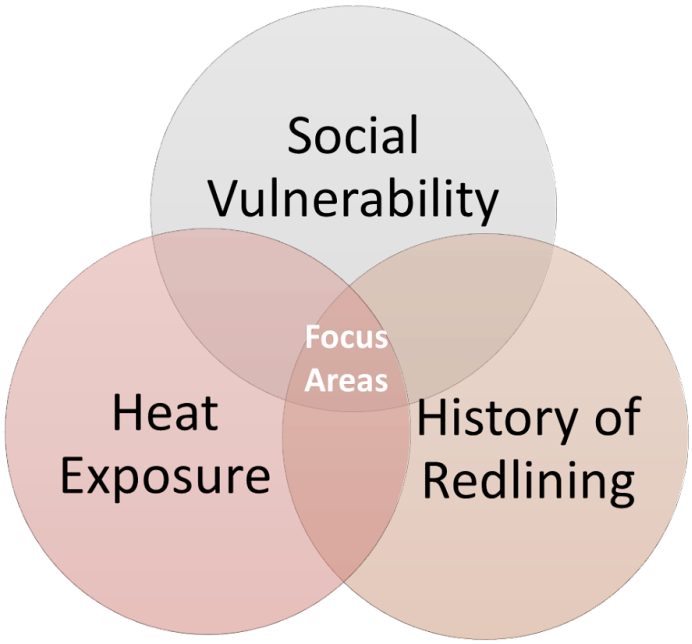

Figure 3.6: Focus area development framework

The criteria for deeming a census tract a Focus Area is a “high” ranking in social vulnerability, maximum summertime temperature, and receiving a HOLC grade of “C” or “D”. The social vulnerability and temperature data both contribute to a vulnerability to extreme heat. Adding the history of redlining as a criterion for Focus Areas aims to mitigate the long-lasting disinvestment of historically redlined areas. Additionally, I conducted a t-test in excel to determine if HOLC grades were statistically significant in determining differences in social vulnerability and maximum temperatures. It was found that census tracts with an average HOLC grade of “A” or “B” were statistically significant in being less vulnerable in terms of social vulnerability and extreme heat than census tracts graded “C” or “D”.

The t-test was conducted through exporting a table with the joined fields for the social vulnerability index, maximum summertime temperature and average HOLC grade from ArcGIS Pro into Excel. From Excel, I sorted all census tracts in order of HOLC grade: A-D. I ran a two-tailed t-test and a two-sample unequal variance to determine if census tracts with a HOLC grade of “A” or “B” were statistically different in terms of social vulnerability and temperature, compared to census tracts graded “C” or “D”.

Focus Areas are visually and spatially represented through ArcGIS Pro. I joined the social vulnerability index and the maximum summertime temperature into one layer. I used a 3 x 3 bivariate matrix in ArcGIS. The 3 x 3 bivariate matrix classified the temperature and social vulnerability data into three categories: high, middle and low. I overlayed this layer with the outline of which census tracts were graded “C” or “D” because those are the census tracts that inform focus areas, rather than “A” or “B”. The nuances of this combination of data are identified in a detailed Focus Area map.

The census tracts that ranked “high” in both temperature and social vulnerability were identified and exported to a new layer. These selected census tracts were then intersected with HOLC data that only included census tracts graded “C” or “D”. The census tracts that remained after the intersect were those that ranked “high” in temperature, social vulnerability, and received a HOLC grade of “C” or “D”. With this, I created a second Focus Area map to denote exactly which census tracts are deemed focus areas.

The results that emerged through this analysis are presented in Chapter 4.

Chapter 4. RESULTS

As explained in the previous chapter, the relationships between three main variables are studied: maximum summertime temperature, HOLC grade, and social vulnerability. The results suggest that there is a linear relationship between the census tract’s HOLC grade and their maximum summertime temperature. There is also a linear relationship between the census tract’s HOLC grade and it’s social vulnerability rating. The values for social vulnerability and maximum summertime temperature are statistically significant in census tracts graded “C” and “D”, compared to “A” and “B”.

4.1 Maximum Summertime Temperature by HOLC Grade

To answer the first research question (*are historically redlined census tracts disproportionately exposed to extreme heat compared to non-redlined census tracts in Seattle*?) we created the box-plot below. Figure 4.1 represents a box-plot of maximum summertime temperature by HOLC grade. When we performed a Spearman test to compare the HOLC grade for each census tract

and that tract's maximum summertime temperature, we noticed a mild positive correlation. The r-square of 0.16 for the two variables indicates that there is a mild correlation. Meaning, a census tract with a lower HOLC grade, is more likely to have a higher maximum summertime temperature than a tract with a higher HOLC grade. The outliers indicated in Figure 4.1 could be partially a result of the imperfect method of using an average HOLC grade rather than an exact HOLC grade.

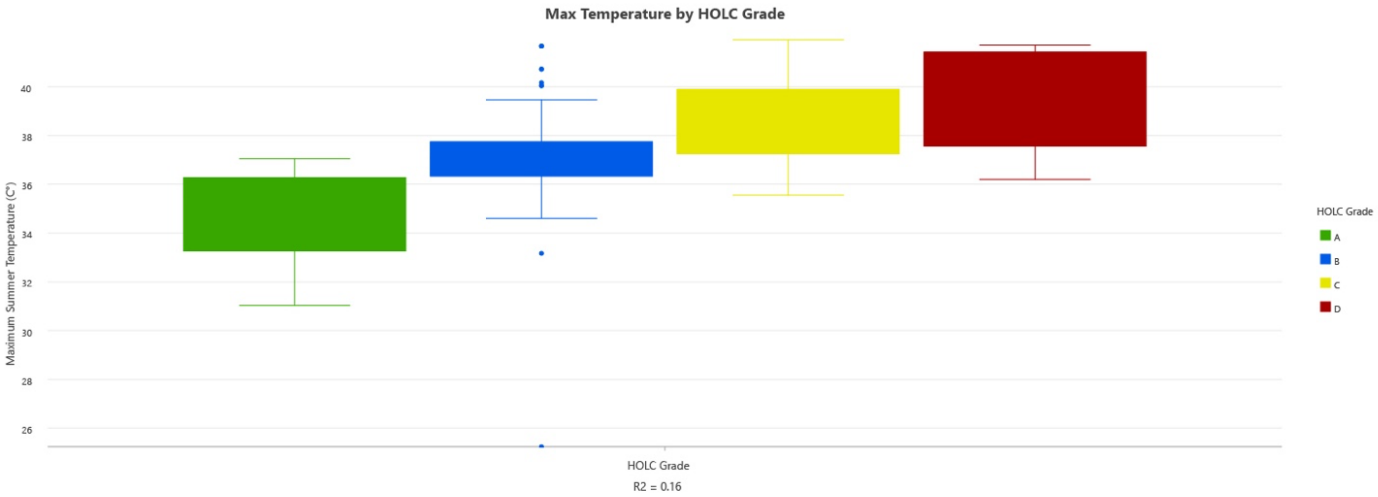

Figure 4.1: Maximum temperature by HOLC grade

To answer the second research question (*what census tracts were historically redlined and today experience higher relative land surface temperatures?*), the map below was made. The map is a spatial representation of the relationship between maximum summertime temperature and HOLC grade. The census tracts colored yellow and red are deemed "redlined" and those that have the largest circle experience higher temperatures. Some of the hottest areas appear to be in the International District, the Duwamish Valley, Beacon Hill, Rainier Beach and the Central District, much of which was graded "C" or "D" by HOLC.

