MAPPING SOCIAL AND ENVIRONMENTAL HEALTH VULNERABILITY IN MADISON, NEW JERSEY

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ABSTRACT

An individual's heat-related illness risk is largely dependent on their socioeconomic status and surrounding environment in which they live. Acting as a feedback mechanism, social demographics and environment are highly interconnected. Public health can be assessed by evaluating spatial relationships between social and environmental determinants. Within our research, we investigated heat-related public health risks across the four census tracts of the borough of Madison, New Jersey. A nested-scale temperature investigation was performed to assess the relationship between location, tree canopy coverage, and surface materials and temperature and perceived heat. We found that nearly all categories tested showed statistically significant associations. Additional spatial data were assessed by evaluating maps and aggregating social and heat data to create vulnerability and risk indexes. Significant disparities were discovered between Madison's four census tracts. Notable findings were the high health vulnerability of Census Tract 429 and the low health vulnerability of Census Tract 431. Future studies can use our disparity findings to target the most effective ways of addressing and amending health risks.

INTRODUCTION

In 2024, the highest global surface temperature was recorded in nearly two centuries, with the ten warmest years all occurring within the last decade (Lindsey and Dahlman, 2025). Rising temperatures increase the risk of heat-related illness and place greater stress on the body, with heat illness morbidity and mortality increasing by 18% for every 1.8 °F rise in temperature (Faurie et al., 2022). Heat exposure can affect urban areas specifically, due to features such as impervious surfaces (e.g., man-made surfaces that prevent draining of water into the ground).

Developed areas are often hotter than surrounding rural areas due to the urban heat island effect, which causes buildings and pavement to absorb and retain heat while limiting natural cooling from vegetation (McDonald et al., 2019). Environmental exposures are not distributed equally. Low-income and marginalized communities are more likely to live near pollution sources, resulting in disproportionate environmental burdens and widening health disparities (Hajat et al., 2015). As climate change intensifies and heat waves become more frequent, extreme heat increasingly threatens vulnerable populations, including older adults, young children, people with chronic illnesses, outdoor workers, and low-income communities (Zafra, 2025). Heat exposure and its associated health risks can be reduced by expanding tree canopies and green space (Heat and Health, 2026).

The degree of one's access to natural environments is closely linked to their physical and mental well-being. A longitudinal study of 3,173 children found that greater access to parks was associated with lower BMI (body mass index) over eight years, with an additional 14.82 acres of parkland within 500 meters of a home corresponding to a 0.14-unit reduction in BMI (Wolch et al., 2010). Natural environments also reduce physical and psychological stress, making green space an important component of healthy urban planning (Ewert and Chang, 2018). Furthermore, permeable surfaces, such as soil, are better at dissipating absorbed thermal energy and tend to be cooler (What Are Heat Islands?, 2024).

Heat-related health risks are also shaped by one's individual characteristics, such as age, education level, income, race, location, etc., which interact together, impacting health. Disparities in these social factors contribute to disparities in health outcomes (Couillard et al., 2022). This links social vulnerability, the capacity of communities to recover from stressors (Social Vulnerability Index, 2024), with heat vulnerability, the susceptibility to heat-related illness (Nanda et al., 2022). Economic barriers to healthcare are common, with 54% of near-low-income individuals experiencing at least one affordability problem (Park and Fung, 2025). Healthcare disparities not only consider socioeconomic factors, but are also influenced by race and ethnicity. For instance, Black patients have a 10% lower likelihood of hospital admission following their emergency department visit and face longer wait times and 1.26 times higher odds of hospital deaths than White patients (Macias-Konstantopoulos et al., 2023; Peitzman et al., 2023). This disparity appears to stem from unconscious stereotypes and biases (Macias-Konstantopoulos et al., 2023). Technical literacy and language barriers pose extensive accessibility issues as well. Prior studies observed perspectives of community members who had limited English ability and their interactions with healthcare (Pandey et al., 2021). It was found that language barriers created space for dissatisfaction and difficulties related to patient privacy, language interpreting, diagnosis clarification, and demotivated patients from actively searching healthcare facilities (Pandey et al., 2021).

Chronic diseases remain the leading cause of death and disability worldwide and are responsible for a substantial portion of healthcare utilization and economic burden. In the United States, six out of ten adults live with at least one chronic disease, while four out of ten have two or more (About Chronic Diseases, 2026). Conditions, including arthritis, heart disease, stroke, diabetes, and chronic kidney disease, serve as primary causes of morbidity, mortality, and healthcare expenditures (About Chronic Diseases, 2026). Age is a key risk factor for heart disease, neurodegenerative diseases, and cancer. Particularly, heart function decreases with age due to loss of heart muscle cells (Niccoli and Partridge, 2012).

The relationship between social vulnerability and heat vulnerability was investigated in Madison Borough in Morris County, New Jersey. Madison is generally affluent, but the sociodemographic and environmental disparities that may exist among Madison's four census tracts have not been investigated in existing literature. This study examines how social demographics and environmental factors are associated with heat-related public health risks in Madison, New Jersey, by reviewing relevant literature, conducting a nested-scale temperature investigation, analyzing ArcGIS spatial data, and rasterizing social vulnerability and health risk indexes.

It was hypothesized that residents in areas of higher social vulnerability and heat susceptibility are more at risk for adverse health outcomes.

METHODS

Study Area

The area of study included the four census tracts of Madison, New Jersey (11.2 km^2). These four tracts are identified by the U.S. Census Bureau as Census Tracts 429, 430, 431, and 432 (Fig. 1A). As of 2025, the human population of Madison, New Jersey, is approximately 16,607 people (QuickFacts: Madison Borough, 2025). Madison is primarily a deciduous forest. Acknowledging this, the selected sampling locations of temperature data were in Drew University's campus, located in Census Tract 432 (Fig. 1B).

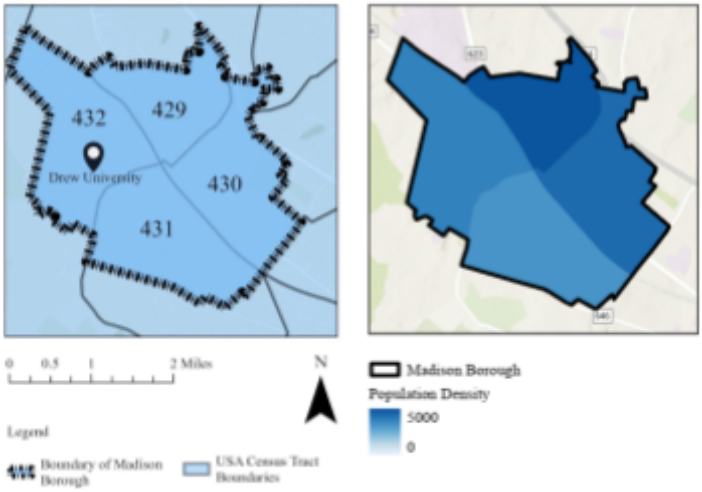


Fig. 1. Map of Madison, New Jersey with labelled Census Tracts (429, 430, 431, 432). Madison municipal boundary layer provided by the New Jersey Office of GIS. Pinpoint at Drew University to identify experimental study area. (left; Fig. 1A) Population Density Map of Madison, New Jersey with darker areas representing a larger population density. Thick black line represents boundary of Madison, New Jersey. A darker blue shade represents a more heavily populated area. Via Esri's USA Demographics (Latest)—2026 Population Density per Square Mile (right; Fig. 1B)

Defining Madison's Social and Heat Vulnerability

Every city contains unique variables that influence vulnerability (Nanda et al., 2022). For this study, social vulnerability is defined as 1) susceptibility of individuals to acquire heat-related illnesses and 2) accessibility and availability of healthcare resources in communities faced with heat-related illnesses based on individual demographics such as median household income, percentage of senior citizens, race, high school education attainment, and English ability. Additionally, heat vulnerability is defined as the frequency and extremity of exposure to high temperatures across different communities, and how readily high temperatures lead to illness based on the physical environment of the different communities, including tree canopy coverage and impervious surfaces. The listed factors were chosen to directly address the socioeconomic environment of Madison. It is important to consider that Madison is relatively affluent, with a median household income of $171,471 compared to Morris County's median household income of $137,326 (QuickFacts: Madison borough, 2025).

