rising heat

UNDERSTANDING EXPOSURE
AND VULNERABILITY
IN THE CITY OF SAN BERNARDINO

tinkercraft

This study was made possible through funding from the California LCI iCARP Program.

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CONTENTS

As cities continue to warm, extreme heat is no longer an abstract climate risk but a lived, unevenly distributed urban condition shaped by land use, development patterns, and social vulnerability.

INTRODUCTION

Extreme heat has emerged as one of the most pressing and inequitable climate challenges facing cities today. In inland Southern California, rising temperatures intersect with decades of urban growth, infrastructure investment, and land-use change, producing localized heat burdens that are experienced unevenly across neighborhoods. San Bernardino, shaped by its transformation from agricultural landscapes to a car-oriented, industrial, and residential city, offers a critical lens through which to examine how urban form, environmental change, and social conditions converge to shape heat exposure.

This study maps patterns of heat exposure and vulnerability across the City of San Bernardino over the past two decades, combining satellite-derived temperature data, fine-grained vegetation analysis, land-use information, and socioeconomic indicators. By visualizing where heat has intensified, where cooling capacity has declined, and which communities face compounding social and environmental risks, the project moves beyond citywide averages to reveal neighborhood-scale disparities. The findings highlight how heat is not only a climatic phenomenon but also a spatial and social one produced through planning decisions, development trajectories, and unequal access to resources, and pointing toward the need for targeted, place-based strategies to address rising urban heat.

MAPPING TEMPERATURE REVEALS HOW PATTERNS OF GROWTH AND LAND COVER SHAPE THE CITY'S THERMAL LANDSCAPE

SUMN
OVERVIEW C

MARY
OF FINDINGS

OVERVIEW OF FINDINGS

Extreme heat is no longer a distant climate projection — it is a lived condition reshaping cities across inland Southern California. In San Bernardino, two decades of warming, land-use change, and vegetation loss have transformed the city's thermal landscape in ways that are measurable, mappable, and deeply unequal.

Our recent study, "Rising Heat: Understanding Exposure and Vulnerability in the City of San Bernardino," examines how heat exposure has intensified between 2000 and 2020 — and which neighborhoods face the greatest compounded risks.

Heat Is Increasing — Almost Everywhere

The data are unambiguous.

Between 2000 and 2020:

- 206 of 207 block groups experienced an increase in summer land surface temperature.
- Average land surface temperatures rose from 37.5°C to 41.4°C.
- Average air temperatures increased from 32.3°C to 34.8°C.
- Heat-wave duration expanded dramatically — from 4.6 days per year in 2000 to 16.8 days per year in 2020.

In short: summers are hotter, and extreme heat lasts longer.

Downtown San Bernardino and surrounding neighborhoods experienced some of the largest increases, particularly in areas with higher building density and reduced vegetation.

Heat is not isolated to a few hotspots — it reflects a citywide shift in baseline conditions.

From Fields to Freeways: Urban Form Shapes Heat

San Bernardino's transformation from agricultural landscape to industrial and car-oriented city has had thermal consequences.

Land use establishes the baseline conditions that shape heat behavior:

- Surface materials (asphalt, roofing),
- Building density,
- Fragmented open space,
- Declining vegetation cover.

Industrial corridors and transportation infrastructure concentrate heat-absorbing surfaces. Residential infill reduces small, dispersed green spaces. The result is an intensified urban heat island effect, especially in more densely built areas.

We found that block groups with higher building counts tend to experience larger increases in extreme heat days — a clear link between development intensity and local warming.

The Disappearing Cooling System: Vegetation Loss

One of the most striking findings is the scale of fine-grained vegetation loss.

Over the past two decades:

- Most block groups lost more than 60% of vegetated area, particularly small, dispersed patches and linear greenbelts.
- Standard land cover datasets underestimated this change, detecting only 20–30% loss because they miss patches smaller than ~4,000 square feet.

Using spectral unmixing techniques, we were able to detect sub-pixel vegetation — sparse street trees, roadside shrubs, and small green fragments that conventional datasets overlook.

These small spaces matter. Their disappearance disproportionately increases exposure in residential neighborhoods.

Heat is Also Social

Heat exposure does not fall evenly across the city.

When we compared the top 25% most heat-exposed areas to the bottom 25%, clear disparities emerged:

- Hispanic population share: 61.6% vs. 39.4%
- Poverty rate: 26.8% vs. 6.4%
- Adults without a high school diploma: 27.4% vs. 9.3%
- Employment in vulnerable outdoor industries: 39.4% vs. 16.2%
- Older housing stock (often lacking efficient cooling): 66.3% vs. 51.2%

Communities experiencing the greatest increase in extreme heat days are also more likely to face economic hardship, aging housing infrastructure, and outdoor employment exposure.

Heat, in this context, is spatial, structural, and social.

A Composite Heat Vulnerability Framework

To move beyond isolated indicators, we developed a heat vulnerability score combining:

1. Heat exposure (surface temperature, air temperature, extreme heat duration)
2. Adaptive capacity (vegetation, built environment characteristics)
3. Sensitivity (poverty, age, race/ethnicity, outdoor work, housing conditions)

The resulting map identifies clusters where rising exposure overlaps with declining adaptive capacity and high social sensitivity — areas where intervention is most urgent.

Why This Matters for California Climate Adaptation

This project, funded by California's LCI iCARP program, demonstrates how climate planning can move from general risk awareness to neighborhood-scale precision.

1. Three key lessons emerge:
2. Heat is accelerating at the neighborhood scale, not just citywide.\
3. Small green spaces matter, and their loss is undercounted.

Equity must be central to adaptation planning, because the communities most exposed are also the least resourced.

As climate change intensifies, extreme heat will increasingly shape public health, infrastructure stress, housing stability, and economic vulnerability.

Targeted, place-based strategies — urban greening, cool roofs, shade infrastructure, tree canopy restoration, housing retrofits — must prioritize neighborhoods where exposure and vulnerability intersect.

Staying Cool, Staying Connected

Urban heat is not inevitable.

It is shaped by planning decisions, development patterns, and resource distribution.

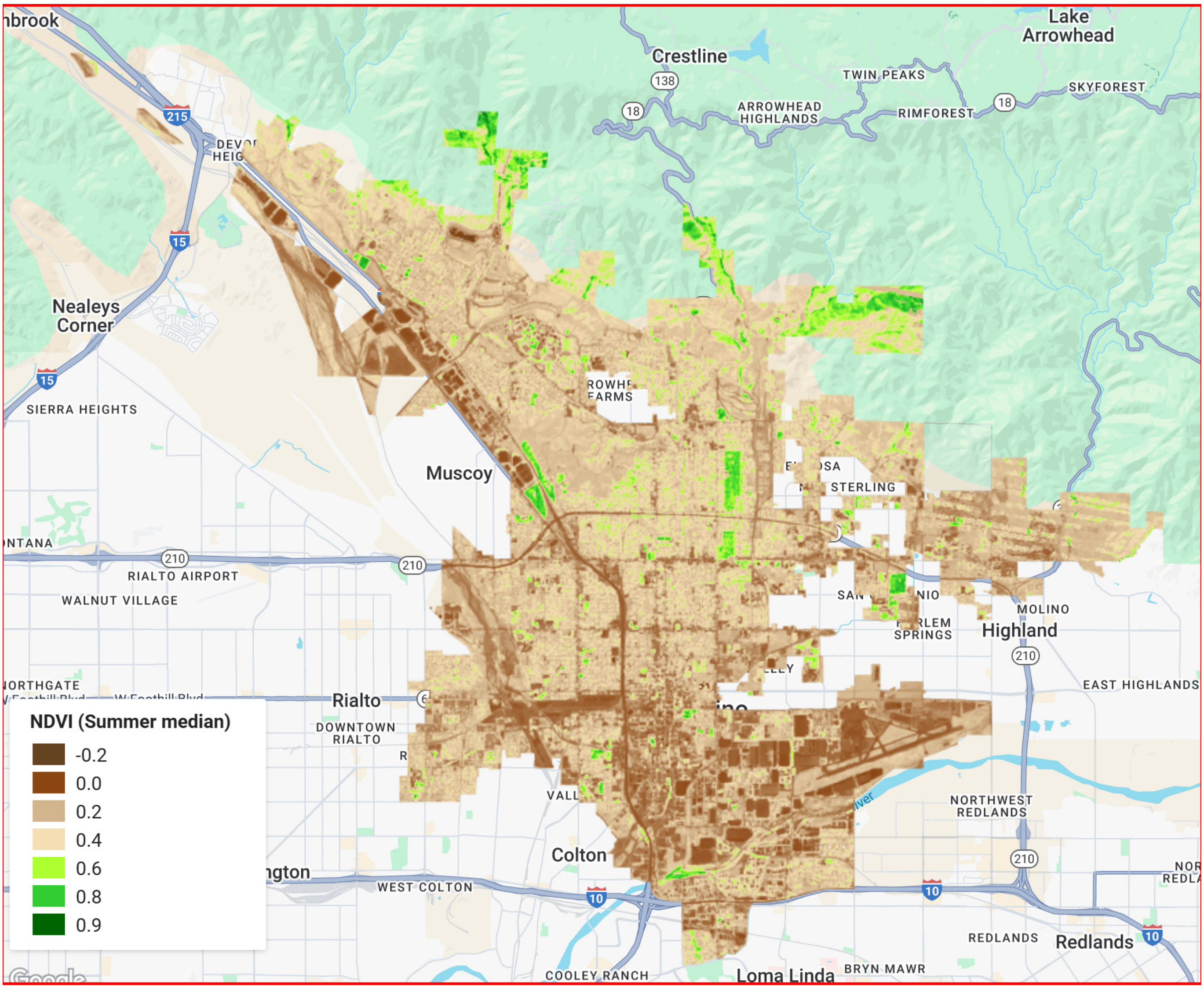
By mapping exposure and vulnerability together, we can design interventions that are not only climate-responsive but equity-driven.

San Bernardino offers a powerful case study — and a call to action — for inland cities across California.