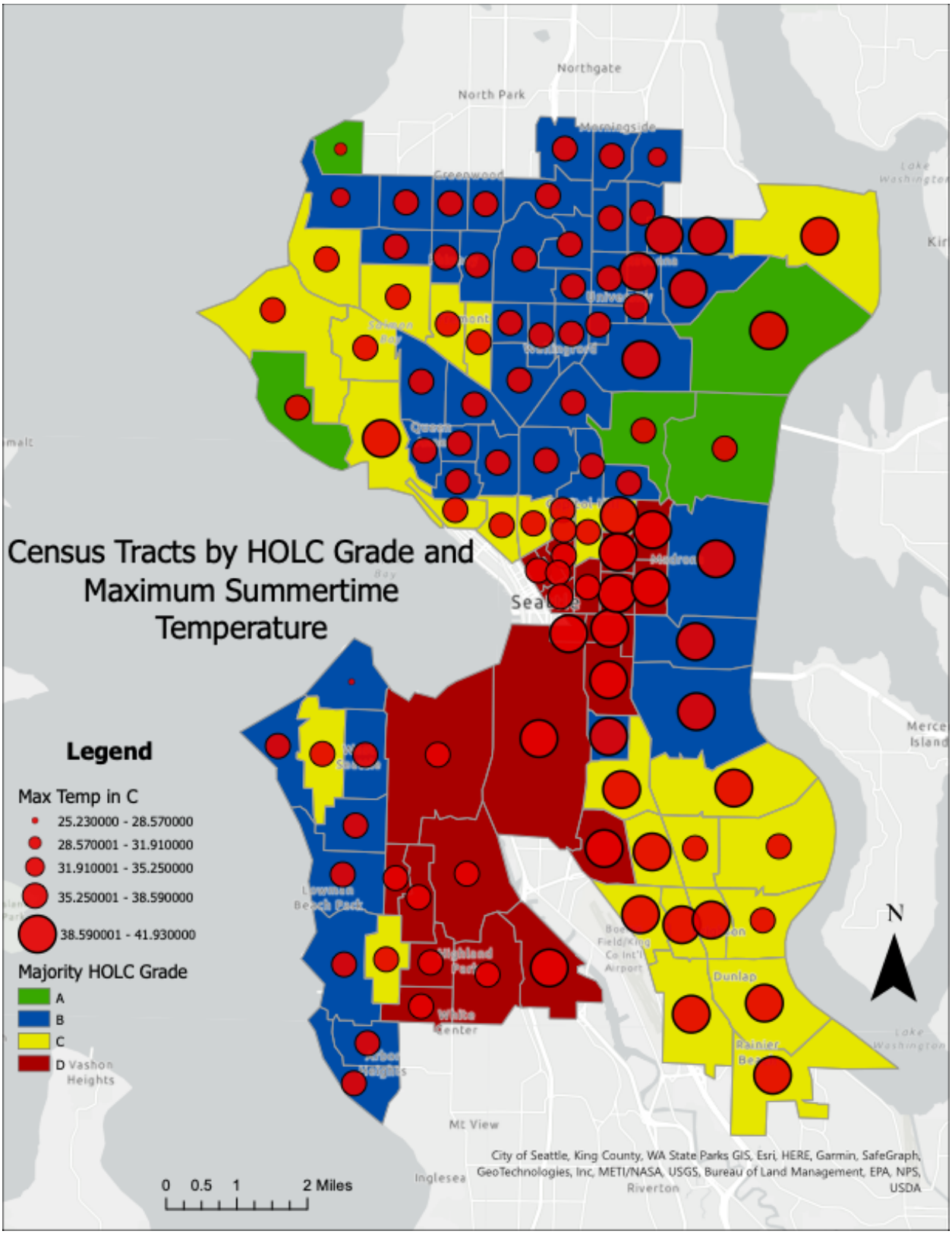

Figure 4.2: Census tracts by HOLC grade and maximum summertime temperature

4.2 Social Vulnerability and HOLC Grade

To answer the third research question (*how does social vulnerability differ, based on a census tract's historic HOLC grade and relative land surface temperature?*), the box-plot below was made. Figure 4.3 represents a box-plot of social vulnerability by HOLC grade. When we performed a similar test, we found that there is an even stronger positive correlation than the aforementioned relationship. Social vulnerability by HOLC grade has an r-square of 0.33 which indicates that there is a moderate positive correlation between these two variables. Meaning, a parcel with a lower HOLC rating (was historically redlined) is more likely to have a higher social vulnerability score.

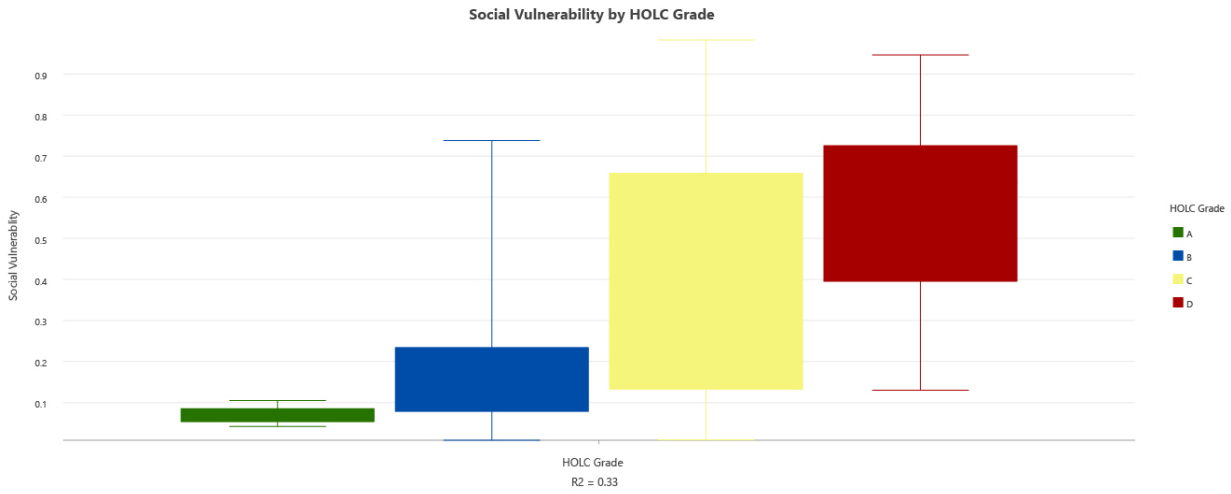

Figure 4.3: Social vulnerability by HOLC grade

The map below is a spatial representation of the relationship between social vulnerability and HOLC grade. The most socially vulnerable census tracts appear to be in the International

District, Beacon Hill, Columbia City, Rainier Beach, South Park and Delridge, all of which was graded “C” or “D” by HOLC.

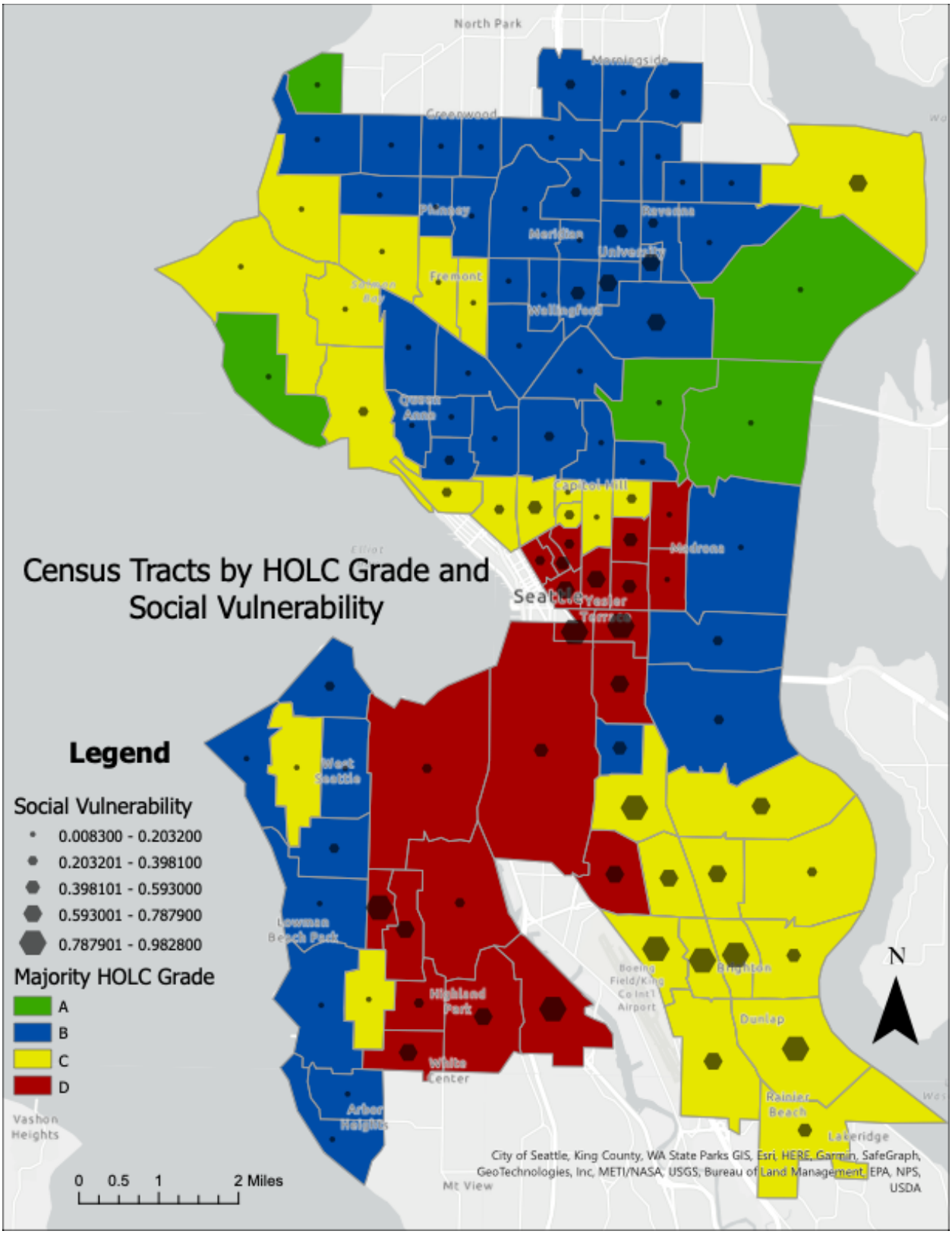

Figure 4.4: Census tracts by HOLC grade and social vulnerability

4.3 Maximum Summertime Temperature and Social Vulnerability

The map below is a spatial representation of the relationship between maximum summertime temperature and social vulnerability. The most socially vulnerable census tracts appear to be in the International District, Beacon Hill, the Duwamish Valley, Rainier Beach, South Park and Delridge, all of which (except Delridge) have relatively hotter temperatures.