Nested-Scale Temperature Investigation

To understand heat comfort levels and the correlation between different surface levels and heat in Madison, our study team held a nested-scale investigation on Drew University's campus in July of 2026. Specifically, Freshliance temperature loggers were placed in 10 locations of different terrain across Drew University's campus. Sites were selected to represent different combinations of tree canopy, surface material, and building density. Surface materials selected included asphalt, slate, grass, brick, dirt, metal, mulch, and vegetation (Table I). Measurements were collected between 1:30 p.m. and 3:00 p.m. on July 22, 2026. Temperature was recorded at five-minute intervals. In addition, a thermal observation survey was conducted among our research team, recording individual observations of thermal sensation, thermal comfort level, wind strength, and desire to stay at the location across the ten sites based on a Likert scale. ANOVA tests were further conducted in RStudio using the "aov" function to

perform ANOVA and the “TukeyHSD” function to find pairwise p-values, with an alpha level of 0.05.

Table I. Surface material type per sampling site in our nested-scale investigation.

Site Number	1	2	3	4	5	6	7	8	9	10
Location	Outside EC	Bleachers	Parking Lot	Tennis Court	Forrest	Behind Riker	Stone Circle	Mead Pillar	Softball Field	Playground
Surface Material Type	Brick	Metal	Asphalt	Asphalt	Vegeta-tion	Brick	Slate & Grass	Brick & Asphalt	Dirt	Mulch

Geospatial Data Investigation

Spatial analysis was conducted using ArcGIS Online and ArcGIS Pro. All datasets were projected to the World Geodetic System 1984 Major Auxiliary Sphere geographic coordinate system for consistency and to support accurate distance and area calculations.

Table II. Layers in Composite Maps

Year Updated	**Name of Data Layer**	**Rasterized Layer Name**	**Source**
2025	Municipal Boundaries of NJ, Hosted, 3857	Municipal Boundaries of NJ, Hosted, 3857	NJOGIS
2026	USA Census Tract Boundaries	USA Census Tract Boundaries	U.S. Census Bureau
2026	Educational Attainment (Latest)	Percent of Population 25 Years and Over whose Highest Education Completed is Less Than High School	ACS
2026	Median Household Income (Latest)	Median Household Income in past 12 months (inflation-adjusted dollars to last year of 5-year range)	ACS
2025	USA 2020 Census Race and Ethnicity Characteristics	Percentage of White Alone, not Hispanic or Latino Population	ACS
2026	English Ability and Linguistic Isolation (Latest)	Percentage of Population in Limited English Households	ACS
2026	Esri’s Updated Demographics USA Variables 2024	2024 Senior Population (Age 65+)	Esri
2026	Lack of Health Insurance Crude Prevalence (%)	Percentage of Population without Health Insurance Coverage	CDC PLACES
2026	USA Fractional Impervious Surface	USA Fractional Impervious Surface	NLCD
2025	Tree Canopy Cover (TCC) Conterminous United States	Tree Canopy Cover (TCC) Conterminous United States	USDA Forest Service
2023	Urban Heat Islands and Land Surface Temperatures in New Jersey	Urban Heat Islands and Land Surface Temperatures in New Jersey	NJDEP Bureau of GIS

Table III. Additional Relevant Layers

Year Updated	Name of Data Layer	Source
2025	Groundwater Contamination Areas (CEA)	NJDEP Bureau of GIS
2025	Land Use/Land Cover 2020 Update, Edition	NJDEP Bureau of GIS
2026	State, Local, and Nonprofit Open Space of New Jersey	NJDEP Bureau of GIS
2026	High Blood Pressure Crude Prevalence (%)	CDC Places
2026	Arthritis Crude Prevalence (%)	CDC Places
2026	High Cholesterol Crude Prevalence (%)	CDC Places
2026	Obesity Crude Prevalence (%)	CDC Places

Vulnerability Analysis

Each layer (Table II & Table III) was clipped to the boundaries of Madison using the "Clip" tool on ArcGIS Pro. Each vector layer representing a social or environmental variable was converted to "Raster" format to facilitate raster-based spatial analysis and multicriteria overlay in ArcGIS Pro. Rasterization allowed variables from different data sources to be standardized onto a common spatial grid so they could be combined using cell-by-cell map algebra. Using the Reclassify feature in ArcGIS Pro, the raster values were converted to new values to create a standardized score. Each raster layer was reclassified to a standardized ordinal scale ranging from 1 (lowest relative vulnerability) to 9 (highest relative vulnerability). Standardization allowed variables measured in different units to be combined into a composite index. To assign point values from 1 to 9, equal intervals were established for each vector layer: "Lack of Health Insurance Crude Prevalence (%)" utilized equal intervals of 0.44 (ranging from 4 to 7.9); "English Ability and Linguistic Isolation (Latest)" utilized equal intervals of 0.644 (ranging from 0 to 5.8); "Median Household Income (Latest)" utilized equal intervals of 9603 (ranging from 144366 to 230795); "Educational Attainment (Latest)" utilized equal intervals of 0.578 (ranging from 0.5 to 5.7); "Esri's Updated Demographics USA Variables 2024" utilized equal intervals of 115.6 (ranging from 464 to 1504); and "USA 2020 Census Race and Ethnicity Characteristics" utilized equal intervals of 2.2 (ranging from 66.6 to 86.2). Equal interval classification was selected because it preserves the continuous distribution of the original variables while providing consistent class widths across the indicators. In order to quantify vulnerable tracts in terms of race, the lowest percentages were given a higher score and vice versa. The Raster Calculator tool was then used to synthesize each of the seven score layers into a final map presenting social vulnerability scores across the census tracts of Madison, New Jersey (Equation 1). Income and age were given higher weights due to prior studies showing high correlation between these factors, healthcare accessibility, and health outcomes.

$$\begin{aligned}\text{Final Social Vulnerability Score} = {} & 0.20(\text{Median Income Reclass}) \\ & + 0.20(\text{Senior Population Percentage Reclass}) \\ & + 0.15(\text{Education Less Than High School}) \\ & + 0.15(\text{Limited English Ability Reclass}) \\ & + 0.15(\text{Percentage Without Health Insurance}) \\ & + 0.15(\text{Percentage of Non-White Population})\end{aligned} \qquad \text{(Equation 1)}$$

To create a composite map concerning heat vulnerability across Madison, New Jersey, the seven layers that created the social vulnerability map, along with the three chosen environmental layers (Table II), were put into the Multicriteria Overlay tool. The overlay method uses a weighted sum method where all the layers' weights equal 1. Social vulnerability and environmental factors had equal weight in the heat vulnerability score. To get the specific weight of each environmental factor, 0.50 was divided by 3. Both "Tree Canopy Cover (TCC) Conterminous United States" (Fig. 9B) and "USA Fractional Impervious Surface" (Fig. 9A) were reclassified with natural breaks (Jenks), with lower ranges corresponding to a lower point value and so forth. The "Urban Heat Islands and Land Surface Temperatures in New Jersey" layer (Fig. 9C) was reclassified using equal intervals of 4, with the ninth interval being 5, between 88 and 120. Again, lower ranges corresponded to lower point values. Once the Multicriteria Overlay tool was run and the layers were added up, a composite layer was created, presenting a heat vulnerability score for each pixel within the map of Madison, New Jersey (Equation 2). To identify the most and least vulnerable areas to heat risk in Madison, New Jersey, the top and bottom 5% scores were calculated. The most and least vulnerable areas were identified using the Reclassify and Extract by Attributes tools. Observed patterns, the composite social vulnerability score, and heat vulnerability score were used to draw conclusions and give further insight into the environmental, socioeconomic, and health-based demographics of the borough of Madison.