FROM FIELDS T
SAN BERNARDINO'

SECTION 1

TO FREEWAYS:
'S GROWTH STORY



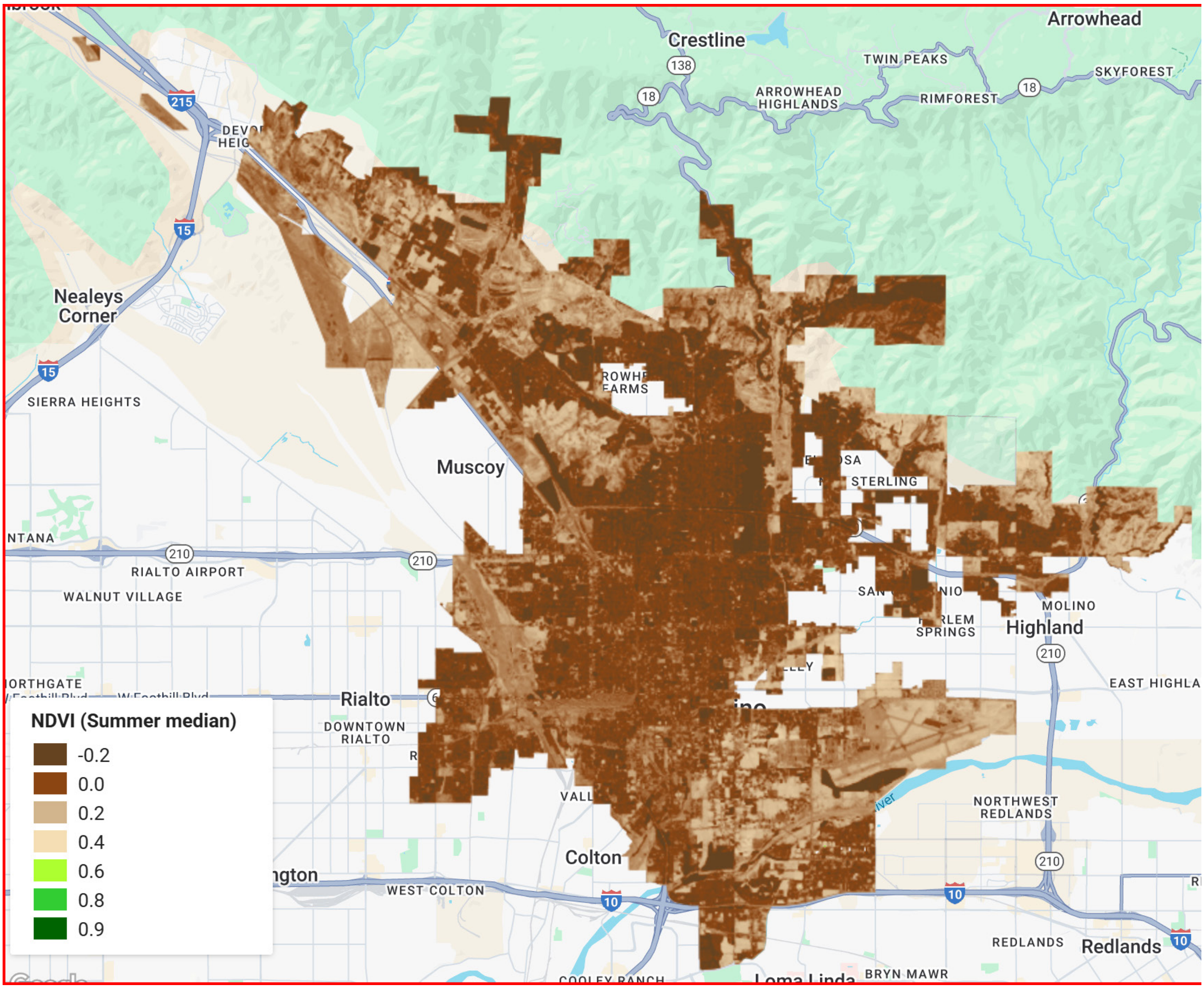
KEY TAKEAWAYS

Downtown San Bernardino experienced the largest increase in summer land surface temperature.

Nearly all block groups show warming trends between 2000 and 2020.

Areas with greater development intensity tend to exhibit larger temperature increases.

VEGETATION GREENNESS BY NDVI IN SUMMER 2000 VS 2020



SUMMER LAND SURFACE TEMPERATURE CHANGE (2000–2020)

This map shows how summer land surface temperatures have shifted across San Bernardino over the past two decades. Rather than absolute heat, it highlights change over time, revealing where warming has accelerated most rapidly as the city has continued to urbanize. Darker areas indicate larger increases in surface temperature, while lighter areas show more modest change.

Across nearly the entire city, land surface temperatures have risen, with the most pronounced increases concentrated in and around downtown San Bernardino and adjacent neighborhoods. These patterns closely align with areas of intensified development, higher building density, and reduced vegetation cover. The widespread nature of the increase—observed in nearly every block group—suggests that rising surface heat is not isolated to a few hotspots, but reflects a citywide shift in thermal conditions over time.

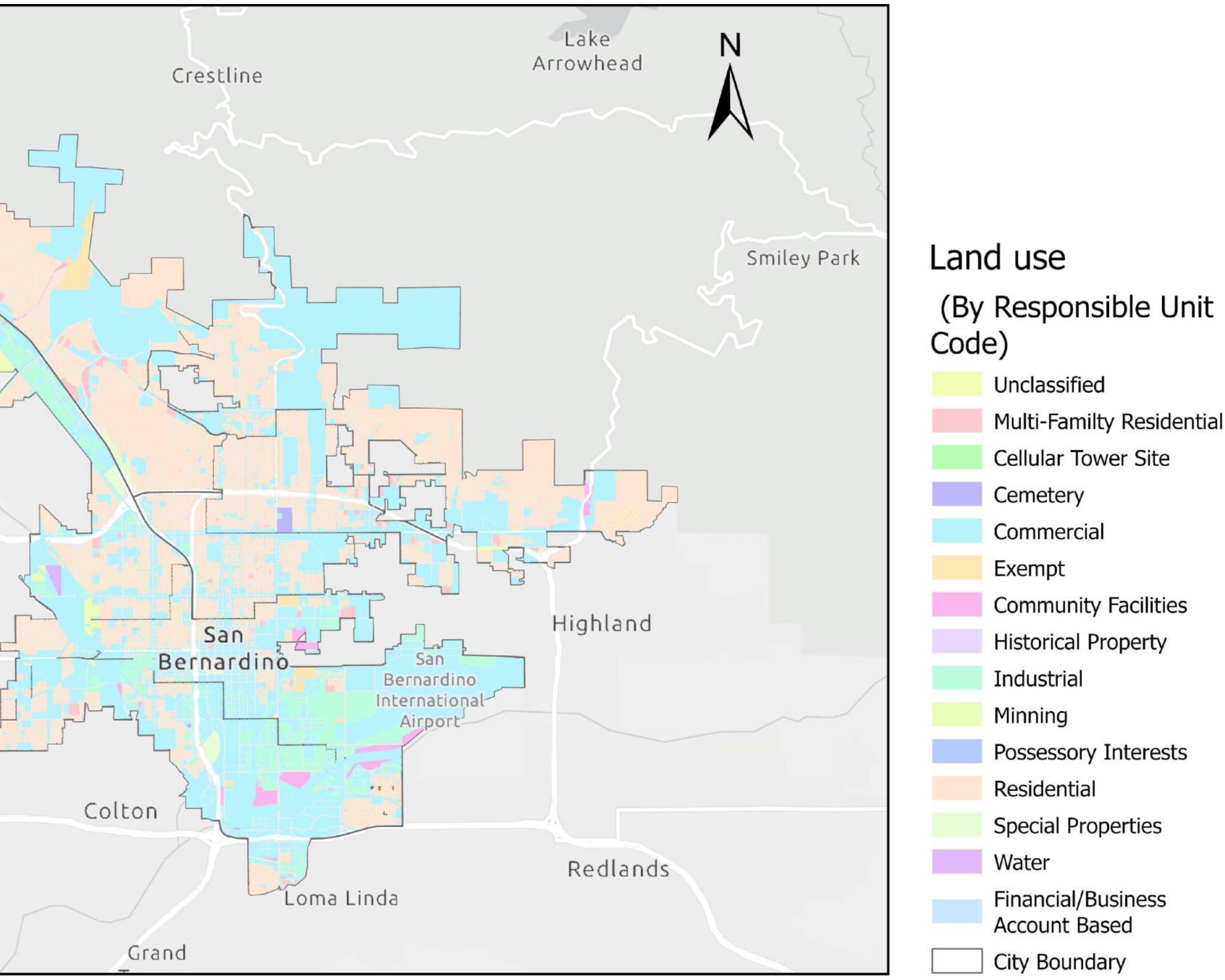
LAND USE

LAND USE ESTABLISHES THE BASELINE CONDITIONS—SURFACE MATERIALS, BUILDING DENSITY, AND VEGETATION COVER—THAT INFLUENCE HOW HEAT BEHAVES ACROSS THE CITY.

Source: San Bernardino Coun

This map shows the distribution of major land-use types across the City of San Bernardino, illustrating how residential neighborhoods, commercial corridors, industrial areas, transportation infrastructure, and open spaces are arranged across the urban landscape. These patterns reflect decades of growth shaped by agriculture, rail and freeway expansion, and suburban development.

Large expanses of industrial and commercial land are concentrated along transportation corridors, while lower-density residential areas extend outward from the city center. Open space and undeveloped land are unevenly distributed, often fragmented by infrastructure and development. Together, these land-use patterns define the physical structure of the city and provide critical context for understanding how heat is absorbed, stored, and distributed across different areas.

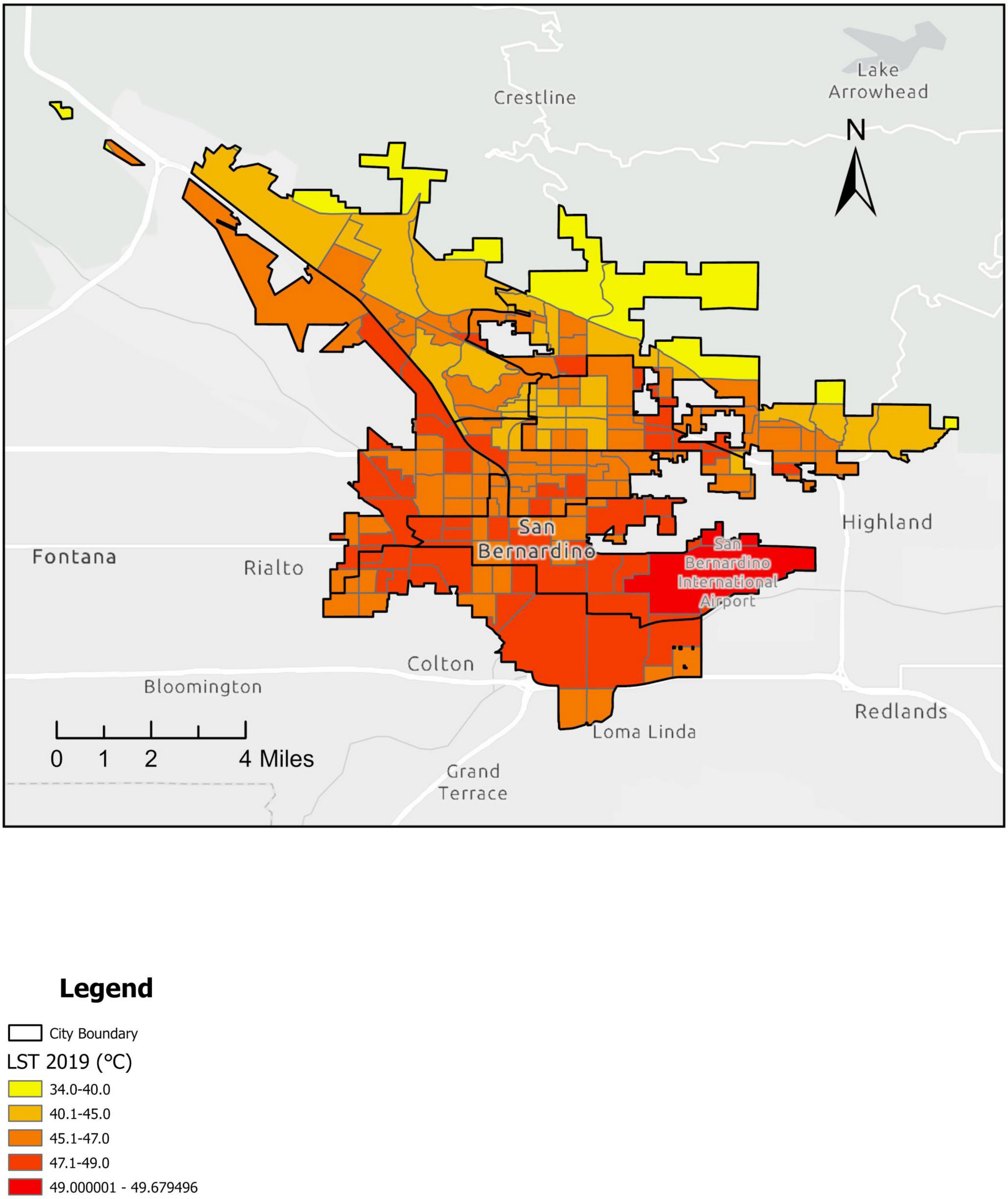


ty Parcel Layer and San Bernardino Property Characteristics File

SECTION 2

RISING
CHANGING PATTE

HEAT:
RNS OF EXPOSURE


Crestline
Lake Arrowhead
N
Highland
San Bernardino
San Bernardino International Airport
Fontana
Rialto
Colton
Bloomington
Redlands
Loma Linda
Grand Terrace
0 1 2 4 Miles
Legend
City Boundary
LST 2019 (°C)
34.0-40.0
40.1-45.0
45.1-47.0
47.1-49.0
49.000001 - 49.679496