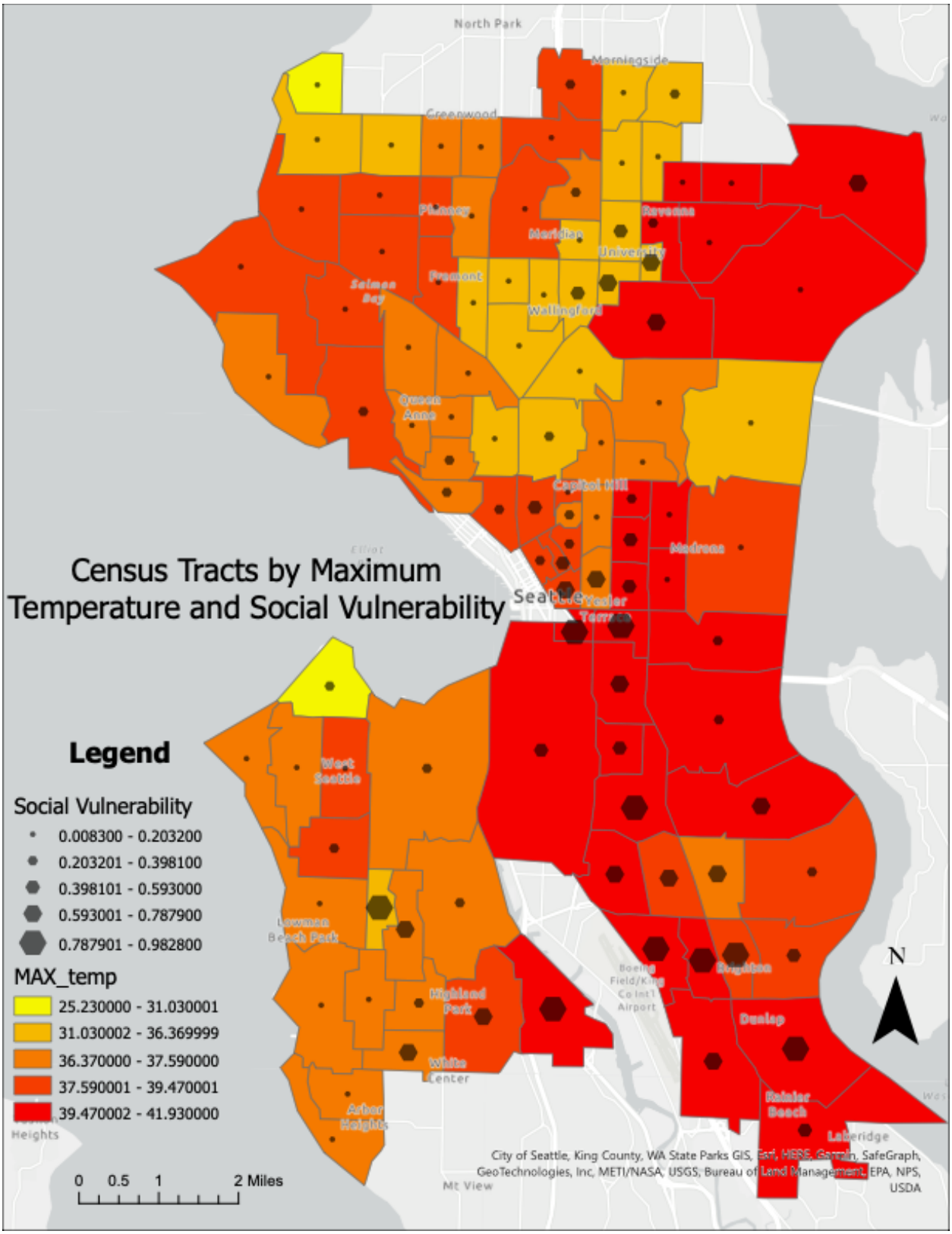

Figure 4.5: Census tracts by maximum summertime temperature and social vulnerability

4.4 Focus Areas

To answer the final research question (*what are the focus areas for resourcing against extreme heat?*), the map below was made. This map indicates which census tracts are identified as Focus Areas. The census tracts that are "high" in both social vulnerability and maximum summertime temperature, as well as having been graded "C" or "D" by HOLC, are deemed focus areas. These areas are the most vulnerable to extreme heat because they are made up of people who are socially vulnerable, the areas experience higher relative temperatures, and they were historically redlined.

Historic HOLC grade is used as a criteria for focus areas because of literature pointing to it being a precursor to many of today's socioeconomic and environmental health injustices (Wilson 2020; Hoffman, Shandas, and Pendleton 2021; Lane et al. 2022; Rigolon and Németh 2021; D. A. Mitchell 2021; Rothstein 2018). In addition to the literature, and the Spearman's test used in the above analysis, a t-test was also used to determine statistical significance within census tracts redlined compared with those that were not.

- Census tracts with a HOLC grade of "A" or "B" have statistically significant lower levels of social vulnerability than census tracts graded "C" or "D". The p-value for this test is 8.12637E-05, which is far below 0.05, meaning it is statistically significant.
- Census tracts with a HOLC grade of "A" or "B" have statistically significant lower maximum summertime temperatures than census tracts graded "C" or "D". The p-value for this test is 9.74936E-05, which is far below 0.05, meaning it is statistically significant.

In the map below, the census tracts that are darkest (high in both social vulnerability and temperature), that also have a hatched symbol indicating redlining, are the census tracts that are deemed focus areas in this research.

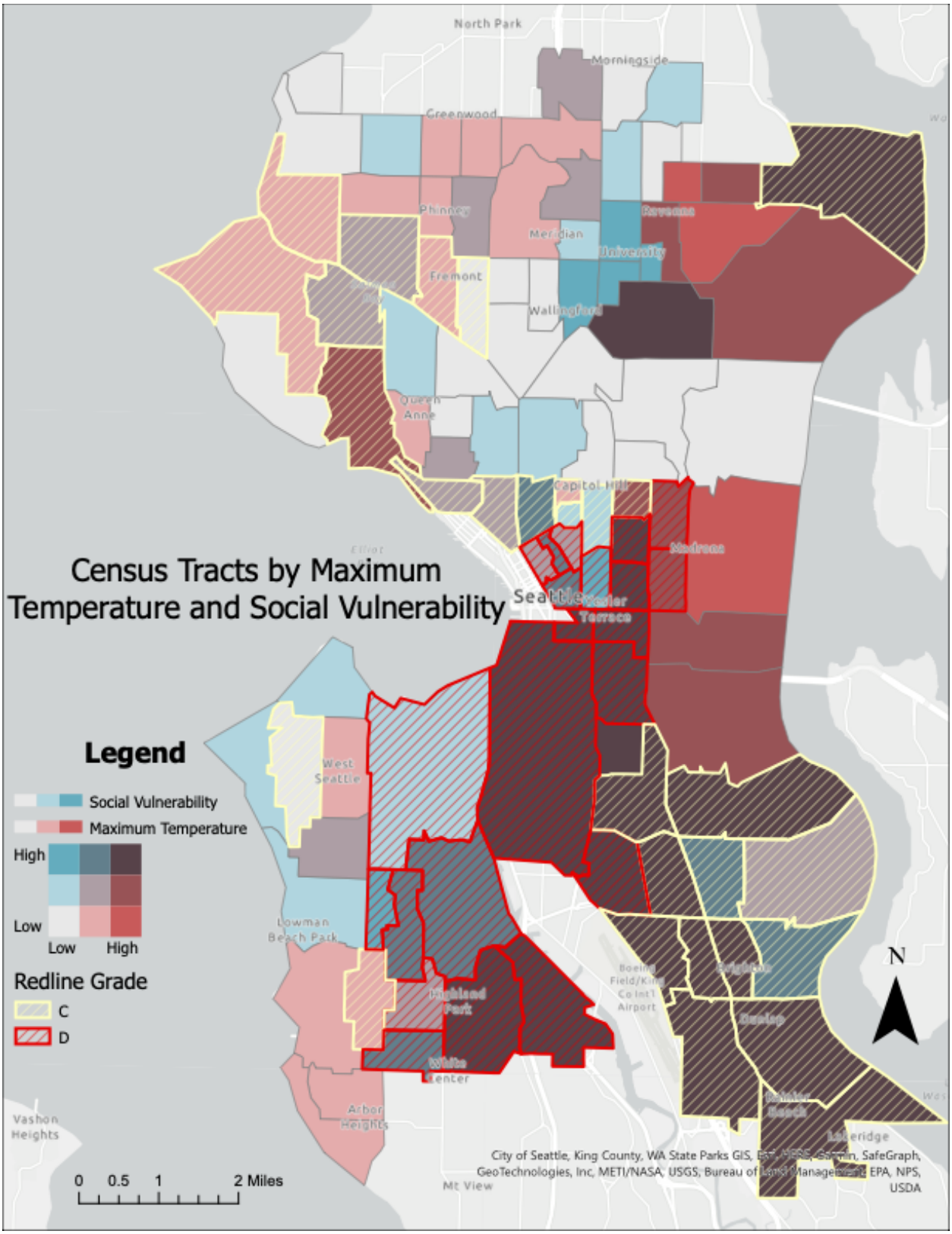

Figure 4.6: Focus area detailed map

The above map has greater detail and reveals the nuance of each census tract. To create more straightforwardness and simplicity on which census tracts should be prioritized in resourcing against extreme heat, the below map was created. The census tracts in red are those that rank "high" in both social vulnerability and extreme heat, *and* received a HOLC grade of "C" or "D".