$$\begin{aligned}\text{Final Heat Vulnerability Score} = {} & 0.167(\text{Impervious Surfaces Reclass}) \\ & + 0.167(\text{Tree Canopy Coverage Reclass}) \\ & + 0.167(\text{Surface Temperatures Reclass}) \\ & + 0.10(\text{Median Income Reclass}) \\ & + 0.10(\text{Senior Population Percentage Reclass}) \\ & + 0.075(\text{Percentage with Education Less Than High School}) \\ & + 0.075(\text{Limited English Ability Reclass}) \\ & + 0.075(\text{Percentage Without Health Insurance}) \\ & + 0.075(\text{Percentage of Non-White Population})\end{aligned} \qquad \text{(Equation 2)}$$

RESULTS

Environmental investigation results

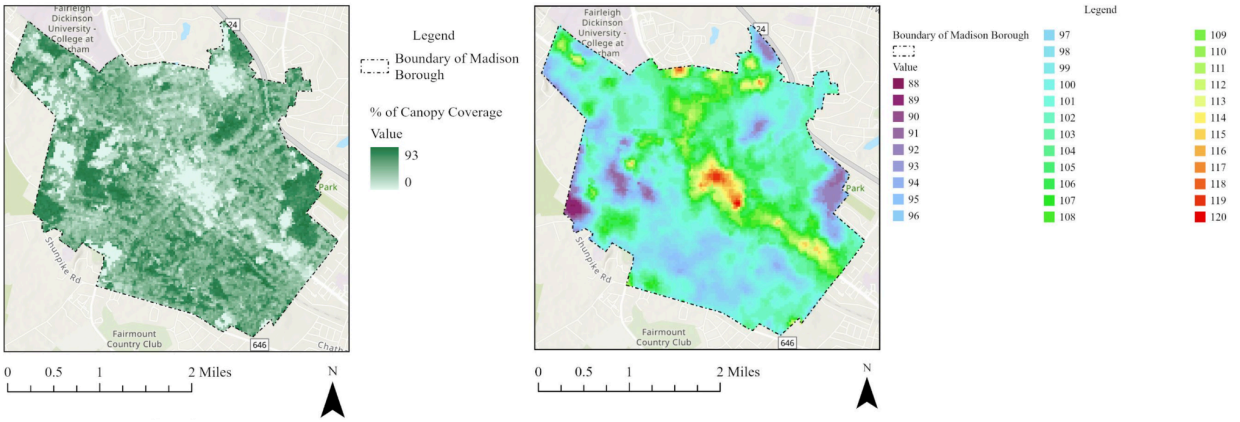


Fig. 2. "National Land Cover Database (NLCD) Tree Canopy Cover (TCC) Conterminous United States" centered on Madison, New Jersey (left; Fig. 2A) and map layered with "Urban Heat Islands and Land Surface Temperatures in New Jersey" (right; Fig. 2B). In Fig. 2A, a darker shade of green correlates to an area of higher coverage from nearby tree canopies (%), whereas the areas of White represent zones of Madison lacking canopies. In Fig. 2B, shades closer to red (~120 degrees Fahrenheit) correlate to higher land surface temperatures, as shades closer to purple (~88 degrees Fahrenheit) correlate to lower land surface temperatures.

In the graphic, the whiter areas of Fig. 2A overlay the same zones as the redder areas in Fig. 2B. Inversely, the greener areas of Fig. 2A overlay the same zones as the blue/purple areas in Fig. 2B.

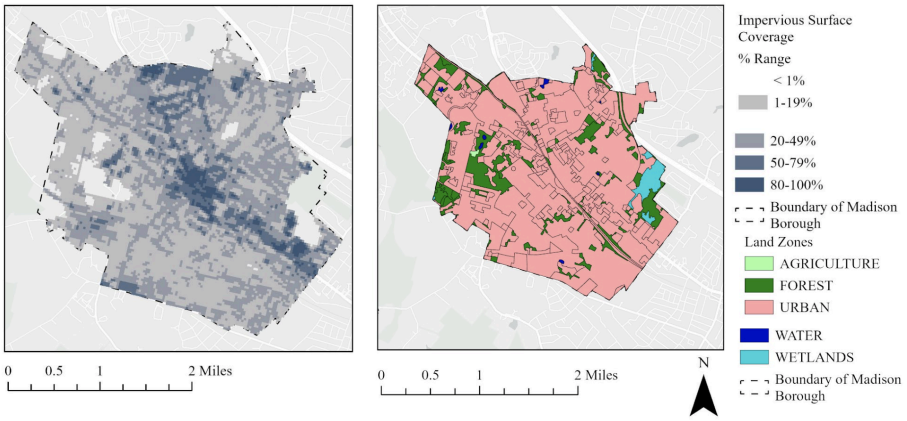


Fig. 3. Map of the impervious surfaces in Madison, New Jersey (left; Fig. 3A). Darker pixels represent a higher concentration of impervious surfaces, and lighter pixels correlate with a higher concentration of natural surfaces. Map depicts the zoning of Madison, New Jersey (right; Fig. 3B). Pink areas represent urban zones. Light green areas agricultural zones. Dark green zones represent forested areas. Teal areas represent wetlands. Bright blue areas represent water.

Grey pixels are consistently seen in Fig. 3A in the zones distinguished as 'urban' in Fig. 3B. There are few to no pixels in Fig. 3A in the zones distinguished as either 'agriculture', 'forest', or 'wetlands'.



Fig. 4. Open space distribution map using the "State, Local, and Nonprofit Open Space of New Jersey" layer (left) (Fig. 4A), and the same map with quarter-mile buffers around each open space (right) (Fig. 4B) to show the range of accessibility to said open spaces.

Since most of Madison is urban, a large portion of the surfaces are made of impervious materials, such as asphalt or concrete. In the borough, where there is the least amount of impervious surfaces, there are the most open spaces and most dense tree canopies. These areas also have the coolest temperatures.

Nested-scale investigation results

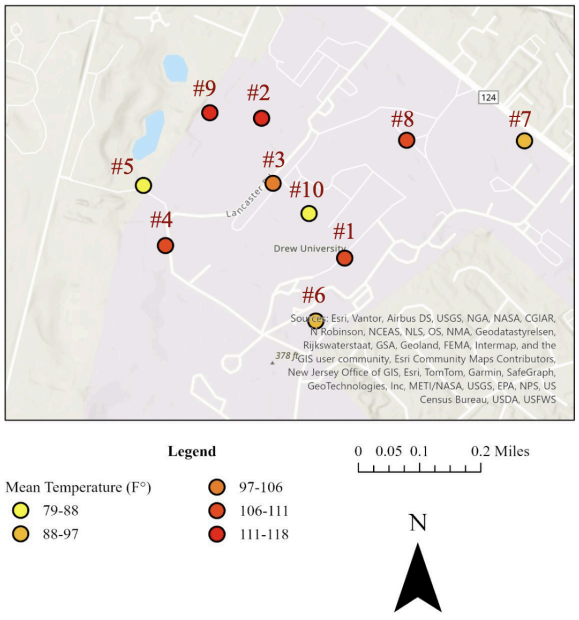


Fig. 5. Mean temperature results provided by Freshliance temperature loggers during the nested-scale investigation across the Drew University campus. Dark red points indicate a higher mean temperature (~111–118 degrees Fahrenheit), while yellow points indicate a lower mean temperature (~79–88 degrees Fahrenheit).

The mean temperature varied across the observation sites, with Sites 5 and 10 displaying the lowest mean temperatures, and Sites 2 and 9 displaying the highest mean temperatures (Fig. 5).