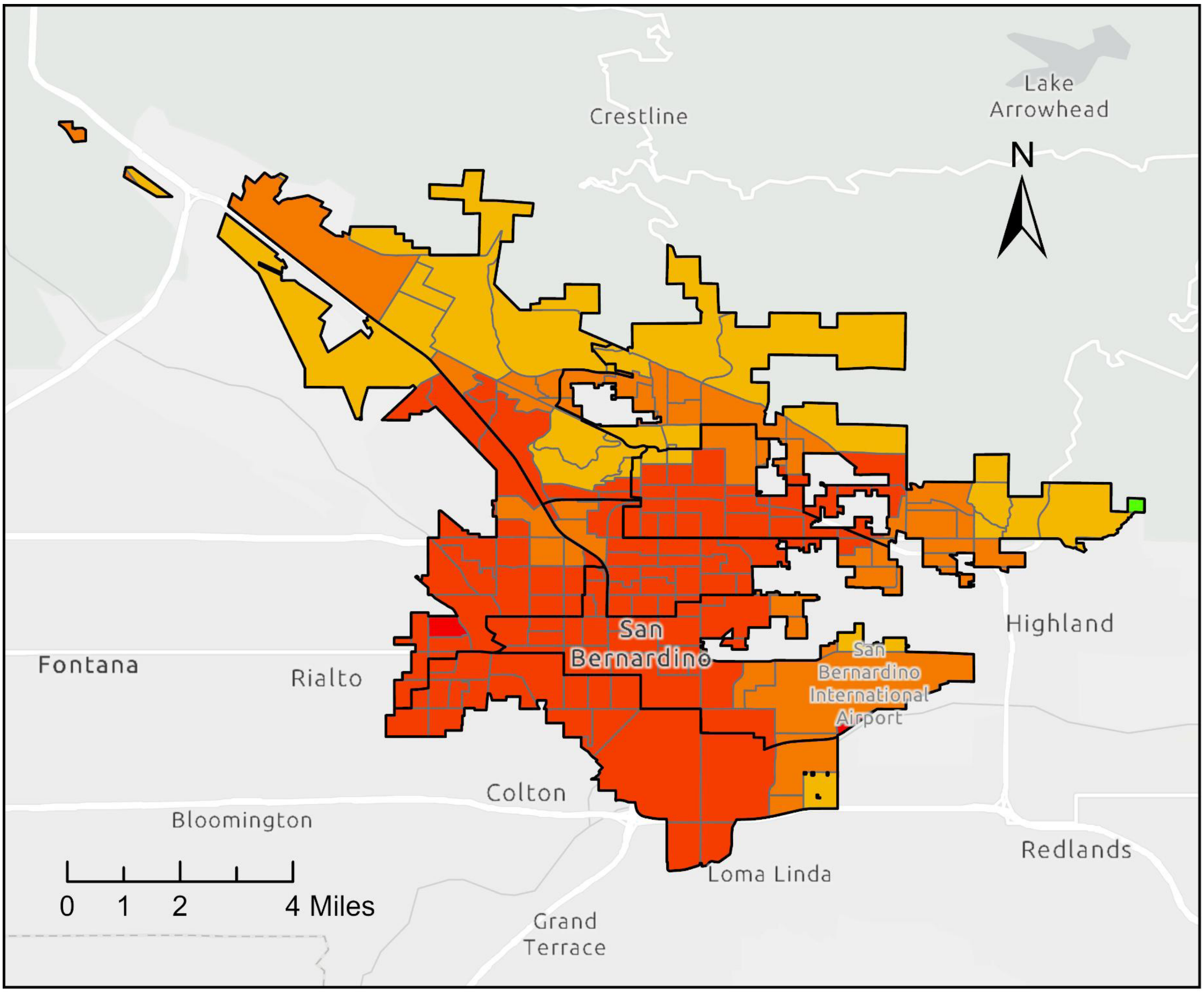
Land use shapes how heat is absorbed, stored, and released across the city.

LAND SURFACE TEMPERATURE

MEASURED IN CELSIUS, FOR THE YEAR 2019

The map here shows the land surface temperature (LST) across San Bernardino during 2019. Darker areas are hotter, while lighter areas are cooler.

Paved streets, rooftops, and industrial zones tend to absorb and hold more heat, while parks, trees, and open spaces stay cooler. By visualizing surface temperatures, we can see which neighborhoods experience the most heat and begin to plan ways to cool the city.



Source: Landsat 8 Images' thermal bands (Cloud Coverage<5%)

City Boundary

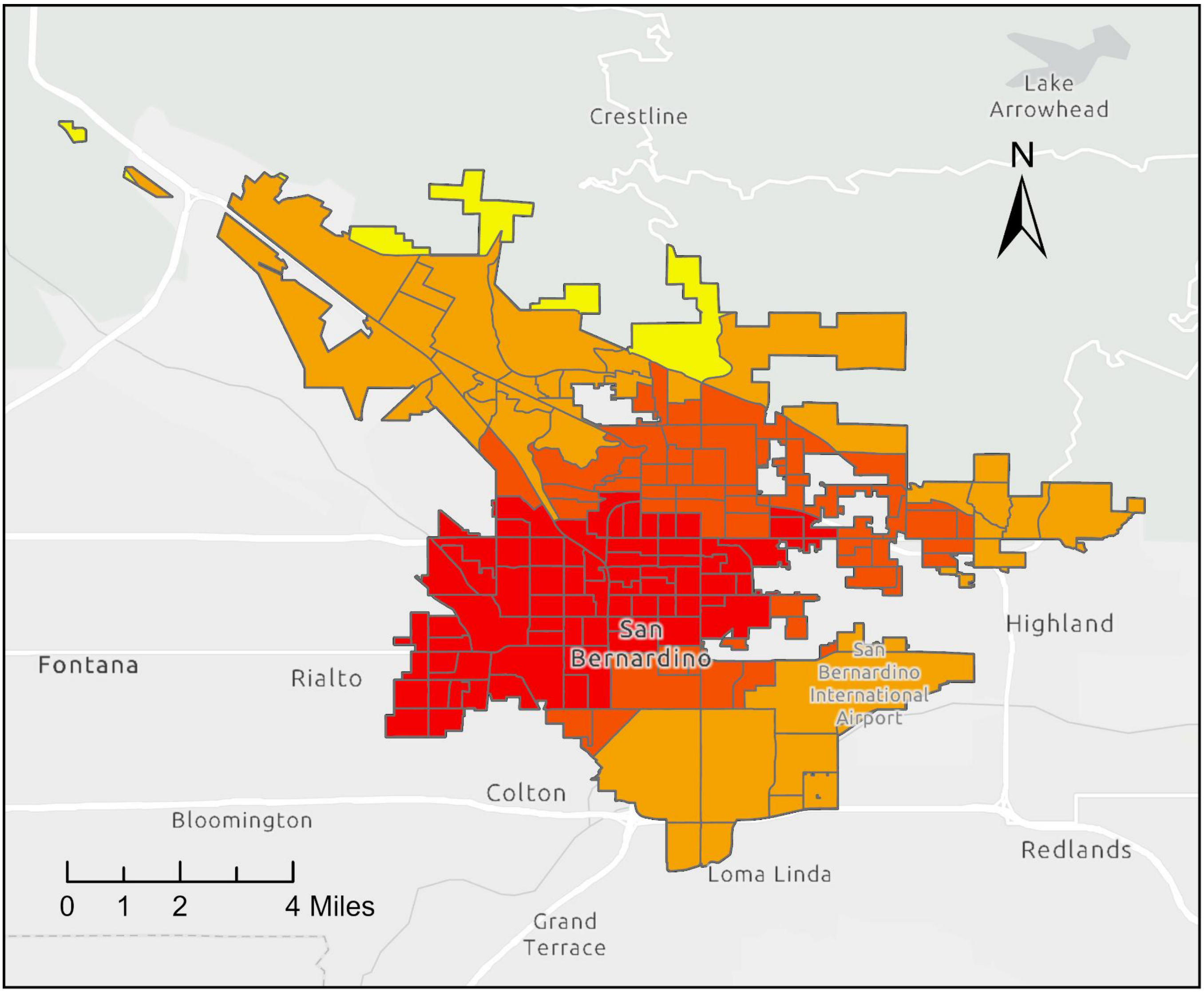
LST Change (°C)

- -0.3-0.0
- 0.1-1.0
- 1.1-1.5
- 1.6-2.5
- 2.5-3.5

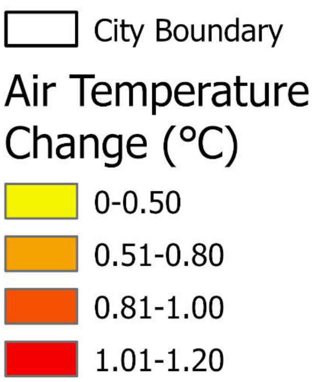
LAND SURFACE TEMPERATURE CHANGE

Takeaways:

+ Downtown San Bernardino saw the greatest increase
+ In 206 out of 207 Block Groups the average Land Surface Temperature increased



Source: Landsat 8 Images' thermal bands (Cloud Coverage<5%)



Mapping population distribution reveals the city's spatial structure.