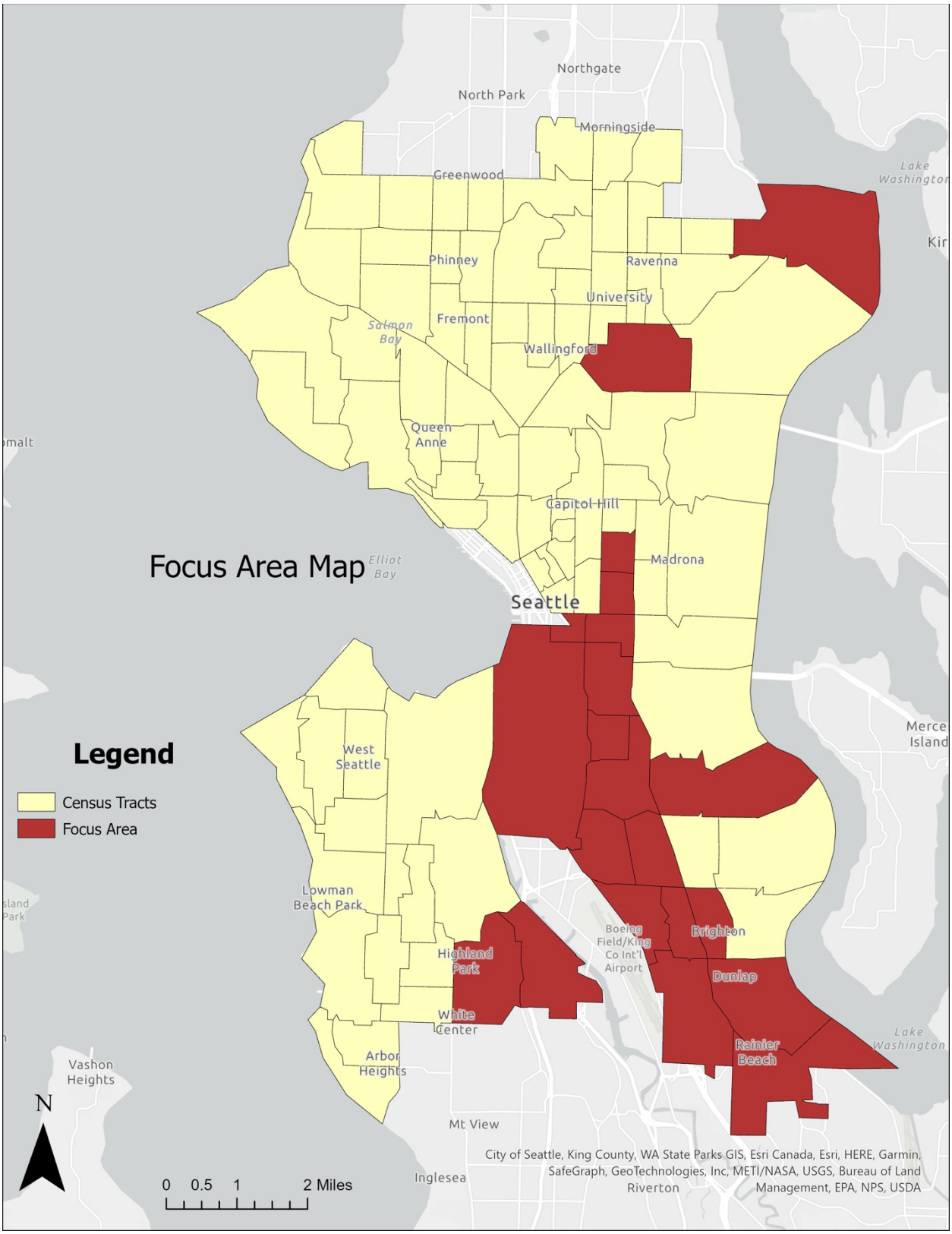

Figure 4.7: Focus area map

Chapter 5. DISCUSSION

The goal of this research is to understand where in Seattle, Washington the highest vulnerabilities to extreme heat exist. The CDC's Social Vulnerability index was used in concert with maximum summertime temperature data to understand a census tract's adaptive capacity as well as levels of exposure. Exposure to extreme heat and social vulnerability together, create a vulnerability to extreme heat events. I wanted to understand if census tracts that experience this level of vulnerability disproportionately exist in census tracts that were historically redlined or not.

As stated in the previous chapter, there is a linear relationship between the census tract's HOLC grade and its maximum summertime temperature. There is also a linear relationship between the census tract's HOLC grade and its social vulnerability rating. The values for social vulnerability and maximum summertime temperature are statistically significant in census tracts graded "C" and "D", compared to "A" and "B". These results align with the expected results. I expected these results for reasons involving impervious/pervious land cover and gentrification, both of which will be discussed in this chapter.

5.1 Impervious/Pervious Land Cover

The mild positive correlation between maximum summertime temperature and HOLC grade was expected. I expected there to be a correlation because there is visibly less tree canopy coverage in the Duwamish Valley and the International District, both of which were redlined. We know from research that impervious land cover leads to an increase in temperature, and an increase in vegetation and pervious land surfaces lead to lower temperatures (Plumer, Popovich, and Palmer 2020). According to the 2016 Seattle Tree Canopy Assessment, higher concentrations of inland

tree canopies clearly help reduce surface temperature. They came to this conclusion from research comparing tree canopy coverage with surface temperature, as demonstrated in Figure 5.1 (O'Neil-Dunne 2016).

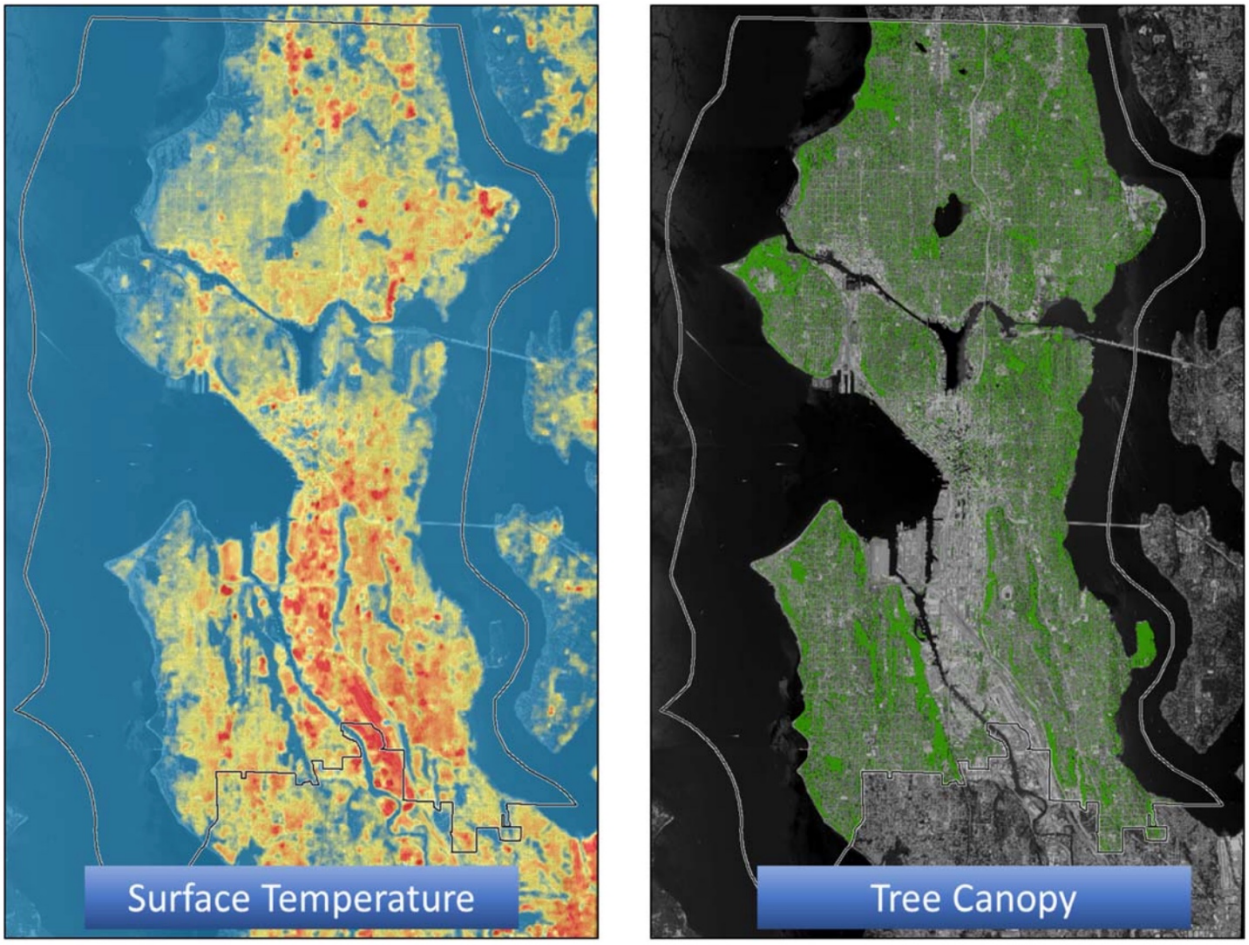

Figure 5.1: Surface temperature and tree canopy coverage (O'Neil-Dunne 2016)

In the 1950s the federal government funded major highway expansion projects. The construction of these highways often occurred in the lowest income neighborhoods of cities, disproportionately impacting communities of color (Hoffman, Shandas, and Pendleton 2021). This disrupted, divided and transformed many redlined neighborhoods (Hoffman, Shandas, and Pendleton 2021). Not only does this disrupt the social and cultural fabric of these neighborhoods,

it also contributes to air pollution and the amount of impervious land surface. This makes these neighborhoods more prone to higher summertime temperatures.