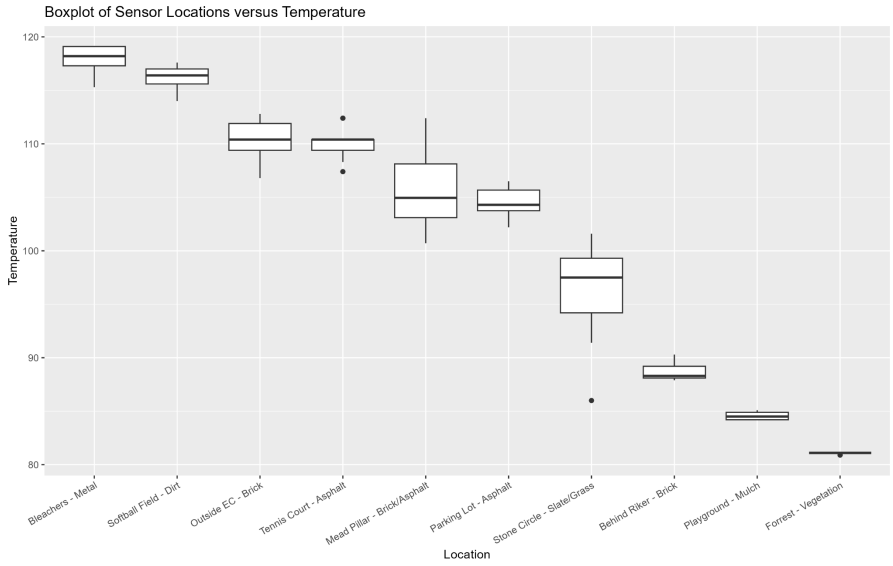


Fig. 6. Boxplots of the recorded temperatures stratified by sensor location. The 10 locations include: Bleachers—Metal, Softball Field—Dirt, Outside the Ehinger Center—Brick, Tennis Court—Asphalt, Mead Pillar—Brick/Asphalt, Stone Circle—Slate/Grass, Behind Riker—Brick, Playground—Mulch, and Forest—Vegetation. The locations are arranged in descending order by mean temperature. The highest temperature (Bleachers—Metal) has a mean temperature of 117.8 °F, and the lowest temperature (Forest—Vegetation) has a mean temperature of 81.1 °F.

The full pairwise-p-value is located in Appendix Table A1. Taking alpha as 0.05, all pairs were found significant (p-value < 0.05) except four: Tennis Court—Asphalt and Outside Ehinger Center—Brick (p-value = 1.000), Softball Field—Dirt and Bleachers—Metal (p-value = 0.928), Mead Pillar—Brick/Asphalt and Parking Lot—Asphalt (p-value = 0.986), and Playground—Mulch and Forest—Vegetation (p-value = 0.0502). The total one-way ANOVA p-value is 2.24e-55.

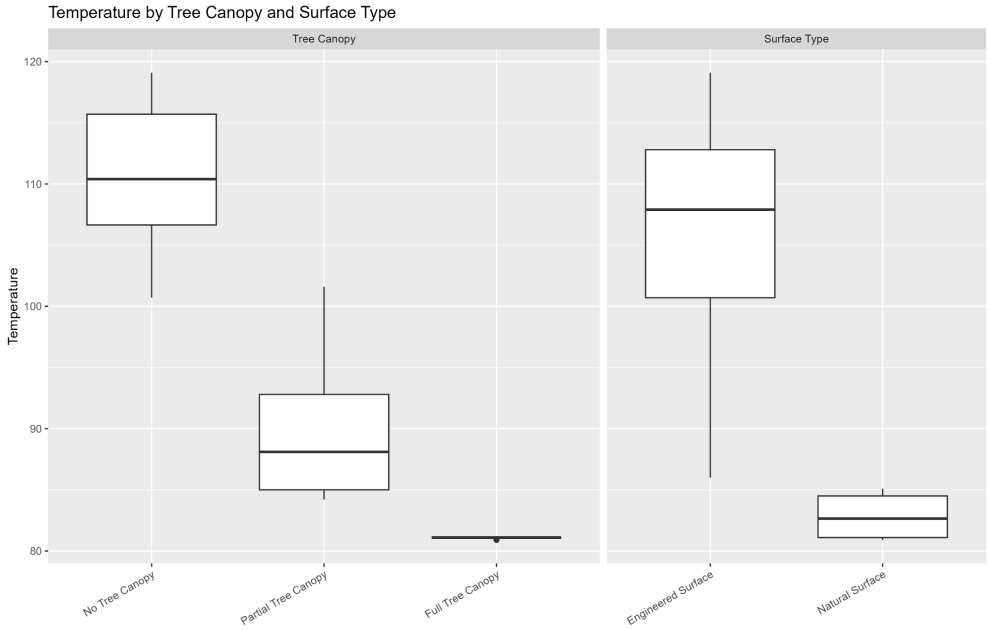


Fig. 7. Boxplots of the recorded temperatures stratified by tree canopy coverage (left; Fig. 7A) and the recorded temperatures stratified by surface type (right; Fig. 7B). In Fig. 7A, there is a difference in temperature between tree canopy coverage levels, with No Tree Canopy having a mean temperature of 110.9 °F, Partial Tree Canopy having a mean temperature of 89.8 °F, and Full Tree Canopy having a mean temperature of 81.1 °F. In Fig. 7B, engineered Surface types have a mean temperature of 106.1 °F, and natural surface types have a mean temperature of 82.8 °F.

The one-way ANOVA p-value of tree canopy coverage versus temperature is 2.29e-34. The ANOVA results of surface type and temperature showed statistical significance with a p-value of 2.08e-10. The full pairwise p-value table is shown in Appendix Table A2.

Table IV. Thermal observations across Drew University terrains

Observation	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**	**Site 6**	**Site 7**	**Site 8**	**Site 9**	**Site 10**
Thermal Sensation	4.1	4.0	4.3	4.1	1.6	3.0	3.1	4.3	4.7	2.4
Thermal Comfort	2.2	2.1	2.0	2.5	4.4	4.2	3.5	1.9	1.8	4.3
Wind Strength	1.7	3.2	3.4	2.7	1.8	1.9	1.2	2.5	1.4	2.9
Desire to Stay	2.1	2.0	1.8	2.4	4.3	4.3	3.3	1.7	1.0	4.7

Across the selected sites, Site 9 (Softball Field—Dirt) elicited the most discomfort amongst our team, while Site 5 (Forest—Vegetation) and Site 10 (Playground—Mulch) prompted the most responses indicating comfort and strong desire to stay among team members. Out of all the locations measured, Site 5 and Site 10 had the lowest mean temperature. The mean subjective wind strength was highest at Site 3 (parking lot) and lowest at Site 7 (bluestone circle).