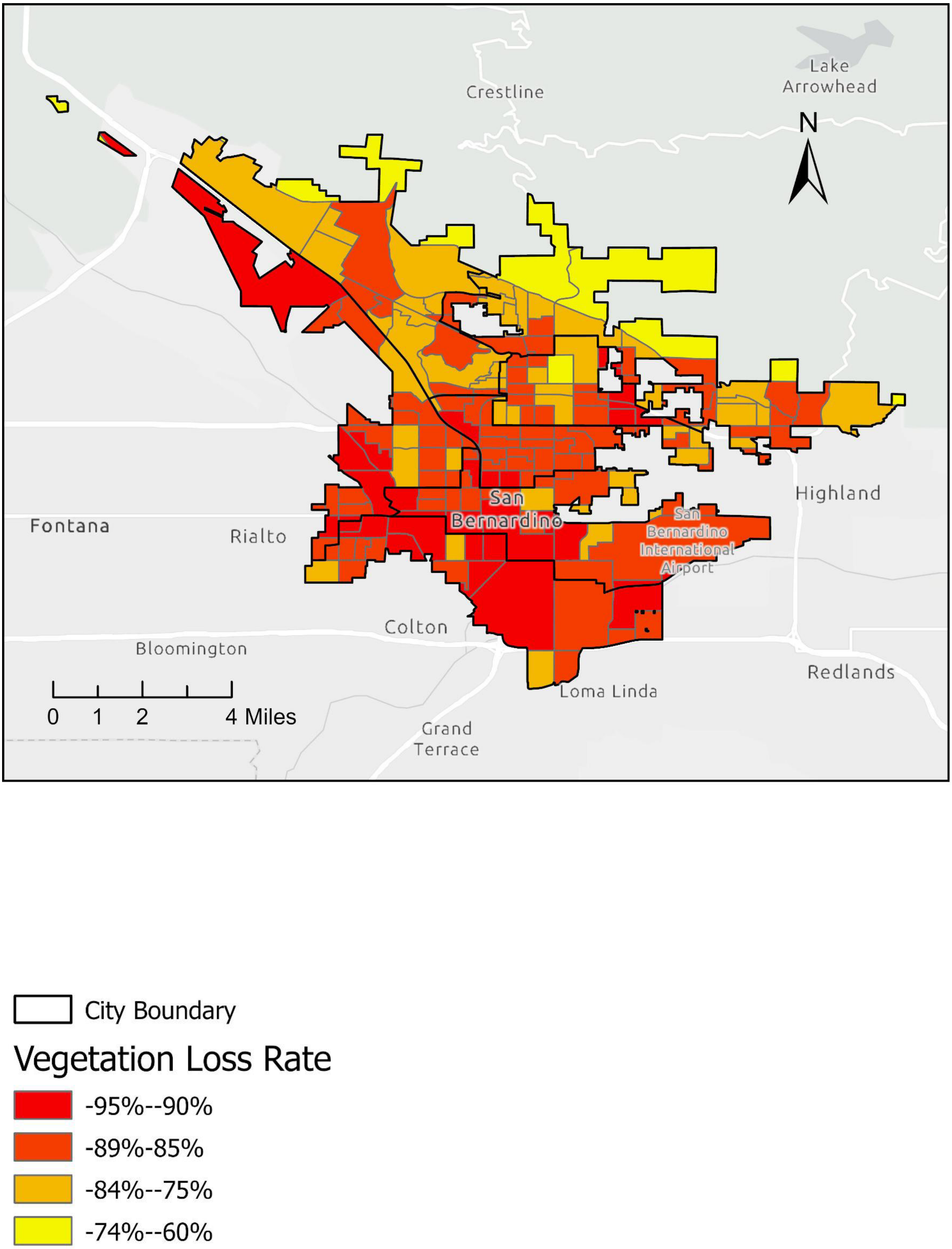
AIR TEMPERATURE CHANGE

SUMMER AVERAGE AIR TEMPERATURE CHANGE 2000 TO 2020

Takeaways:

+ Downtown San Bernardino and Lytle Creek neighborhoods saw the greatest increase.

+ All 207 Block Groups experienced an increase in average air temperature


Crestline
Lake Arrowhead
N
Fontana
Rialto
San Bernardino
San Bernardino International Airport
Highland
Colton
Bloomington
Redlands
Loma Linda
Grand Terrace
0 1 2 4 Miles
City Boundary
Vegetation Loss Rate
-95%--90%
-89%-85%
-84%--75%
-74%--60%

Small and dispersed green spaces are increasingly fragmented. Changes in land cover reshape the city's thermal landscape.

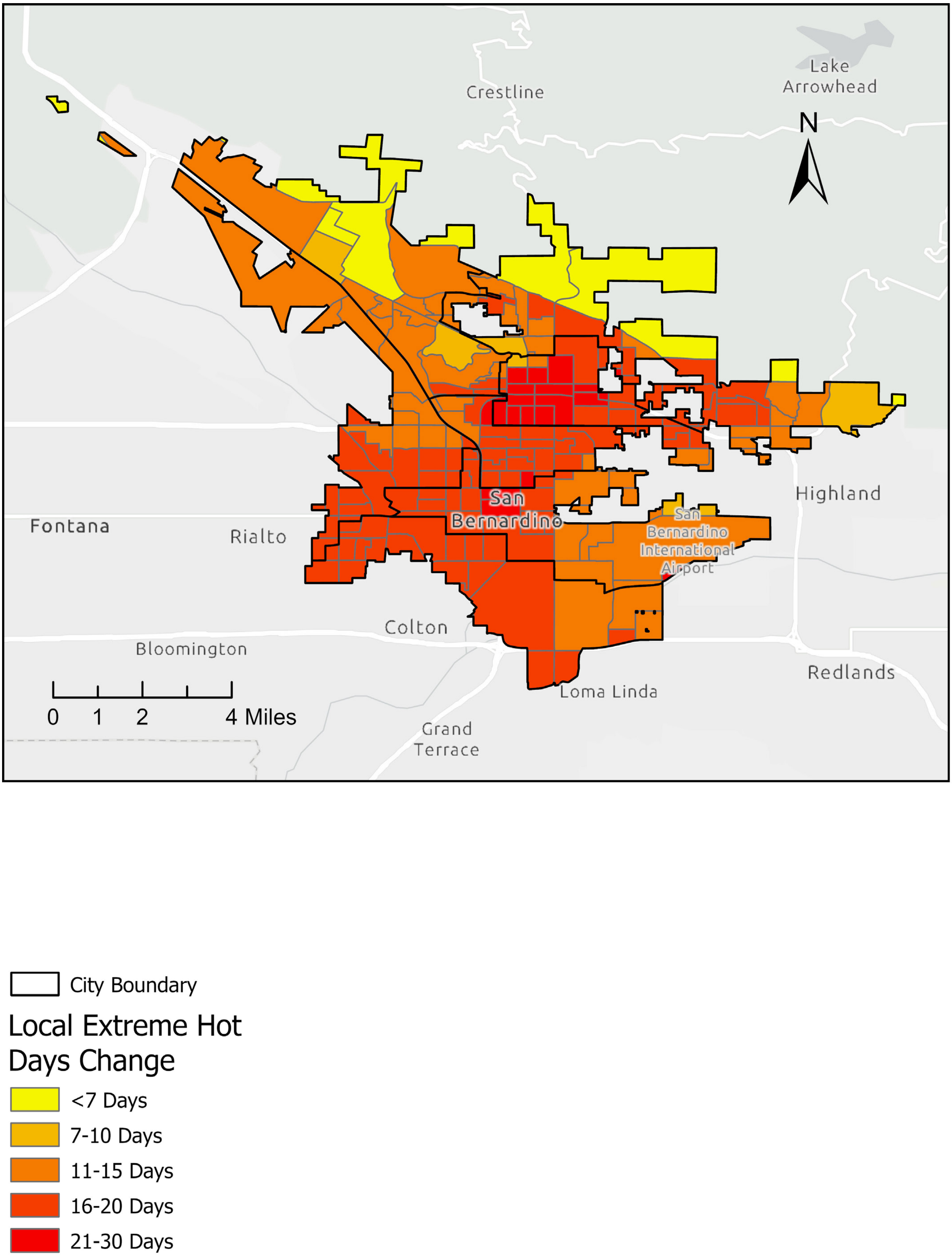
VEGETATION LOSS 2000 TO 2020

Takeaways:

+ Over the past two decades, the vast majority of block groups have lost more than 60% of their vegetated area, driven primarily by the disappearance of fine, sparse patches and linear greenbelts.

+ By contrast, estimates derived from NLCD, whose 1,000-ft^2 pixels effectively capture only vegetation patches ≥ 4,000 ft^2, suggest an average loss of just 20–30% per block group.

+ Taken together, these results indicate that urbanization disproportionately erodes small green spaces near residential areas and along built-up edges, amplifying heat exposure in those neighborhoods.


Lake
Arrowhead
Crestline
N
Highland
San
Bernardino
San
Bernardino
International
Airport
Fontana
Rialto
Colton
Bloomington
Redlands
Loma Linda
Grand
Terrace
0 1 2 4 Miles
City Boundary
Local Extreme Hot
Days Change
<7 Days
7-10 Days
11-15 Days
16-20 Days
21-30 Days

LOCAL EXTREME HEAT WAVE DURATION CHANGE

Takeaways:

+ All block groups saw a significant increase in heat wave duration

+ Downtown Area saw the biggest increase in heat wave duration

+ Fair comparison: Each place is judged against its own past summers, so we see clearly when local conditions become unusually hot

+ Direct impact on people: By catching these local heat extremes, we can better understand risks to residents' health, comfort, and daily life, and prepare stronger protections

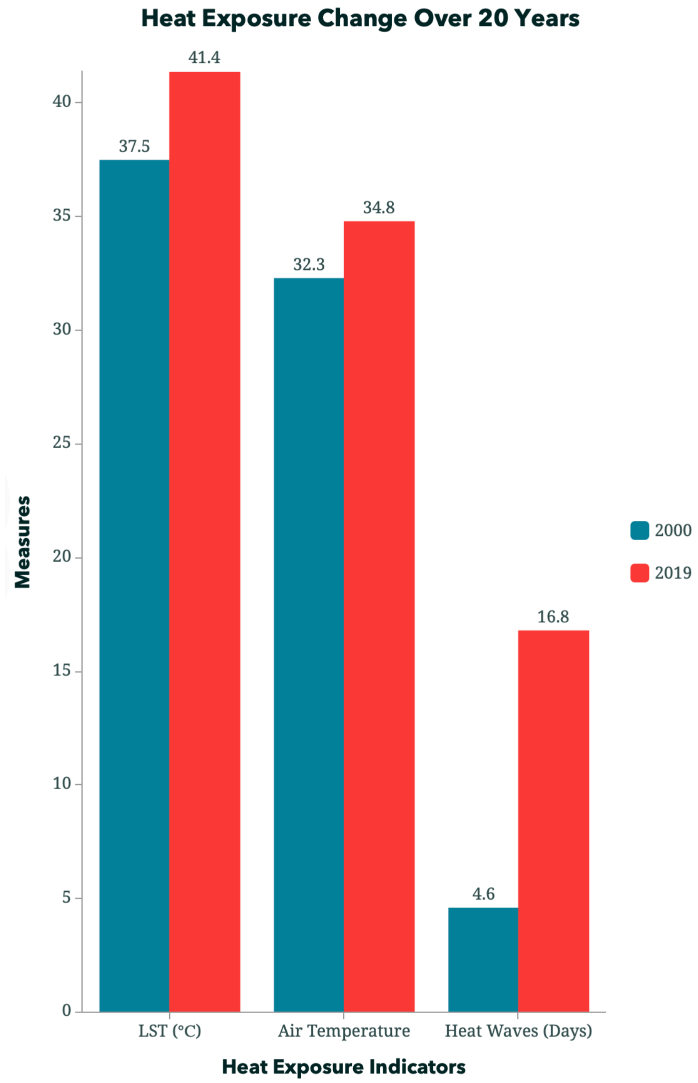
Notes:

1.Defined at pixel level (spatially explicit)

2.Summer season only (June–September)

3.Baseline: each pixel's 2000–2001 summer mean

4.Threshold: mean + 2 × standard deviation



Heat Exposure Change Over 20 Years
Measures
0
5
10
15
20
25
30
35
40
37.5
41.4
32.3
34.8
4.6
16.8
LST (°C)
Air Temperature
Heat Waves (Days)
Heat Exposure Indicators
2000
2019

Rising temperatures and longer heat events define recent change. Multiple indicators point to sustained warming over time.