5.1.1 *Single-Family Zoning*

After redlining and other explicit racially restrictive zoning was deemed illegal, planners at the time (e.g., Harland Bartholomew) began using another tactic to sustain racial segregation in cities: single-family zoning ("This Is How You Slow-Walk into a Housing Shortage" 2018; Mohler 2020). Kingsella writes about how, in a number of US cities, historically redlined areas have the lowest concentration of single-family zoning today (Kingsella 2019).

About 56% of Seattle's land area is zoned single-family, and only 11% is zoned multi-family (O'Neil-Dunne 2016). Seattle's percentage of land zoned single-family is significantly more than other peer cities that also experience housing pressure ("Rapidly Growing Seattle Constrains New Housing through Widespread Single-Family Zoning" 2018). The significance of single-family zoning in Seattle is twofold: it increases housing prices and contributes to the social stratification of extreme heat exposure. As any city grows in population, which Seattle has, the housing supply needs to increase to accommodate this growth. When demand for housing is greater than the supply, housing prices soar and become increasingly inaccessible to households earning below the median income, families lacking intergenerational wealth, and other marginalized communities. Areas zoned single-family have significantly more canopy coverage (32%) than areas zoned multi-family (23%) (O'Neil-Dunne 2016). With tree canopy coverage as a key indicator for heat vulnerability, people who live in areas zoned single-family are less likely to experience disproportionate exposure to extreme heat.

The below figure is a generalized zoning map of Seattle. There is a higher cluster of multi-family zoning in the International District and Central District, both of which were historically redlined.

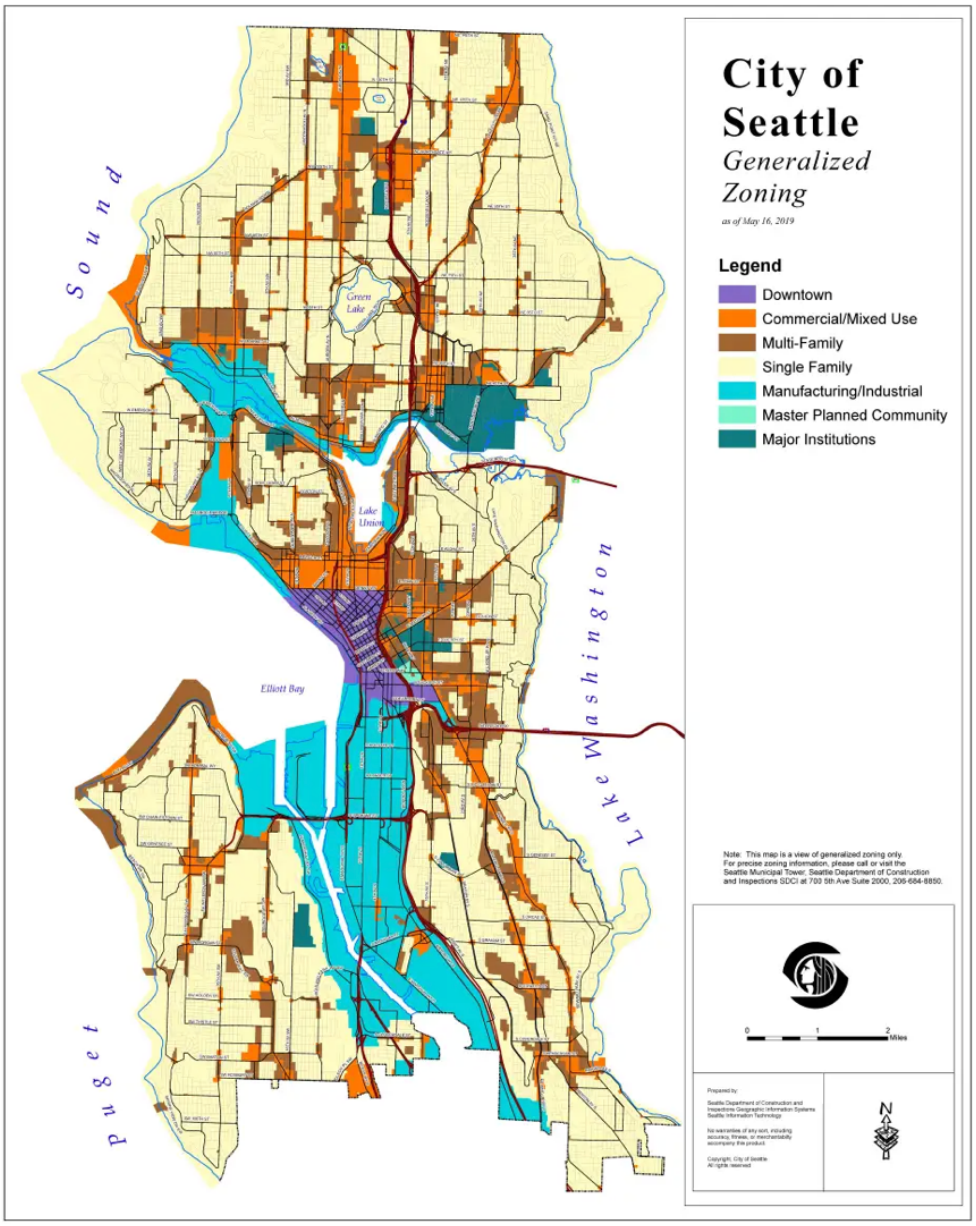

Figure 5.2: Generalized zoning map (City of Seattle, Office of Planning & Community Development 2018)

5.2 GENTRIFICATION

It does not come as a surprise that the correlation of maximum summertime temperature and HOLC grade was only mild. This is mainly because many historically redlined areas have experienced high rates of gentrification, such as the Central District (Balk 2019). Many areas that were graded “C” and “D” have income levels lower than the city’s median, according to the map below. This 2000 map cannot account for today’s levels and spatial relationship to gentrification, but it does reveal that the Central District has been gentrifying at least since 2000. This could have contributed to an increase in investment leading to an increase in tree canopy coverage, as shown in Figure 5.1.