Social demographic investigation results

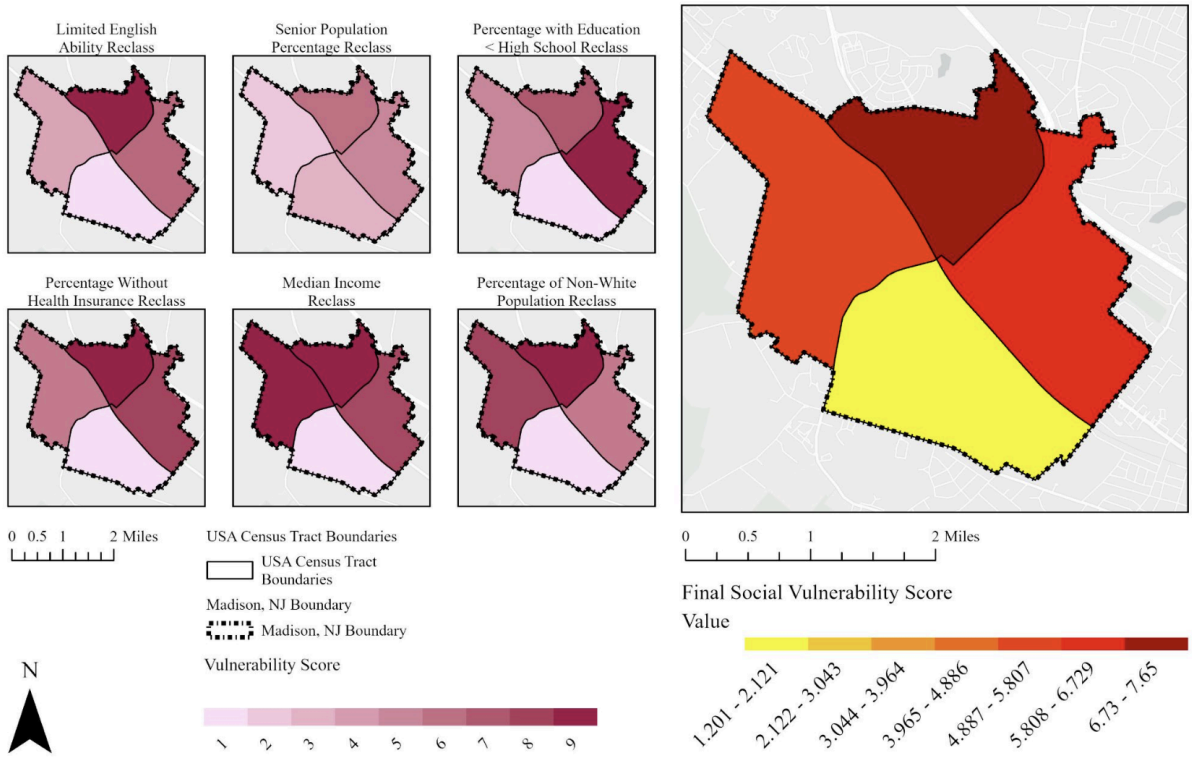


Fig. 8. Social demographic factors that influence social vulnerability in Madison, New Jersey. A thick dashed line shows the boundary of Madison, New Jersey. Thinner black lines show the boundaries between the four census tracts. Socioeconomic factors (left) considered were limited English ability (top left; Fig. 8A), senior population (top middle; Fig. 8B), completed education less than high school (top right; Fig. 8C), lack of health insurance (bottom left; Fig. 8D), median income (bottom middle; Fig. 8E), and non-White population (bottom right; Fig. 8F). In each of the factor layers, a darker shade of pink represents a higher vulnerability score, whereas a lighter shade of pink represents a lower vulnerability score. The composite map made up of the six layers presents a final social vulnerability score for each tract (right; Fig. 8G). A dark red corresponds to the highest social vulnerability, while a yellow corresponds to the lowest social vulnerability score.

Census Tract 429 displayed the highest prevalence in each of the six social vulnerability factors. For instance, Tract 429 had the highest score in limited English ability (Fig. 8A), senior population (Fig. 8B), lack of health insurance (Fig. 8D), and non-white population (Fig. 8F). Census Tract 431 also consistently displayed the lowest prevalence in each of the factors. Specifically, Tract 431 had the lowest score in limited English ability (Fig. 8A), lack of high school education (Fig. 8B), lack of health insurance (Fig. 8D), low median household income (Fig. 8E), and non-white population (Fig. 8F). Tract 429 had the highest social vulnerability score of 7.65, followed by Tract 430 (6.65), Tract 432 (5.2), and Tract 431 (1.4).

Heat Vulnerability Rasterization

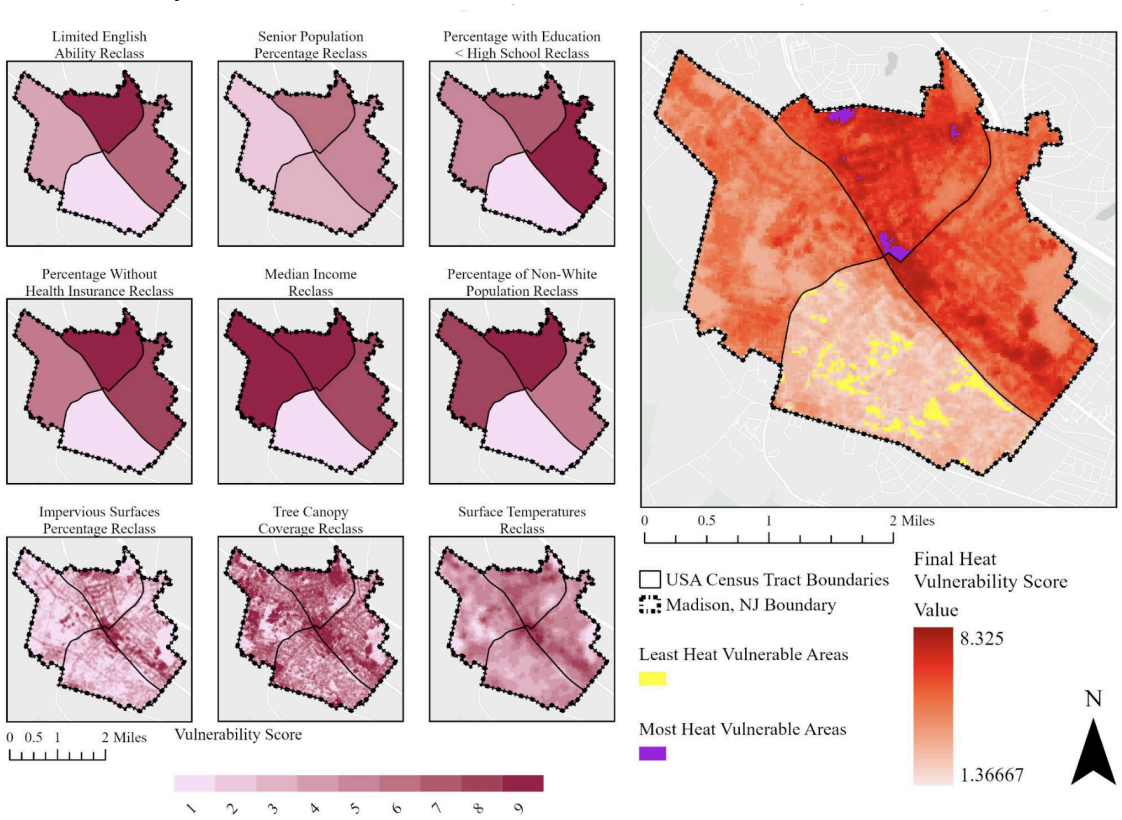


Fig. 9. Social and environmental factors that influence heat vulnerability in Madison, New Jersey. A thick dashed line shows the boundary of Madison, New Jersey. Thinner black lines show the boundaries between the four census tracts. Social factors considered were limited English ability, senior population, completed education less than high school, lack of health insurance, median income, and non-White population. Environmental factors considered were impervious surfaces (bottom right; Fig. 9A), tree canopy (bottom middle; Fig. 9B), and surface temperatures (bottom left; Fig. 9C). In each of the factor layers, a darker shade of pink represents a higher vulnerability score, whereas a lighter shade of pink represents a lower vulnerability score. The composite map made up of the six layers presents a final social vulnerability score for each tract (right; Fig 9D). A dark red corresponds to the highest heat vulnerability score, while a lighter shade of red corresponds to the lowest heat vulnerability score. Purple pixels represent the top 5% of the most heat-vulnerable areas. Yellow pixels represent the bottom 5% least heat vulnerable areas.

Tract 429 has the top 5% most heat vulnerable areas with scores ranging from 7.977 to 8.325 (Fig. 9D). Tract 431 has the bottom 5% least heat vulnerable areas with scores ranging from 1.715 to 1.36667 (Fig. 9D).