HEAT EXPOSURE OVER 20 YRS

SUMMARY OF HEAT EXPOSURE CHANGES

All heat-exposure indicators have increased over the past 20 years, with land-use–associated changes in land surface temperature (LST) most pronounced (from 37.5C to 41.4C).

Average air temperature has increased over the past 20 years (from 32.3C to 34.8C).

Heat-wave duration—central to residents' health and well-being—has lengthened significantly; heat waves are now more frequent and more persistent (from 4.6 days annually in 2000 to 16.8 days annually by 2020).

Considered alongside widespread vegetation loss—i.e., declining local heat-adaptive capacity—these trends suggest that, under ongoing climate change, extreme heat will translate into greater heat vulnerability.

SECTION 3

MAPPING SAN BERNA

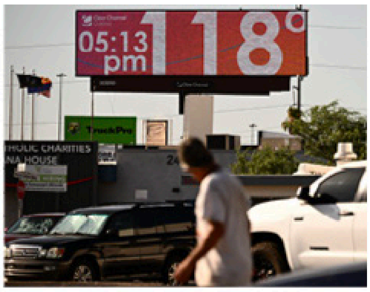
ARDINO'S HEAT RISKS

Against a backdrop of rising exposure and declining adaptivity over the past two decades, we evaluated temporal trends in sensitivity and examined spatial concordance between high-sensitivity populations and areas with worsening thermal conditions.

We find that sensitivity has intensified in a subset of block groups—driven by higher poverty rates, aging residents, stagnant or declining incomes, and growth in outdoor employment—and that these high-sensitivity communities disproportionately co-locate with neighborhoods experiencing increased exposure and reduced adaptivity.

To make these patterns actionable, we further mapped each heat-sensitivity indicator and their composite, revealing clusters where compounding risks are most likely to accumulate.

HEAT EXPOSURE: ADAPTIVE CAPACITY + SENSITIVITY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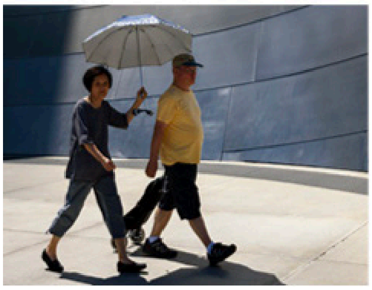
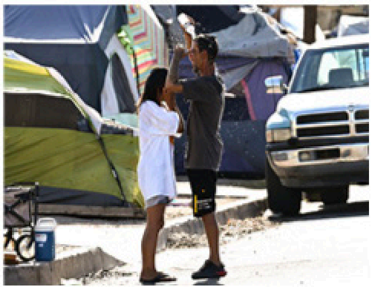
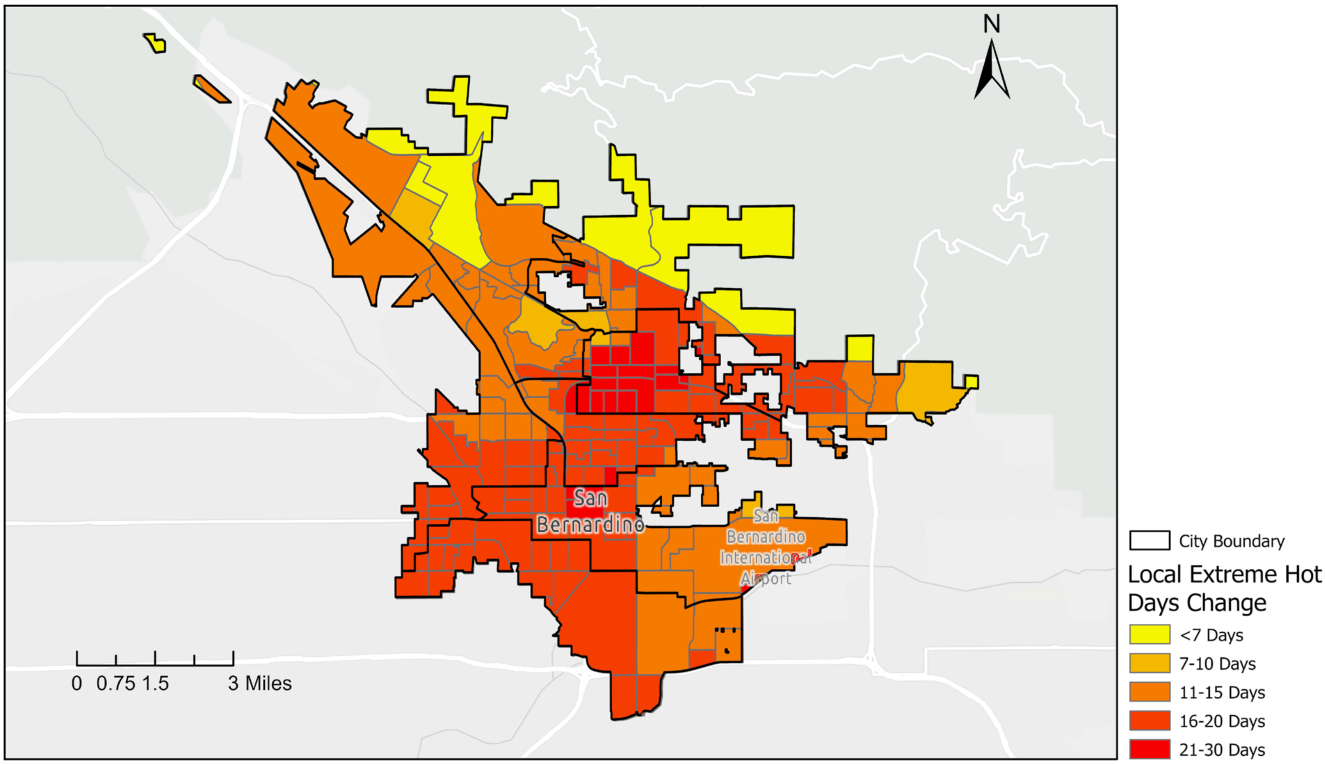


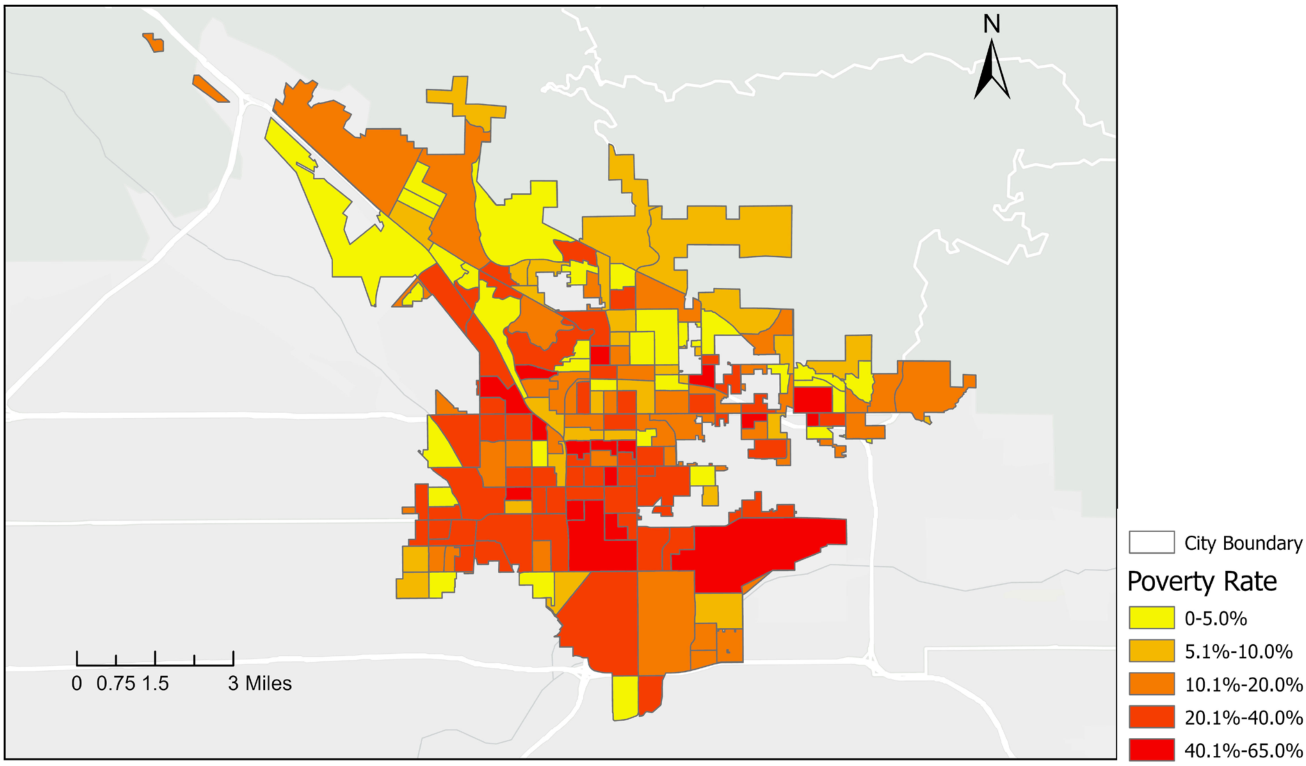




Source: Landsat 8 Images' thermal bands (Cloud Coverage<5%)