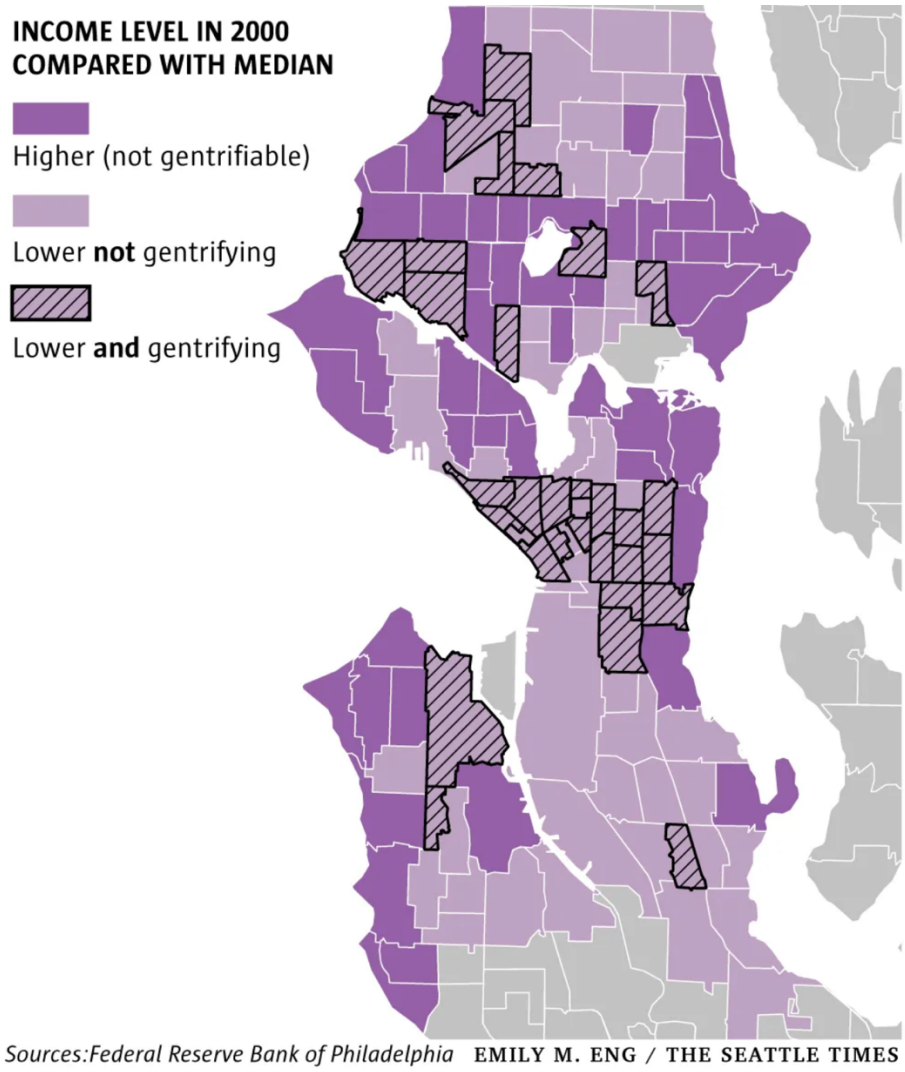

Figure 5.3: Gentrification in Seattle (Balk 2019)

The map below describes a person's/household's risk of displacement based on their census tract of residency. The Displacement Risk Index, developed by the City of Seattle's Office of Planning and Community Development, compile the following indicators to create this index: people of color, linguistic isolation, educational attainment, housing tenancy, housing cost-burdened households, severely housing cost-burdened households, household income, proximity to current or future Link light rail and streetcar, proximity to core businesses, proximity to civic infrastructure, proximity to high-income neighborhood, proximity to job center, development

capacity, median rent. The aforementioned data points, when combined, increases an area's risk to displacement. Some of the highest risk areas for displacement are the same areas that were graded "C" or "D" by HOLC.

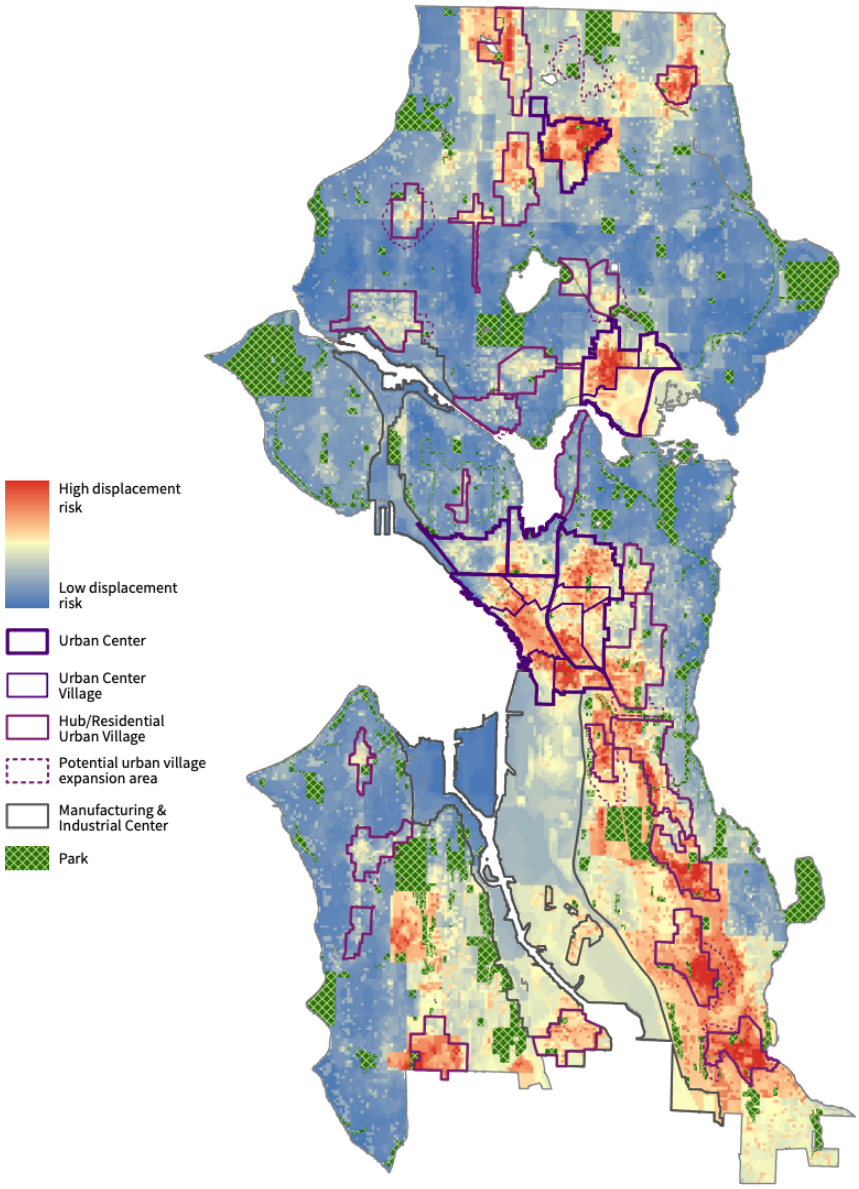

Figure 5.4: Seattle displacement risk index (Seattle Office of Planning and Community Development 2016)

Gentrification and displacement could contribute to why the correlation between HOLC grade, maximum summertime temperature, and social vulnerability was not stronger. If lower income communities and communities of color were pushed out of these census tracts and replaced with people of higher incomes, changes to the built environment, land surface, and the socioeconomic makeup of these areas likely occurred.

5.3 Social Vulnerability

The moderate positive correlation between social vulnerability and HOLC grade was expected. I expected there to be a correlation because there are extensive indices implying that the International District, SODO, Beacon Hill, Columbia City, Rainier Beach, Duwamish Valley and the South Park area experience disproportionate health disadvantages, socioeconomic disadvantages, higher shares of people of color, and more. Many of these areas were also redlined.

The following three maps are shown below: Racial and Social Equity Index, The Washington Health Disparities Map, and the Social Vulnerability Index. All three maps reveal a similar pattern. South Seattle and South Park are consistently deemed the more vulnerable areas within Seattle. These same areas were historically graded “C” or “D” by HOLC during the practice of redlining.

The Racial and Social Equity Index explains spatially where the highest disadvantaged populations live. They use the following data within three categories to determine this:

- “Race, ELL, and Origins
    - (Persons of color, English language learners, foreign born)
- Socioeconomic Disadvantage

    - (Income below 200 percent of poverty level, educational attainment less than a bachelor's degree)
- Health Disadvantage
    - (No leisure-time physical activity, diagnosed diabetes, obesity, mental health not good, asthma, low life expectancy at birth, disability)"

("About Seattle - OPCD | Seattle.Gov" 2022)