Health investigation results

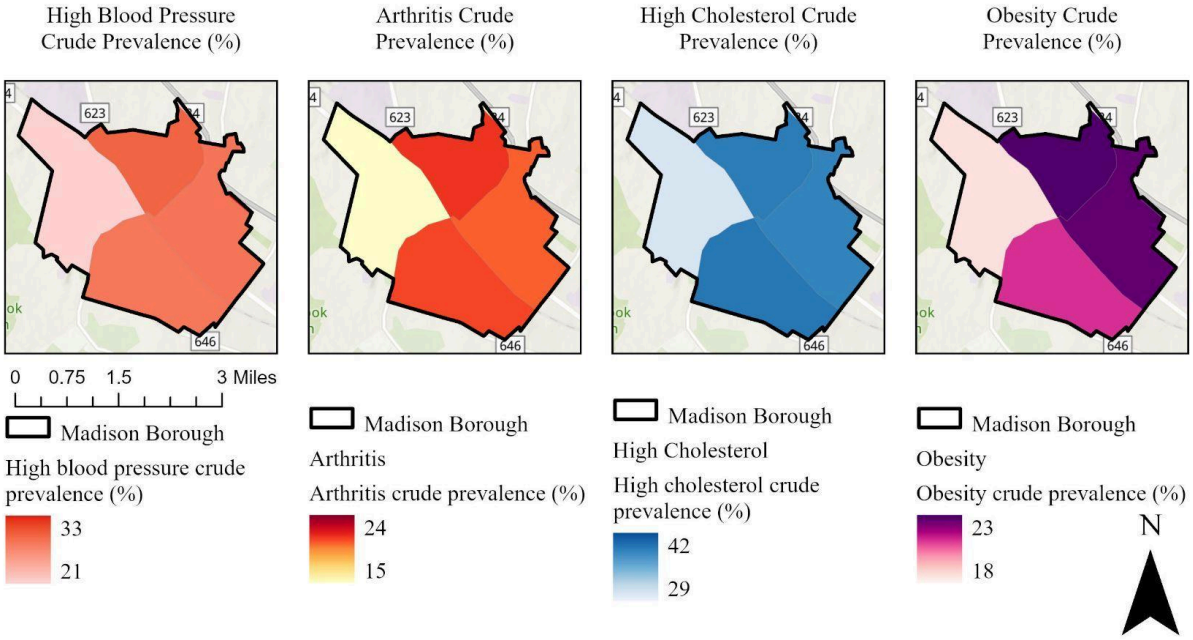


Fig. 10. Spatial distribution of crude prevalence estimates for high blood pressure (Fig. 10A), arthritis (Fig. 10B), high cholesterol (Fig. 10C), and obesity (Fig. 10D) across Madison Borough by census tract. Darker colors indicate higher prevalence while lighter colors represent lower prevalence.

The prevalence of high cholesterol, obesity, high blood pressure, and arthritis all exhibit similar spatial distributions across the Madison Borough (Fig. 10). Across all four conditions, Census Tract 429 consistently exhibited the highest prevalence while Census Tract 432 demonstrated the lowest prevalence. Tracts 430 and 431 display intermediate values between those of Tracts 429 and 432.

DISCUSSION

Based on our aggregation of heat vulnerability (Fig. 9) and sociodemographic (Fig. 8) indexes, Census Tracts 429 and 430 are more vulnerable to acquiring a heat-related illness than Census Tracts 431 and 432, with Census Tract 431 being the least vulnerable.

There is a clear disparity in public park acreage and accessibility throughout Madison, with Census Tracts 429 and 430 having far greater park acreage and accessibility than Census Tracts 431 and 432 (Fig. 4). Census Tracts 429 and 430 have greater population densities than the other tracts (Fig. 1B), but the difference alone cannot account for the large difference in park accessibility. One might expect denser areas to have less available open space, but the opposite pattern is observed. This spatial dynamic concentrates environmental benefits within dense urban pockets, potentially reinforcing systemic health and quality-of-life disparities for residents in lower-density tracts who lack equal local access to public green space.

Our results also substantiate the relevance of different environmental factors to average temperature in the area. The areas with little-to-no tree canopy are seen to repeatedly overlap,

with areas of Madison containing noticeably hotter surface temperatures (Fig. 2). This result corroborates past research studies and investigations, as it reinforces the concept that urban tree cover is imperative to cooler surface temperatures in metropolitan areas (McDonald et al., 2019), which is supported by the nested-scale investigation we conducted (Table IV). Fig. 1 and ANOVA results (Fig. 7A) showed that tree canopy coverage is highly correlated with temperature (p-value = 2.29e-34). The small range of the Full Tree Canopy boxplot (Fig. 7A) implies that a full tree canopy is associated with low temperature variance. Also, Fig. 1 suggests that surface type is highly correlated with temperature. The small range of the Natural Surface boxplot compared to the Engineered Surface boxplot (Fig. 7B) implies that natural surfaces are associated with low temperature variance, making both natural surfaces and tree canopy convergence pivotal in naturally regulating urban temperatures. This is especially relevant considering the many areas of Madison with significant concentrations of impervious surfaces (Fig. 3A) and municipally-established urban zones dominating the town's plan (Fig. 3B)

Furthermore, we show that there are clear disparities in sociodemographic factors such as education, median household income, race, and age across the different tracts in Madison (Fig. 8). Specifically, tracts 429 and 430 emerge as locations of relatively high social vulnerability, having consistently shown lower median household income (Fig. 8E), higher limited English ability (Fig. 8A), higher lack of health insurance (Fig. 8D), lower educational attainment (Fig. 8C), and a higher percentage of non-White residents (Fig. 8F) compared to the other two tracts. Additionally, it is to note that Tract 429, the most socially vulnerable, is also the most heavily populated (Fig. 1B). These spatial patterns suggest that socioeconomic differences across Madison are not isolated occurrences, but instead contribute to and fortify each other. For instance, lower educational attainment may be contributing to limited English proficiency, which may directly restrict access to higher-paying job opportunities, subsequently reducing the median household income in these areas. These socioeconomic limitations may result in communities facing more challenges when facing heat-related health hazards—whether it be communicating with healthcare providers or becoming aware of heat-related risks.

Similarly, consistent spatial patterns were also observed in health conditions across Madison (high cholesterol, obesity, high blood pressure, and arthritis) (Fig. 10), which suggest that these chronic health conditions may share common underlying determinants within Madison Borough. High blood pressure and arthritis crude prevalence (%) are both visibly elevated in Census Tract 429 (Fig. 10), the same tract that scores highest on both the Social Vulnerability Score and the Heat Vulnerability Score (Fig. 8G, 9D). The convergence is consistent with many of the existing underlying variables, including limited English proficiency, an aging population, low income, and lack of health insurance (Fig. 8). These variables can all restrict access to air conditioning, preventative cardiovascular care, and timely treatment, while chronic heat exposure independently strains the cardiovascular system (Chen, 2025). Obesity prevalence follows a similar trend (Fig. 10), as it tracks more closely with Census Tract 430's moderately high vulnerability scores (Fig. 8G, 9D). High cholesterol appears to be an exception, as it has the highest crude prevalence (%) in Census Tract 431 while having the lowest social and heat vulnerability (Fig. 8G, 9D, 10). This indicates that this outcome is likely shaped by factors that fall outside what the social and heat vulnerability maps capture. Together, three of the four health indicators analyzed reinforce the idea that Madison's most socially and heat vulnerable residents also carry the greatest chronic disease burden.

A major limitation of this study is that the open space analysis considers only publicly accessible open spaces included in the New Jersey Department of Environmental Protection (NJDEP) dataset. It does not consider private recreational spaces such as backyards, gyms, and private sports facilities that provide opportunities for physical activity outside of designated open spaces. Moreover, certain neighborhoods may be more walkable than others and do not factor in differences in park quality. Additionally, while this study identifies spatial patterns in park distribution, it is unable to assign a causal relationship to these patterns. Future investigations evaluating the accessibility of physical activity across Madison should analyze backyard space, private recreational facilities, neighborhood walkability, and park quality when evaluating accessibility.

The nested-scale temperature investigation also leaves room for error. Due to the natural movement of the sun, certain surfaces that would be otherwise exposed to direct sunlight at a different time of the day could have been shaded during the experiment, affecting temperature and thus survey results.

When assessing social demographic factors, there is a lack of statistics for more specific areas inside census tracts. Therefore, any disparities within the census tracts were not considered. Additionally, because there are two private universities in Madison's Census Tract 432, the student population may heavily influence age-related demographics, suppressing local population proportions.

The results we present in this study progress our understanding of the influence the environment and social demographics have on community health, and in particular, its imbalances within Madison, New Jersey. For this reason, the research conducted in this study can be utilized by the borough to narrow the identified disparities between census tracts. In regard to lowering the lack of higher education attainment in Census Tract 429, we recommend adding career-development and college-planning programs. Since education is correlated with income, increased higher education attainment in a census tract may lead to increased socioeconomic status and therefore higher quality of life and improved health.