HEAT EXPOSURE: ADAPTIVE CAPACITY + SENSITIVITY

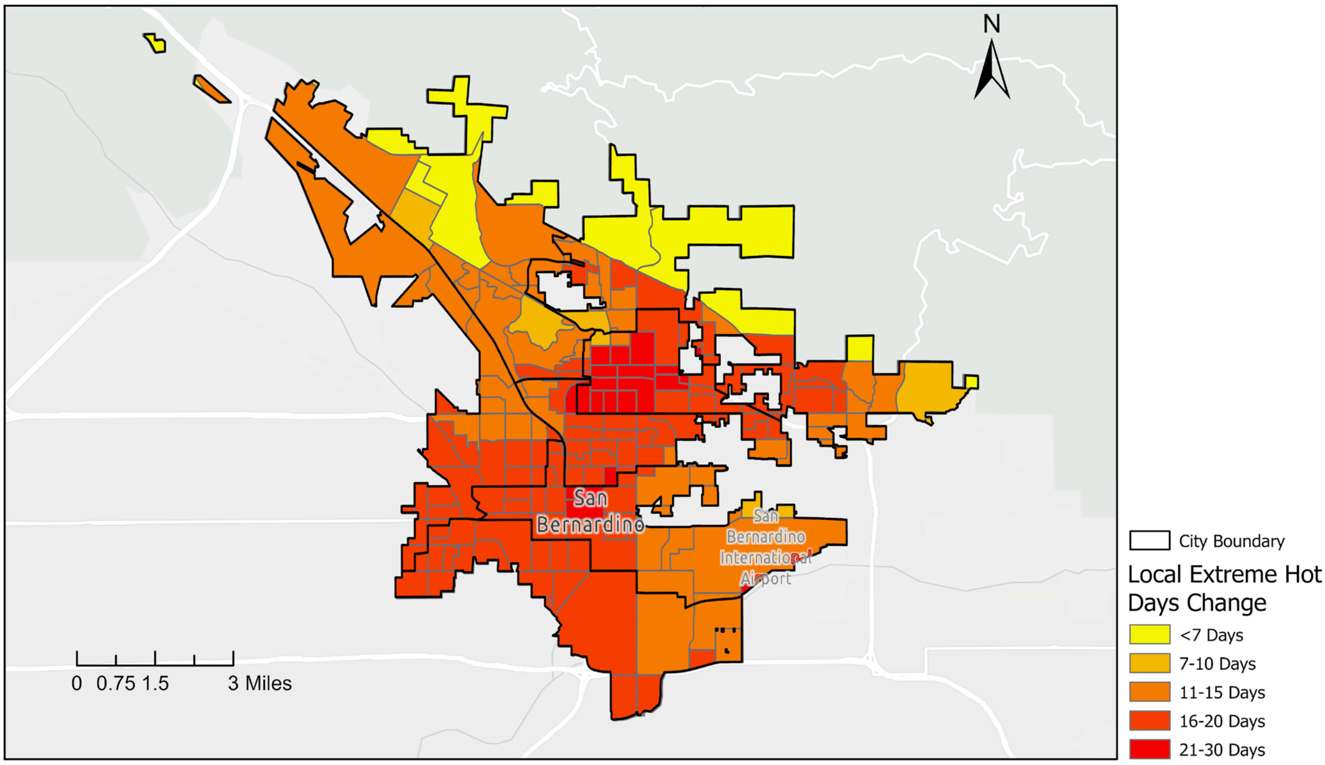
+ The map on the left (above) shows the change in the number of local extreme heat days from 2000 to 2020. Larger increases in these hot days are shown in red (16-30 more hot days), and lower increases in hot days are shown in yellow and light orange (10 more days or less of extreme heat).



Source: 5-Year American Community Survey (ACS) 2018-2022

POVERTY

+ This map shows Poverty Rate in each census tract, with higher poverty rates shown in red and lower ones in yellow and orange.



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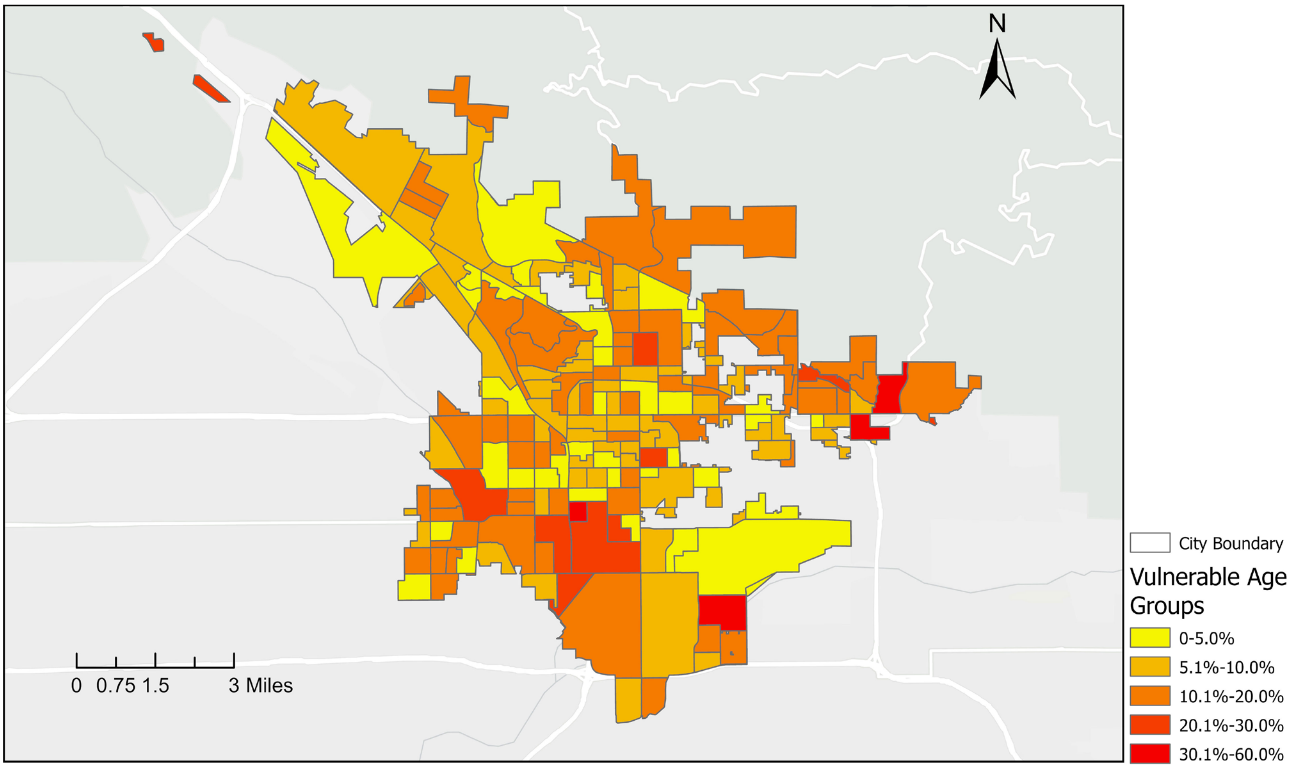
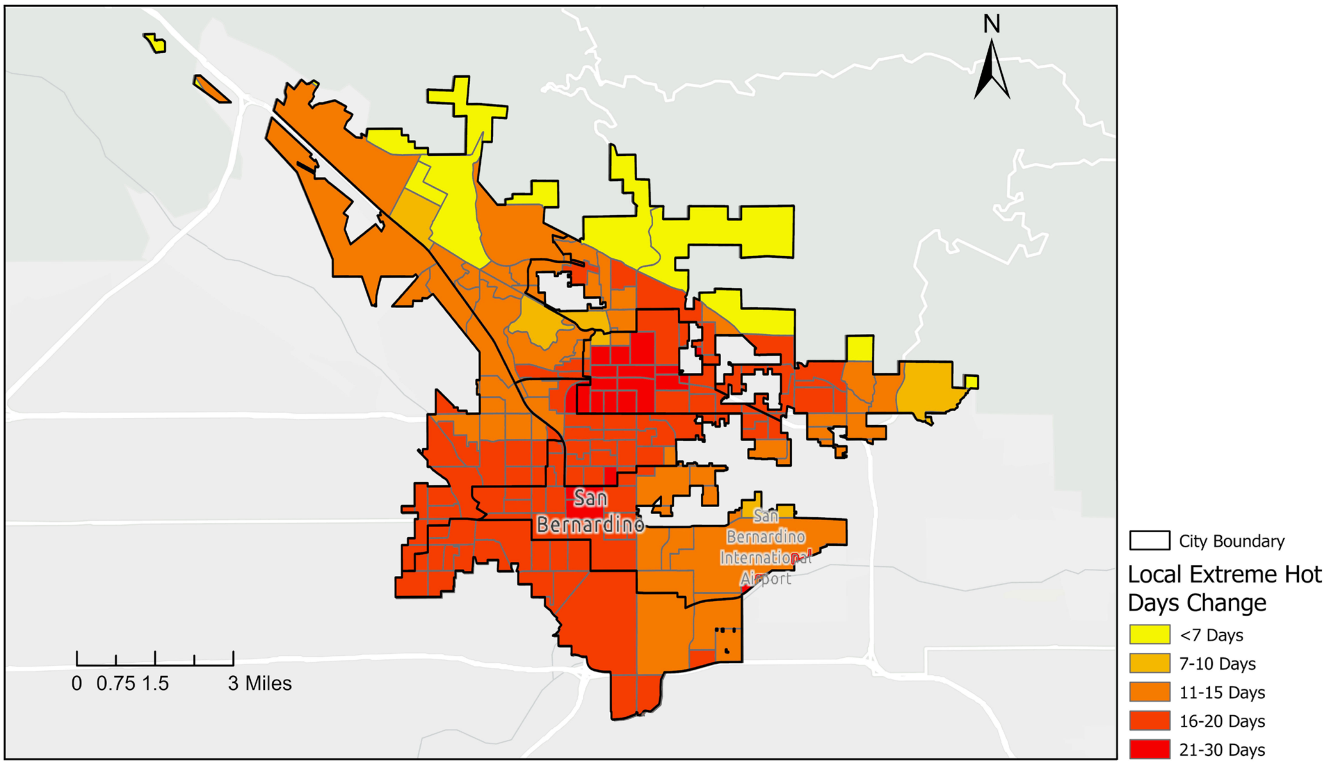


Source: 5-Year American Community Survey (ACS) 2018-2022

VULNERABLE AGE GROUPS

+ This map shows Vulnerable Age Groups by census tract, with higher concentrations of vulnerable age groups shown in red and lower ones in yellow and orange.

Research on extreme heat shows that Vulnerable Age Groups are defined as those who are 65 years and older and those who are 5 years or younger.