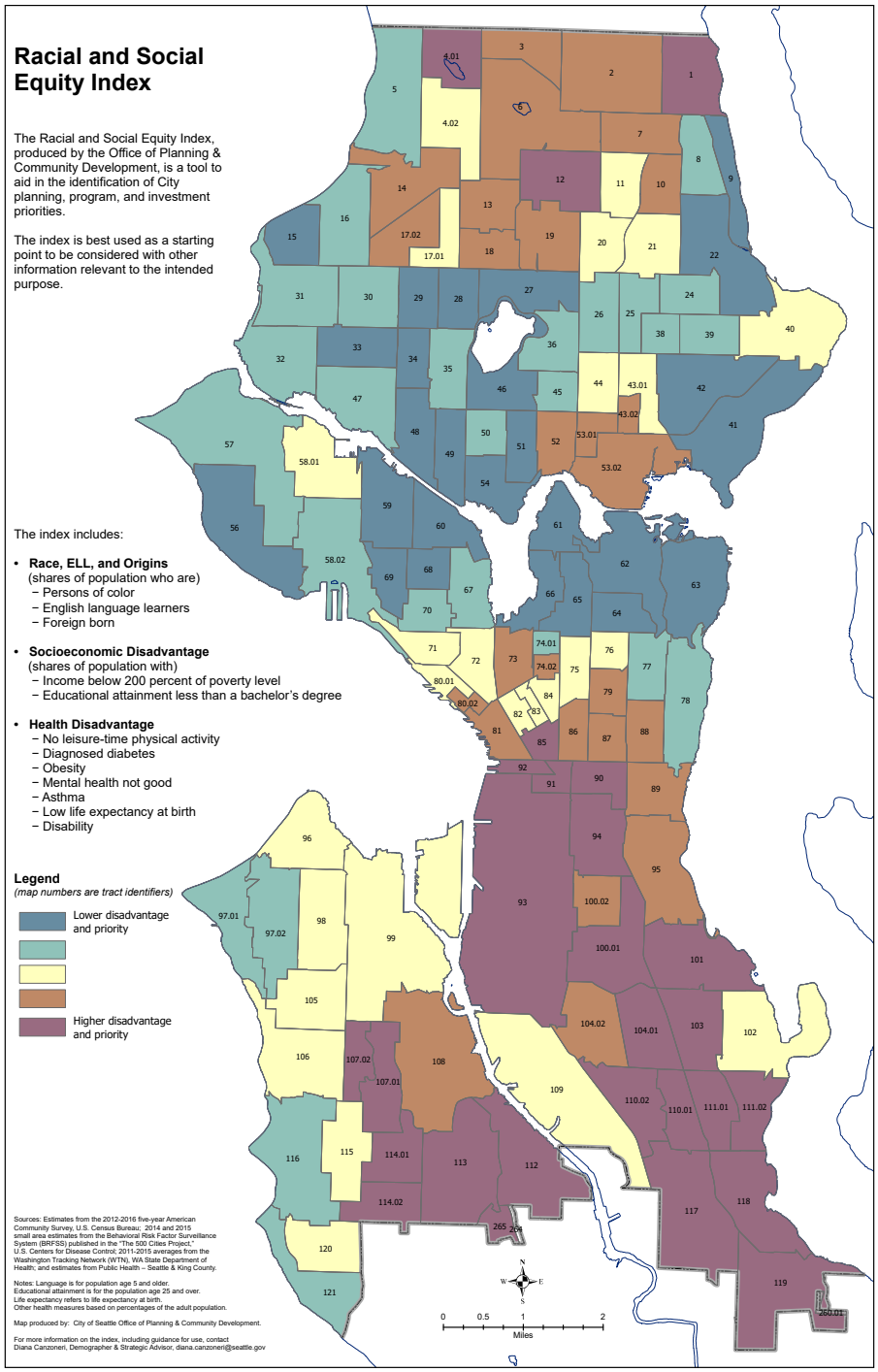

Figure 5.5: Racial and social equity index ("About Seattle - OPCD | Seattle.Gov" 2022)

The Washington Health Disparities Map uses data in the following indicators within four categories to determine which census tracts experience higher levels of health disparities:

- *"Environmental Exposures*
    - (NOx-diesel emissions; ozone concentration; PM2.5 Concentration; populations near heavy traffic roadways; toxic release from facilities (RSEI model))
- *Environmental Effects*
    - (Lead risk from housing; proximity to hazardous waste treatment, storage, and disposal facilities (TSDFs); proximity to National Priorities List sites (Superfund Sites); proximity to Risk Management Plan (RMP) facilities; wastewater discharge)
- *Sensitive Populations*
    - (Death from cardiovascular disease; low birth weight)
- *Socioeconomic Factors*
    - (Limited English; no high school diploma; poverty; race - people of color; transportation expense; unaffordable housing; unemployed)"

("Washington Environmental Health Disparities Map | Washington State Department of Health" 2022).

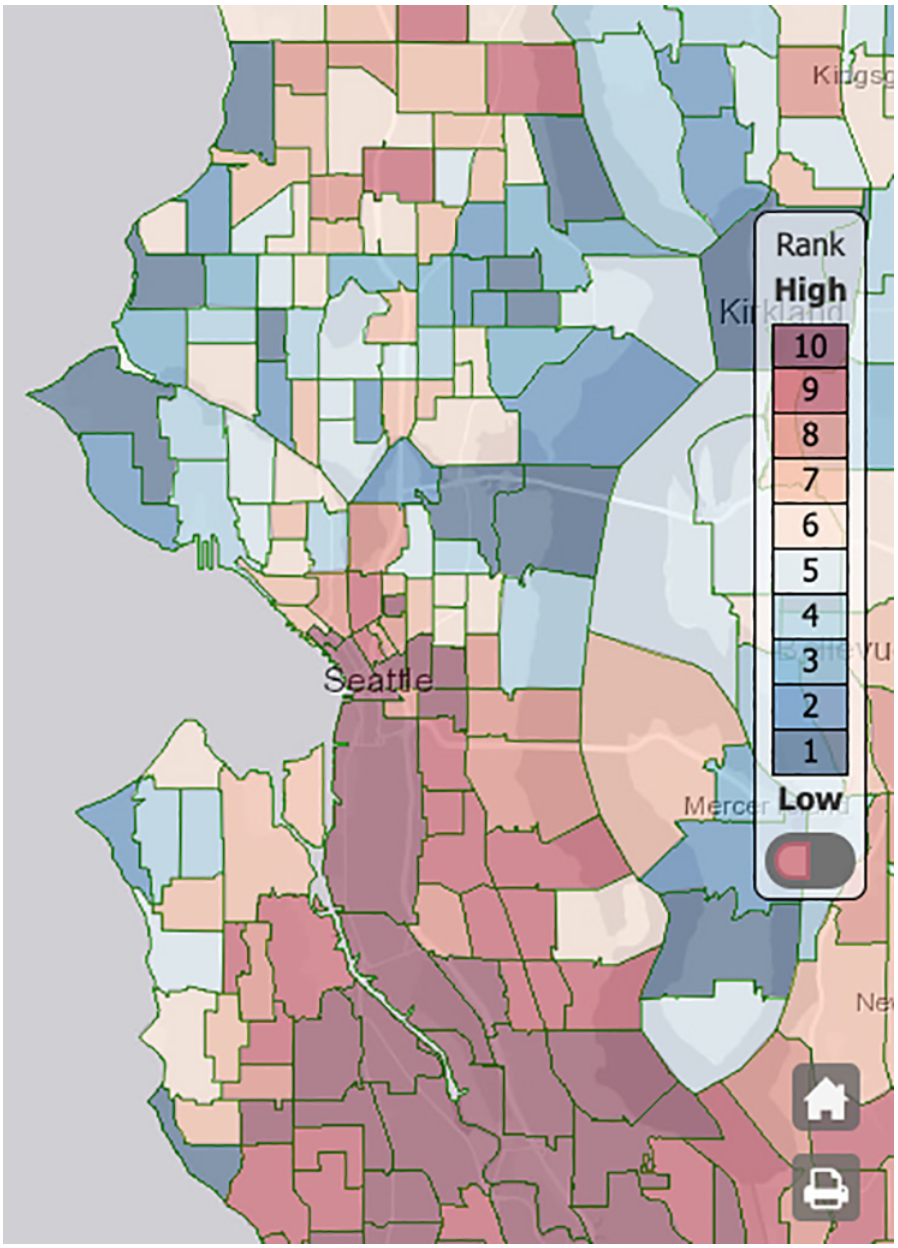

Figure 5.6: Washington health disparities map ("Washington Environmental Health Disparities Map | Washington State Department of Health" 2022)

The CDC's Social Vulnerability Index was used throughout this research. For reference, and to see the data stand alone, it is shown below. They compile data within the following four categories to determine which census tracts are the most socially vulnerable to understand better how to respond and prepare for hazardous events: socioeconomic status, household composition

and disability, minority status and language, housing and transportation ("The Social Vulnerability Index (SVI): Interactive Map | CDC" n.d.).