Given that the quantity of tree canopy coverage and other vegetation is highly linked to lower surface temperatures, the most natural step forward would be maximizing green space throughout Madison, especially in the areas with disproportionately high surface temperatures (Fig. 2A, 2B) (McDonald et al., 2019). This can be achieved through expanding planting spaces, implementing structural innovations such as bioswales, and selecting resilient species to plant. Other high-impact strategies include expanding sidewalk cutouts, building continuous bioswales, and installing suspended overhead greenery or shade structures to minimize overly hot areas of town (Nazish et al., 2024).

The health findings point to several actions the Madison Borough Board of Health could pursue. Given that high blood pressure and arthritis prevalence cluster exactly where there is more social and heat vulnerability in Census Tract 429, we propose that the board should prioritize this tract for targeted cardiovascular health outreach. Potential initiatives include increased blood pressure screening events, reduced costs for primary care access, and

partnerships with local health providers to reach residents who may face language or insurance barriers to routine care. For Census Tract 430, where obesity prevalence is elevated and there are moderate vulnerability scores, Madison's Board of Health could consider investing in more walkable infrastructure, accessible recreation spaces, or fitness programs. The high cholesterol prevalence in Census Tract 431 suggests that a different kind of initiative is needed, such as a nutrition assessment and an awareness program. Overall, the health investigation data argue for tract-specific initiatives rather than a strategy for the entire borough.

Our team concluded that Census Tract 429, the most dense in population of the four census tracts in Madison, New Jersey, is the most socially vulnerable, heat-susceptible, and prone to health complications. Our study demonstrates that environmental, social, and health disparities are closely interconnected within Madison, New Jersey. This highlights the importance of localized public health planning. By addressing these inequities through targeted environmental and community interventions, the borough can build greater resilience to heat-related risks while improving long-term health outcomes for its residents.

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APPENDIX

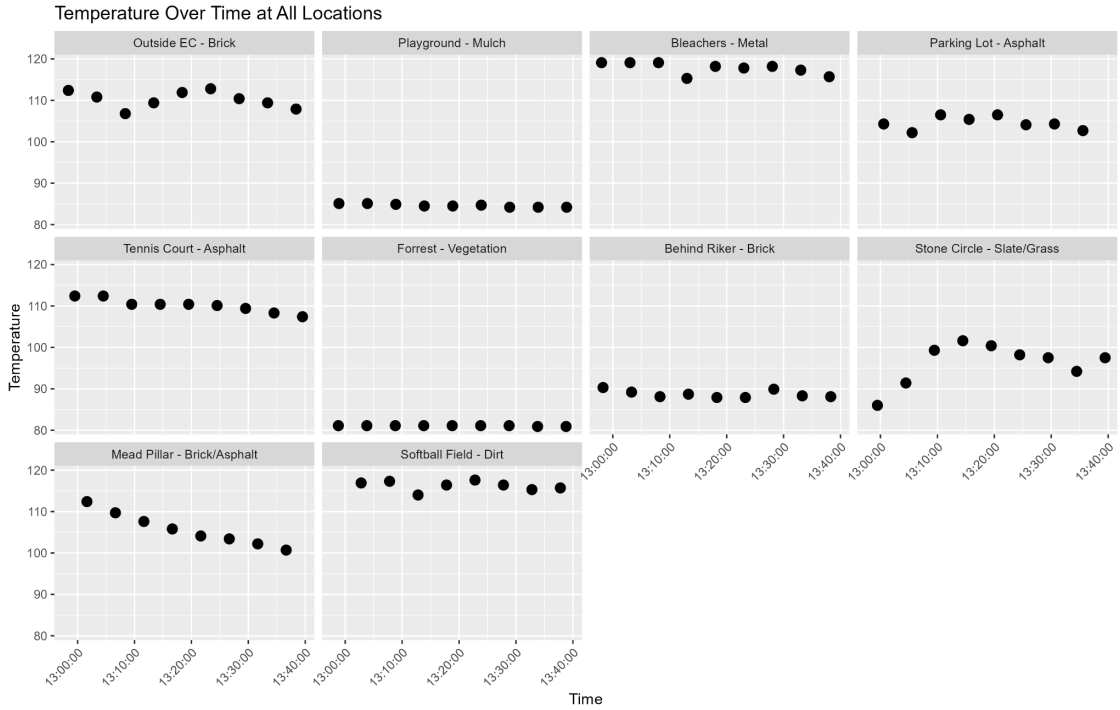


Fig. A1. All data points of temperature over time at all 10 temperature sensor locations. Time recorded in UTC -6:00.

Table AI. Pairwise p-value results of the one-way ANOVA test done on tree canopy coverage and temperature. Taking alpha as 0.05, all pairs were found significant (p-value < 0.05).

Tree_Canopy	No Tree Canopy	Partial Tree Canopy	Full Tree Canopy
No Tree Canopy			
Partial Tree Canopy	1.582e-10		
Full Tree Canopy	1.582e-10	8.361e-05	

Table AII. Pairwise p-value results of the one-way ANOVA test done on sensor location and temperature.

Sensor	Outside EC—Brick	Bleachers—Metal	Parking Lot—Asphalt	Tennis Court—Asphalt	Forrest—Vegetation	Behind Riker—Brick	Stone Circle—Slate/Grass	Mead Pillar—Brick/Asphalt	Softball Field—Dirt	Playground—Mulch
Outside EC—Brick										
Bleachers—Metal	< 0.001									
Parking Lot—Asphalt	< 0.001	<0.001								
Tennis Court—Asphalt	1.000	<0.001	<0.001							
Forrest—Vegetation	< 0.001	<0.001	<0.001	< 0.001						
Behind Riker—Brick	< 0.001	<0.001	<0.001	< 0.001	<0.001					
Stone Circle—Slate/Grass	< 0.001	<0.001	<0.001	< 0.001	<0.001	<0.001				
Mead Pillar—Brick/Asphalt	0.00572	<0.001	0.986	0.00695	<0.001	<0.001	<0.001			
Softball Field—Dirt	< 0.001	0.928	<0.001	< 0.001	<0.001	<0.001	<0.001	<0.001		
Playground—Mulch	< 0.001	<0.001	<0.001	< 0.001	0.0502	0.0109	<0.001	<0.001	<0.001	

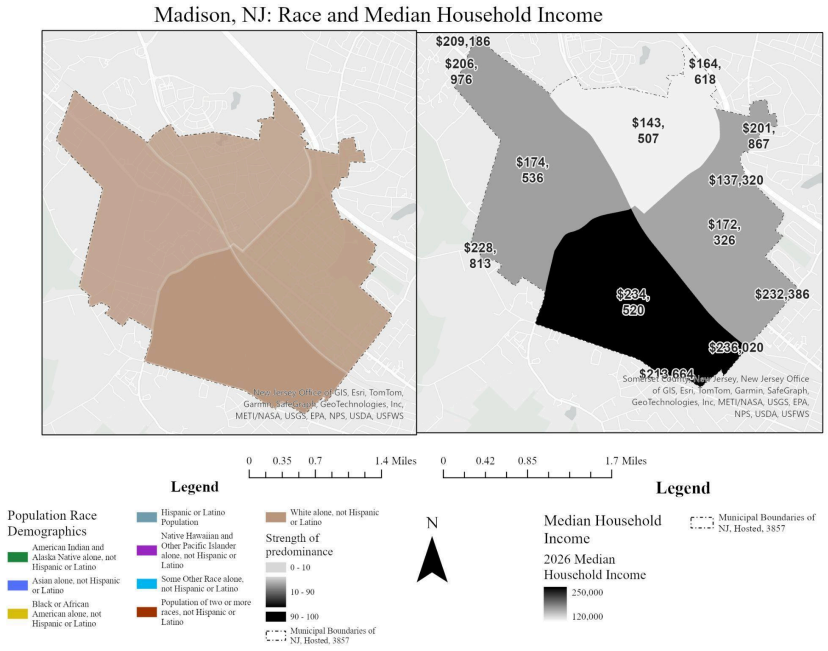


Fig. A2. Predominant race and median household income by census tract in Madison, New Jersey. Darker colors indicate higher concentrations of the predominant race and higher median household income.