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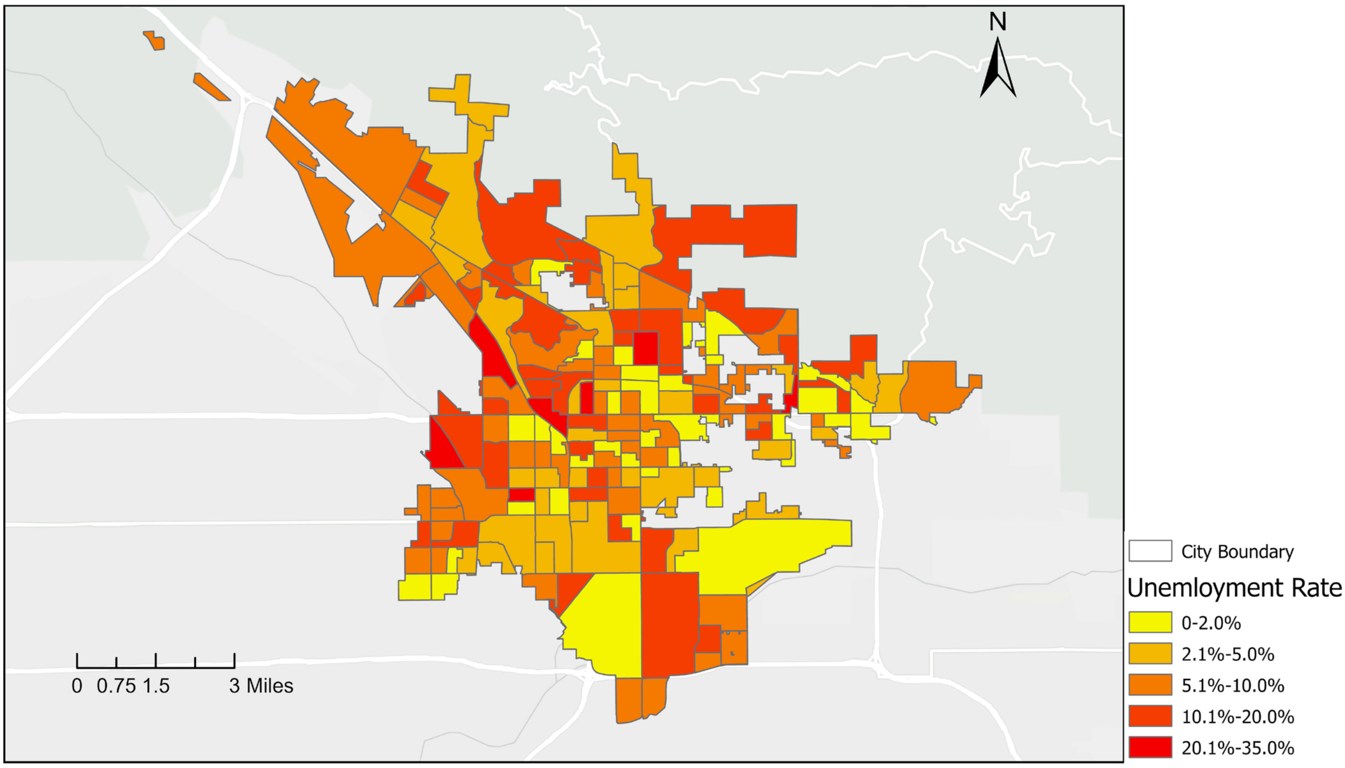
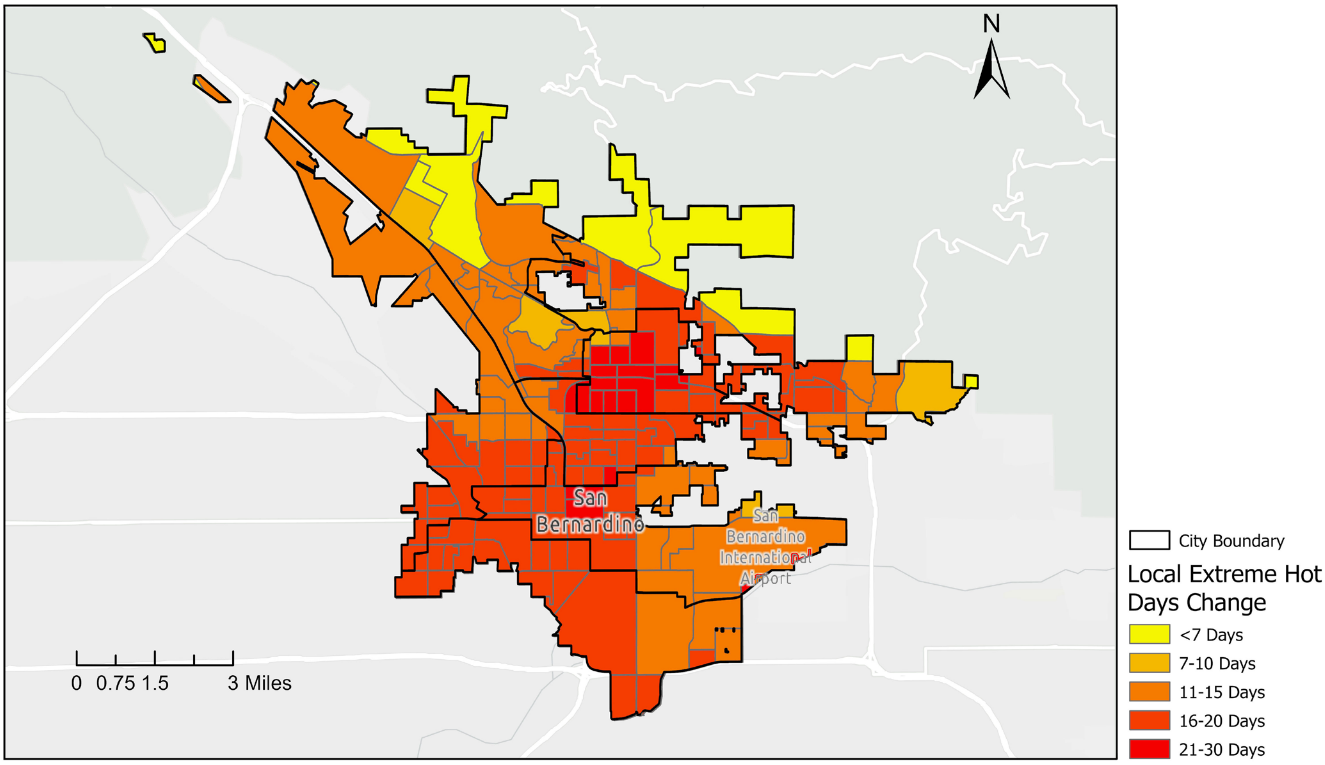
HEAT EXPOSURE:
ADAPTIVE CAPACITY + SENSITIVITY



Source: 5-Year American Community Survey (ACS) 2018-2022

UNEMPLOYMENT

+ This map shows Unemployment Rate in each census tract, with higher unemployment rates shown in red and lower ones in yellow and orange.



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HEAT EXPOSURE: ADAPTIVE CAPACITY + SENSITIVITY

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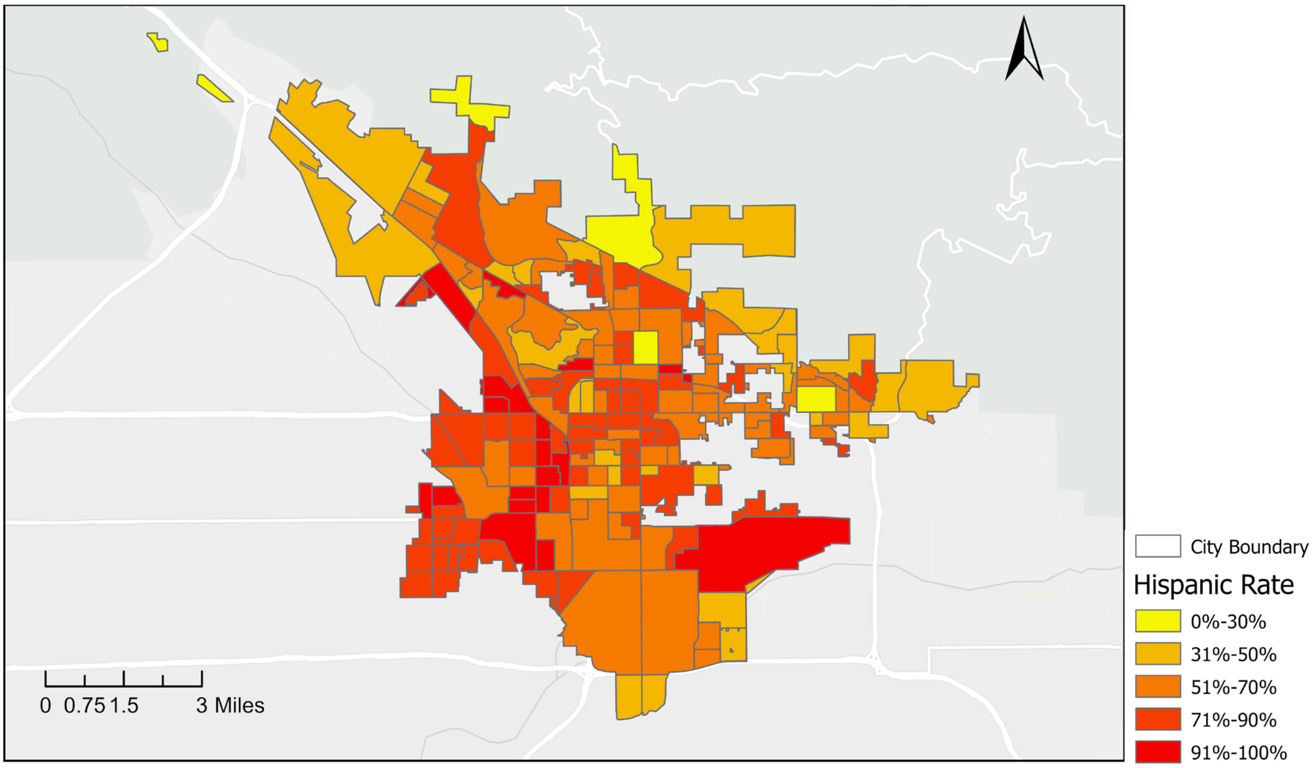
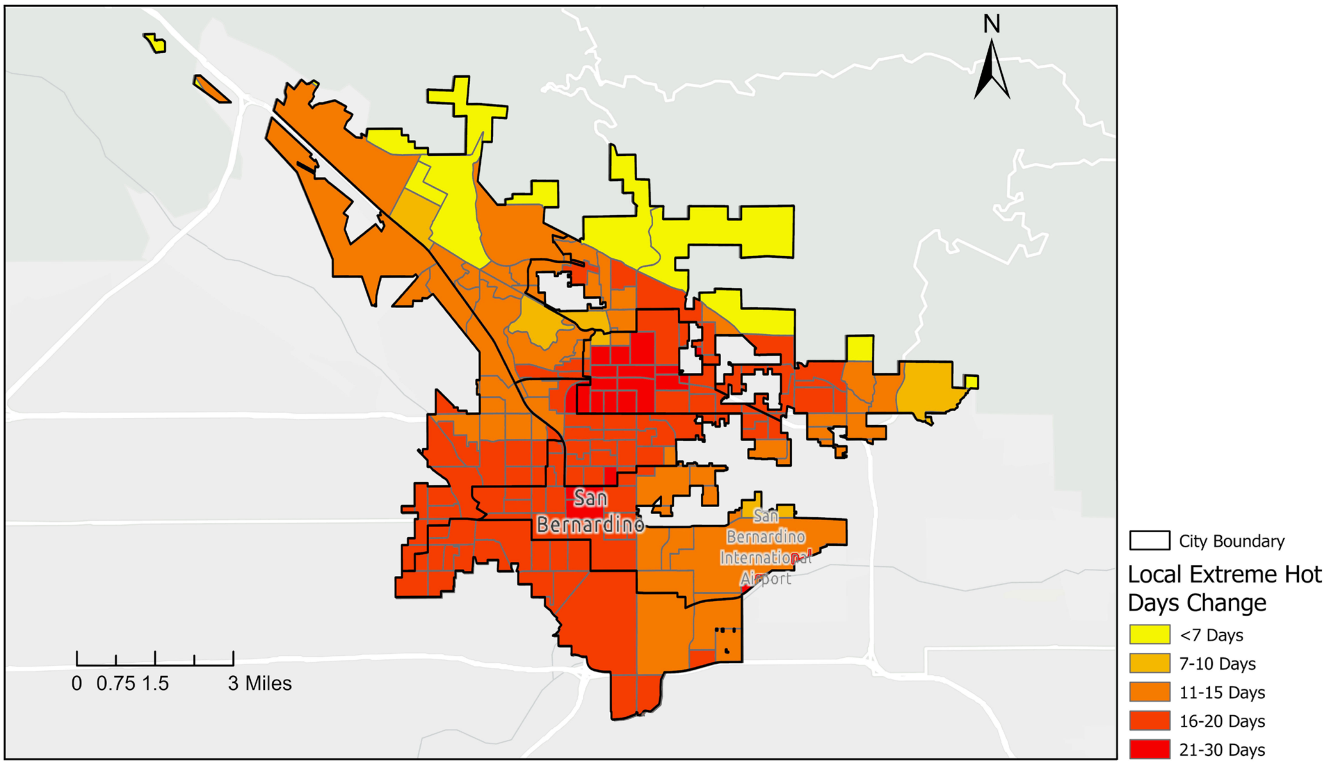


Source: 5-Year American Community Survey (ACS) 2018-2022

HISPANIC POPULATIONS

+ This map shows Hispanic Rate in each census tract, with higher Hispanic rates shown in red and lower ones in yellow and orange.