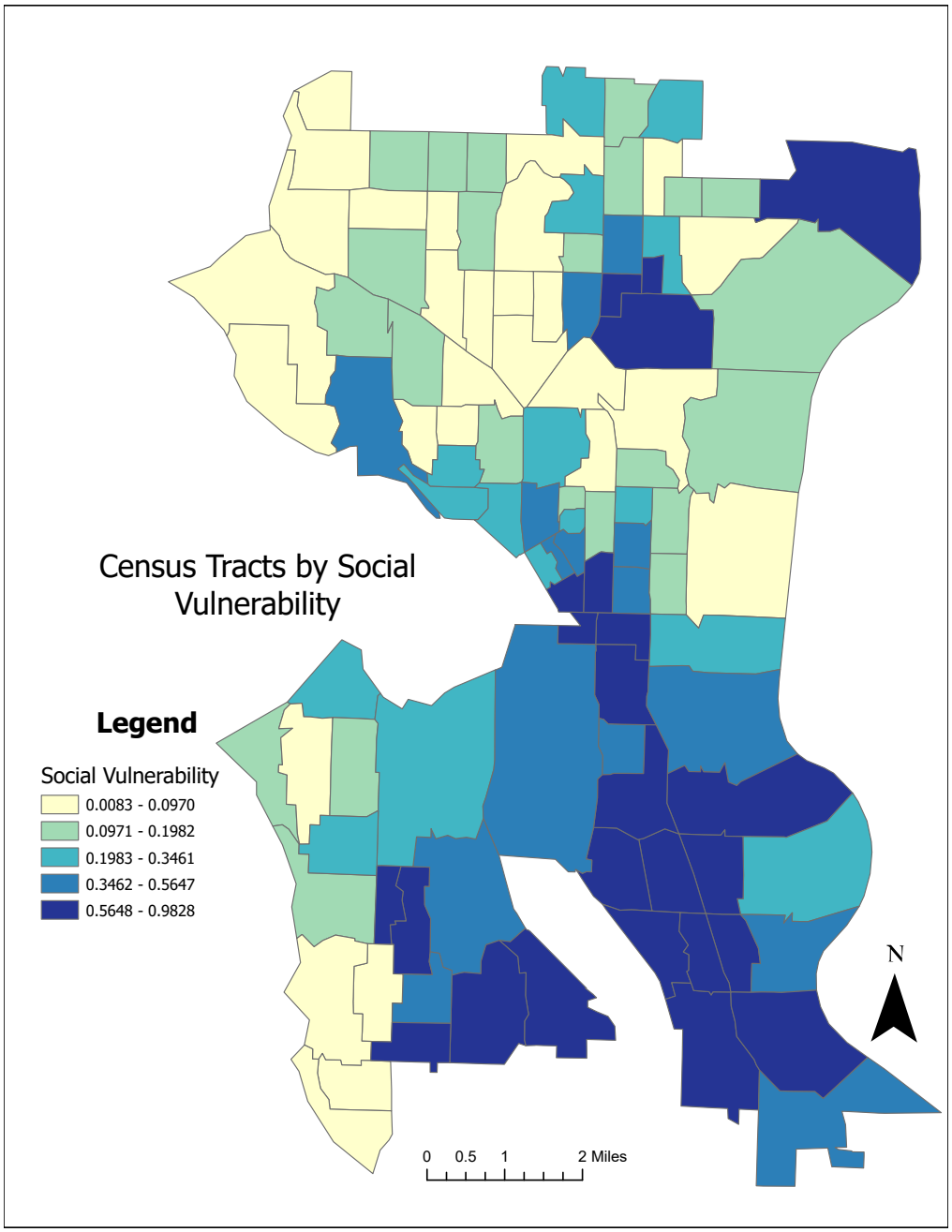

Figure 5.7: The CDC's social vulnerability index

Chapter 6. CONCLUSION

6.1 LIMITATIONS

There are two primary limitations of this study. The first is that the census tract boundaries and HOLC grade boundaries do not align. The second is that the resolution of the temperature data was not high enough. Methods we used to address these limitations and the possible impact it had on this research is described below.

The unit of analysis for this research was at the census tract scale. Since HOLC grading occurred at a different time, for different purposes and by a different governing body, it makes sense that the boundaries do not align with 2010 census tracts. This issue was addressed by applying an average HOLC grade for each census tract, rather than using the exact HOLC grade. This is a limitation because it can create misrepresentations. A census tract could contain multiple HOLC grades, but then be characterized as only representing one grade. For example, if a census tract contains areas of a neighborhood that received a HOLC grade of "A" and other parts of a neighborhood graded "C", then the tract would receive a "B" grade. A potential method of accounting for this limitation in the future, could be using census blocks rather than census tracts. This could be useful because blocks are smaller in area and may align better with the HOLC boundaries.

The second limitation in this research is the spatial and temporal resolution of the LST data. The spatial resolution was large, with each cell being 1-square-kilometer. In order to use this data in the "zonal statistics as a table" tool, the raster file had to be resampled to each cell being 10-square-feet. This means that some cells in the raster could be an average between multiple temperatures, which can be misrepresentative. The temporal resolution poses a

limitation because the temperature data was gathered in 2013. Climate change reports and projections explain that temperature has risen in recent years, so using data from almost a decade ago could be misrepresentative (Rogers and Mauger 2021). To account for these limitations, future researchers should use new temperature data that is collected at a smaller scale (e.g., 10-square-meters).

6.2 Policy Implications

Multi-pronged work needs to be happening on many different levels of government, community-based organizations, local agencies, etc. to address the widespread impact redlining and other racist and exclusionary practices have had on marginalized communities. Solutions to disproportionate exposure to extreme heat are those that mitigate or adapt to extreme heat, *and* mitigate the root causes of it. It is important to understand the root causes of current day challenges to better devise solutions. This research is meant to contribute to the body of knowledge related to the intersection of redlining and intraurban heat variation, as well as provide insight as to where attention and resources need to be invested to build heat resilience before future heat waves.

6.2.1 *Work Already Happening*

The following table is a non-exhaustive list of local government plans, programs, initiatives, and state legislation that address some of the sustainable and equitable solutions to the problems outlined in this thesis.

Table 6.1: Non-exhaustive list of current, local, relevant policies/plans/initiatives

Managing Agency	**Plan/Initiative/Act**	**Objective**
Seattle's Office of Sustainability and Environment	Environment and Equity Agenda	"Advance racial equity in Seattle's environmental programs and policies" through the following four goal areas: community driven strategies; the influence and decision-making of those most affected; strong accountability; solutions that recognize complexity and interdependence ("Equity & Environment Agenda," n.d.).
Green New Deal Oversight Board (GNDOB)	Seattle's Green New Deal	"GNDOB connects frontline community-led voices and the Seattle city government to eliminate Seattle's climate pollution by 2030, while resolving racial, social, and economic inequities. We do this by 1) recommending systemic changes and budget priorities to the Mayor, City Council, City departments and advisory boards, 2) supporting departmental planning and implementation, and 3) coordinating efforts with City departments and related advisory groups pursuant to Ordinance 125926"(GNDOB 2021).

Trees for Seattle: "the umbrella for all of the City of Seattle's urban forestry efforts"	Urban Forest Management Plan	The goal of Trees for Seattle is "to ensure that Seattle's urban forest is healthy, vital, and growing" (City of Seattle 2020).
Seattle's Office of Planning and Community Development	The Comprehensive Plan	Long-range plan to "manage growth to become an equitable and sustainable city" through the following core values: race and social equity, environmental stewardship, community, economic opportunity and security (City of Seattle, Office of Planning & Community Development 2018).
City of Seattle	The Race and Social Justice Initiative and Racial Equity Toolkit	"The vision of the Seattle Race and Social Justice Initiative is to eliminate racial inequity in the community. To do this requires ending individual racism, institutional racism and structural racism. The Racial Equity Toolkit lays out a process and a set of questions to guide the development, implementation and evaluation of policies, initiatives, programs, and budget issues to address the impacts on racial equity" (Race and Social Justice Initiative, n.d.).

King County	2020 Strategic Climate Action Plan	This plan is a "five-year blueprint for County climate action, integrating climate change into all areas of County operations and work with King County cities, partners, communities, and residents. The SCAP outlines King County's priorities and commitments for climate action to residents and partners" ("King County Climate Action" n.d.). The plan involves reducing greenhouse gas emissions, and addressing and promoting sustainable and resilient frontline communities.
WA State Departments of Agriculture, Commerce, Ecology, Health, Natural Resources, and Transportation	Healthy Environment for All (HEAL) Act	This law includes the incorporation of environmental justice into the work of 7 state agencies ("including incorporating environmental justice into agency strategic plans, developing community engagement plans and tribal consultation frameworks, and conducting environmental justice assessments for certain significant actions."); promotes investing in communities that experience the highest levels of environmental health burdens; heighten the voice of communities most affected by environmental injustices ("Environmental Justice | DOH" n.d.).

WA State Department of Health	Health Equity Zones Initiative	Areas that experience disproportionate health disparities will be identified as "Health Equity Zones." These communities will receive resources to see through their own community-led projects to address health in their communities ("Health Equity Zones Initiative | Washington State Department of Health" n.d.).

6.2.2 *Suggestions*

This research reveals that disproportionate heat exposure does not happen in a vacuum, and needs to be addressed holistically. Actions to mitigate heat should be paired with actions to mitigate the impacts of racism, displacement, income inequality, and other oppressive systems. Leaders need to be wary of "Green Gentrification" so their solutions to extreme heat don't contribute to worsening social inequities.

The Health Equity Zones Initiative is used as a framework in this section. The Health Equity Zones Initiative used data to identify areas that have been disinvested in and experience disproportionate levels of health disparities. Once these areas were identified, the governing body works with the community to capacitate them in implementing their own projects to improve their community's health. This is important, because no one understands the nuances of health disparities better than those experiencing them. It is suggested that this model be used in the wake of this research.

Using the Focus Area Map (see page 49, Figure 4.7), census tracts of high vulnerability to heat waves are identified. The City of Seattle should identify community leaders in each of

these areas and compensate them to collaborate with other residents in identifying solutions and developing projects/programs that mitigate extreme heat and health disparities. A community advisory council can be created to collectivize around which programs and projects should receive funding and support. The City of Seattle releases all decision-making power to this Community Advisory Council. The Community Advisory Council will be made-up of people from that community, and selected by other community members.

As explained by the HEAL act, expenditures should be focused in communities that have been burdened with the highest levels of environmental and health disparities ("Environmental Justice | DOH" n.d.).

6.3 Conclusion

This research examined the relationship between historic redlining, social vulnerability and disproportionate exposure to extreme heat in Seattle. The relationship between these three variables is important because communities who live in areas that are disproportionately exposed to higher summertime temperatures *and* experience social vulnerabilities are vulnerable to future extreme heat events. The finding that census tracts that were historically redlined are positively correlated with higher social vulnerability and maximum summertime temperature reveals the political and racialized context through which communities continue to bear the brunt of environmental injustices.

This finding also reveals that we need to be very intentional about how we mitigate extreme heat. Community-led solutions within Focus Areas that address both heat mitigation and structural inequities should be prioritized and resourced.

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