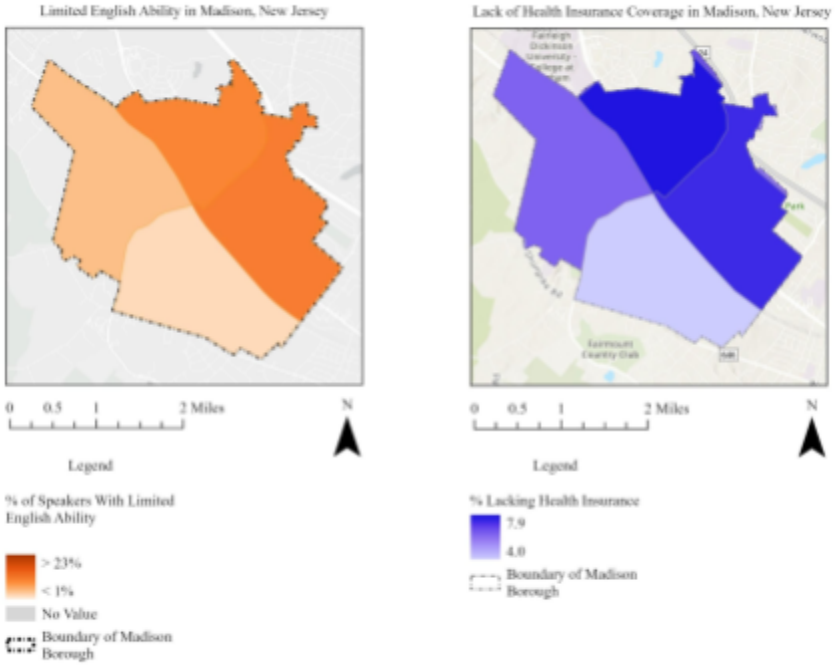


Fig. A3. Limited English ability and health insurance coverage by census tracts in Madison, New Jersey. Darker colors indicate less English ability and more individuals without health insurance coverage.

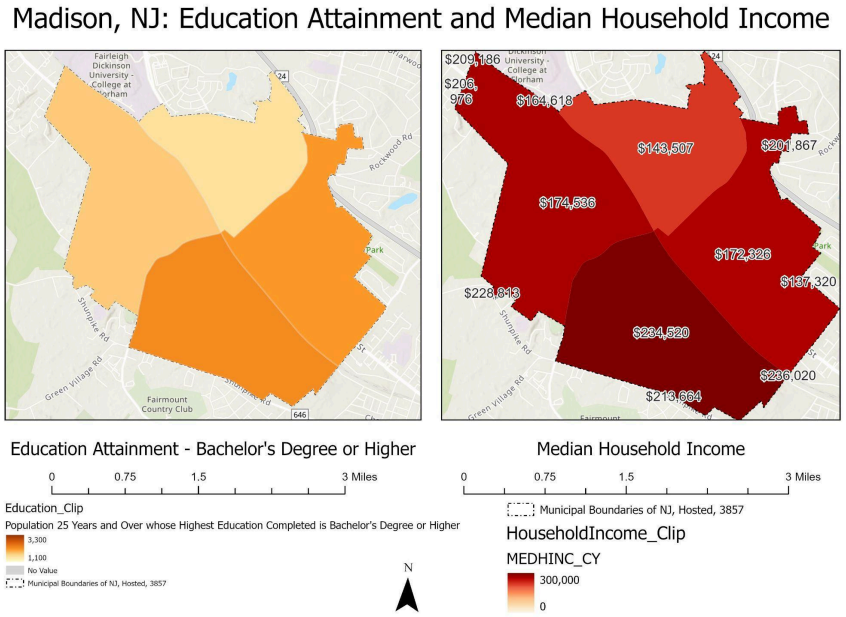


Fig. A4. Percent bachelor's degree attainment among adults 25 years or older and median household income by census tracts in Madison, New Jersey. Darker colors indicate attainment of a bachelor's degree or higher and higher median household income.

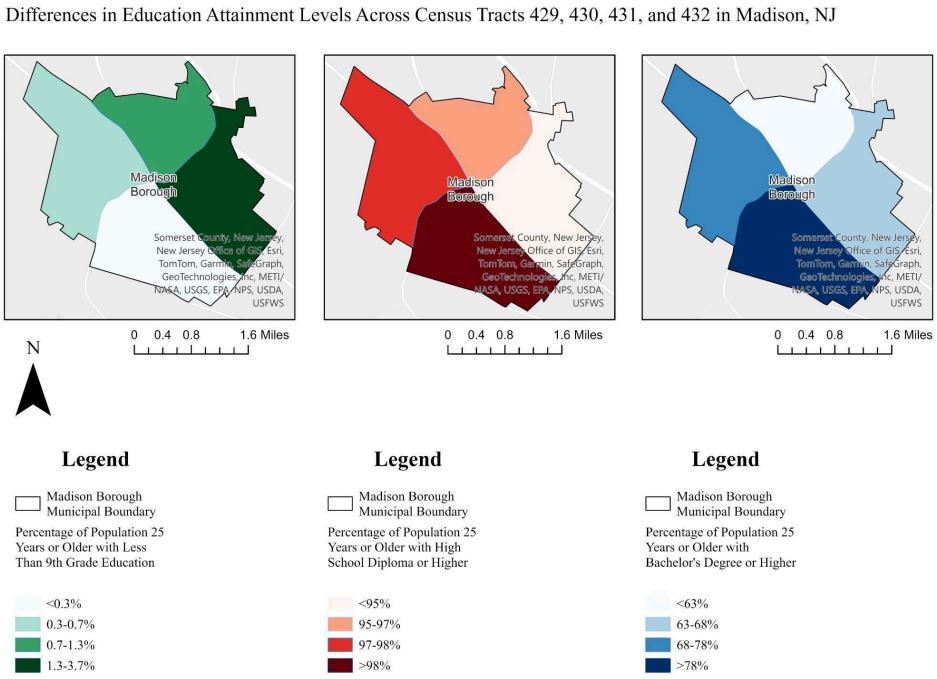


Fig. A5. 9th grade education attainment or lower, high school diploma or higher attainment, and bachelor's degree or higher attainment among adults 25 years or older by census tract in Madison, New Jersey. Darker colors indicate attainment of education up to 9th grade or lower, high school or higher, and bachelor's degrees or higher.

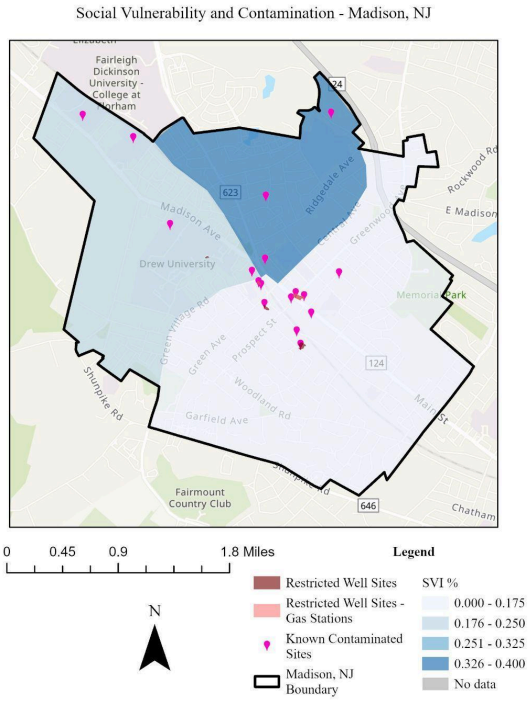


Fig. A6. All restricted well areas (NJDEP Classification Exception Areas) and contamination sites (NJDEP Known Contaminated Sites), with the gas station contamination sites in red, and Social Vulnerability Index (SVI, CDC/ATSDR 2022) of each Census Tract.

Abbreviations

NJOGIS	New Jersey Office of GIS
ACS	American Community Survey
CDC	Centers for Disease Control and Prevention
NLCD	National Land Cover Dataset
USDA	United States Department of Agriculture
NJDEP	New Jersey Department of Environmental Protection