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HEAT EXPOSURE: ADAPTIVE CAPACITY + SENSITIVITY

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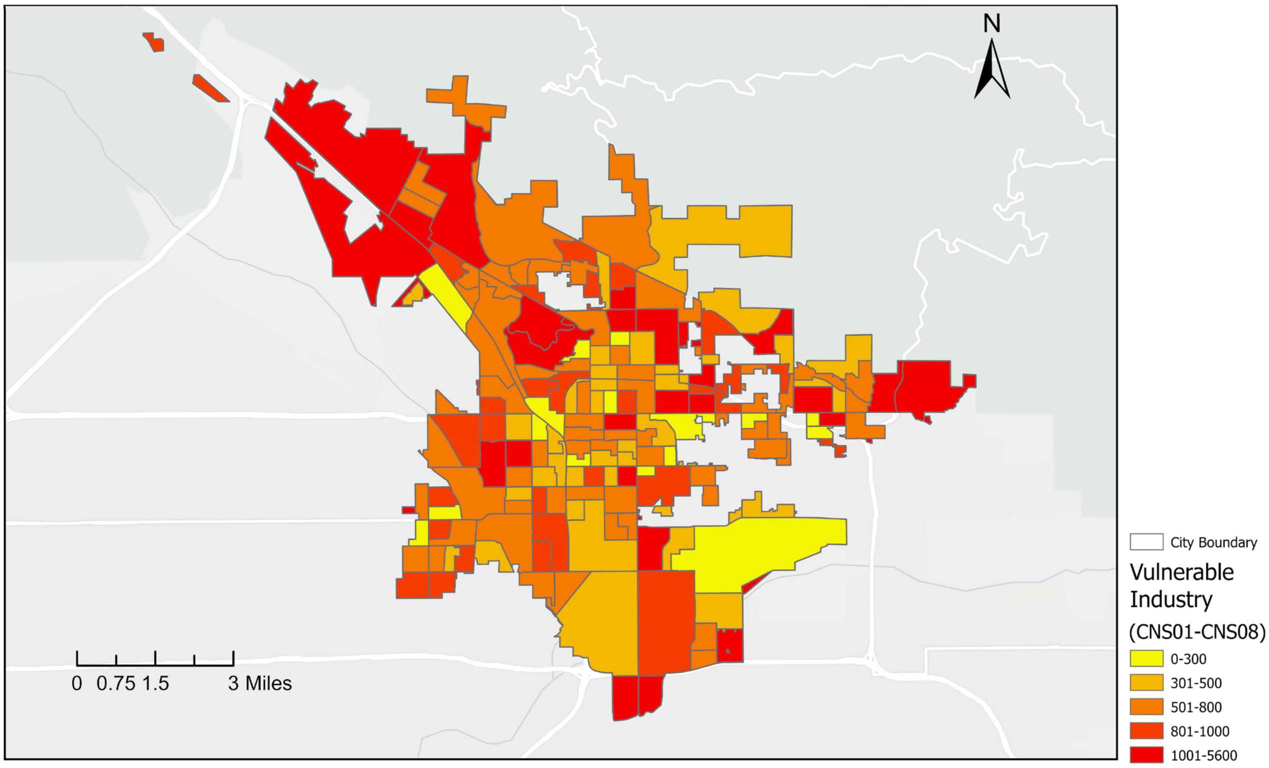
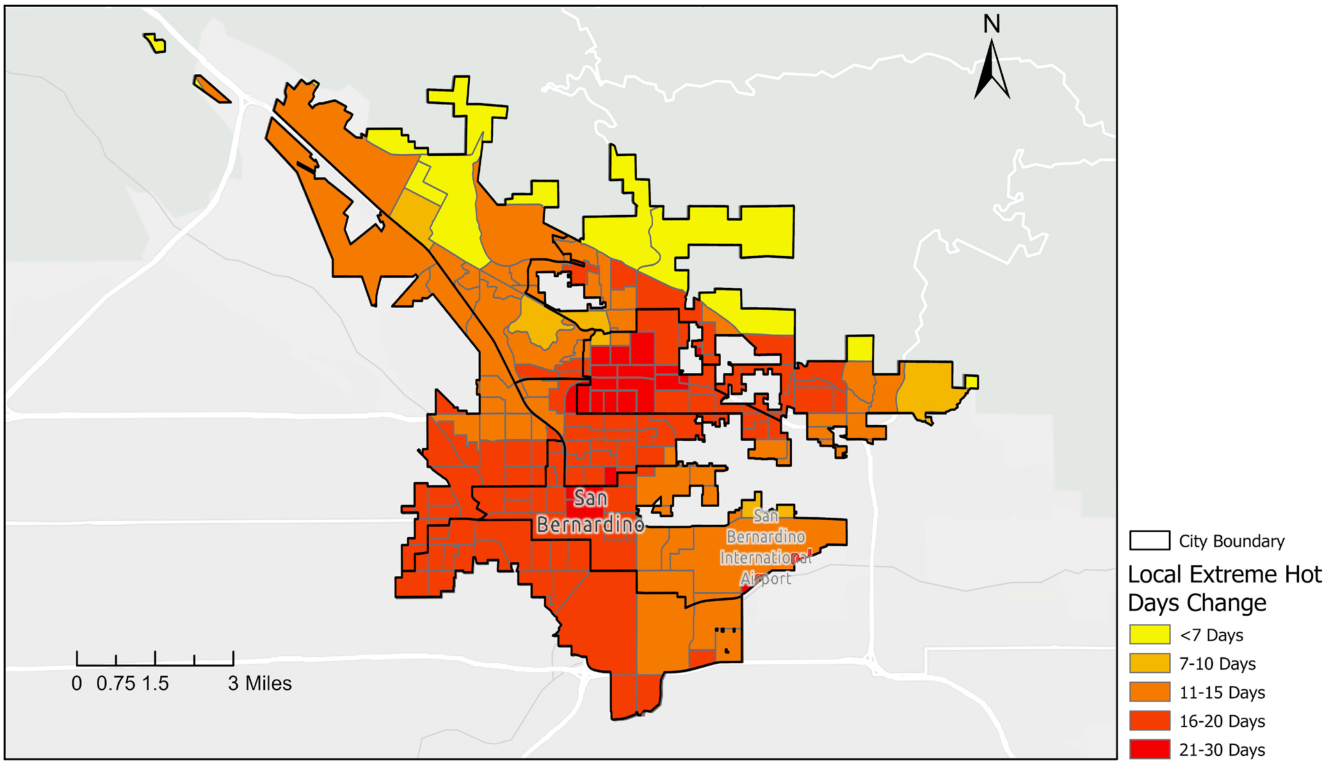


Source: 5-Year American Community Survey (ACS) 2018-2022

VULNERABLE INDUSTRY

+ This map shows Vulnerable Industry rates in each census tract, with higher vulnerable industry rates shown in red and lower ones in yellow and orange.

Vulnerable Industries CNS01 through CNS08 are defined as Agriculture, Forestry, Fishing and Hunting; Mining, Quarrying, and Oil and Gas Extraction; Utilities; Construction; Manufacturing; Wholesale Trade; Retail Trade; Transportation and Warehousing.

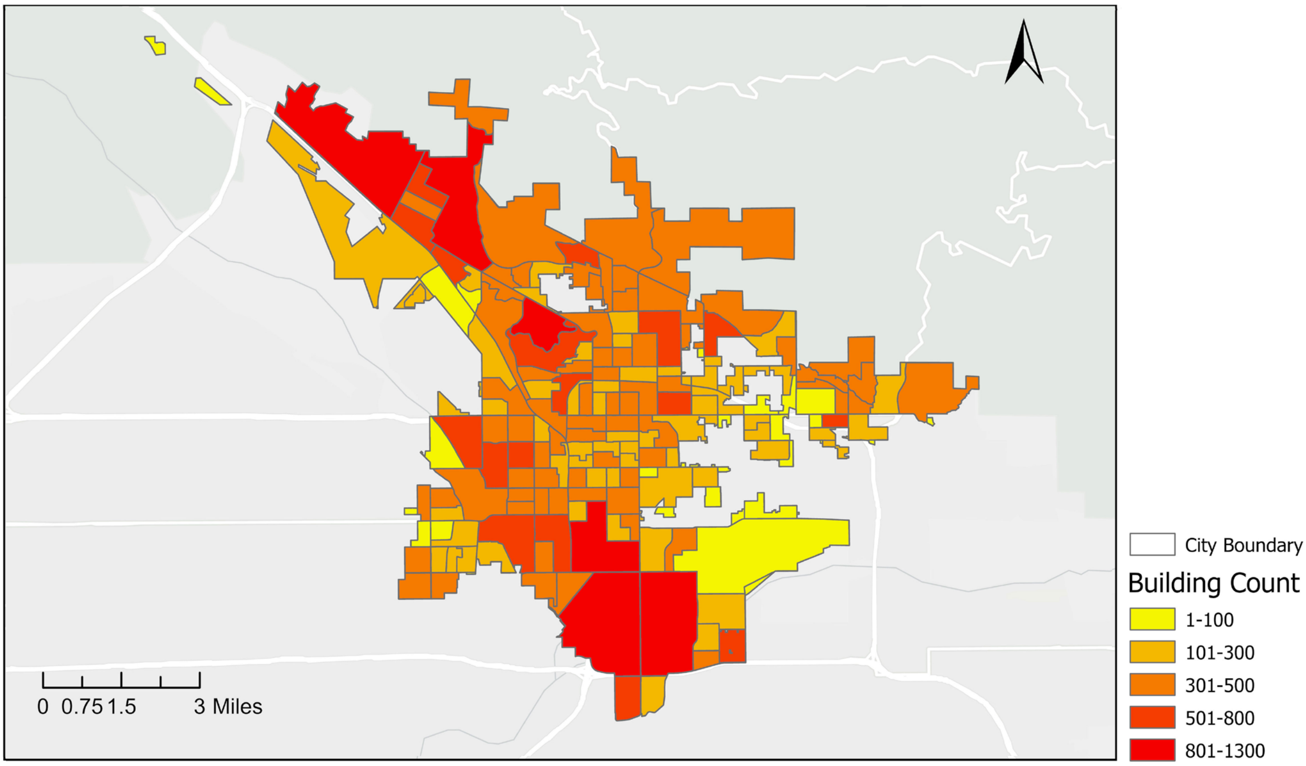


Source: Landsat 8 Images' thermal bands (Cloud Coverage<5%)

HEAT EXPOSURE: ADAPTIVE CAPACITY + SENSITIVITY

+ These maps illustrate the relationship between urban development intensity and changes in local extreme heat days across San Bernardino.

+ The map on the left (above) shows the change in the number of local extreme heat days from 2000 to 2020. Larger increases in these hot days are shown in red (16-30 more hot days), and lower increases in hot days are shown in yellow and light orange (10 more days or less of extreme heat).



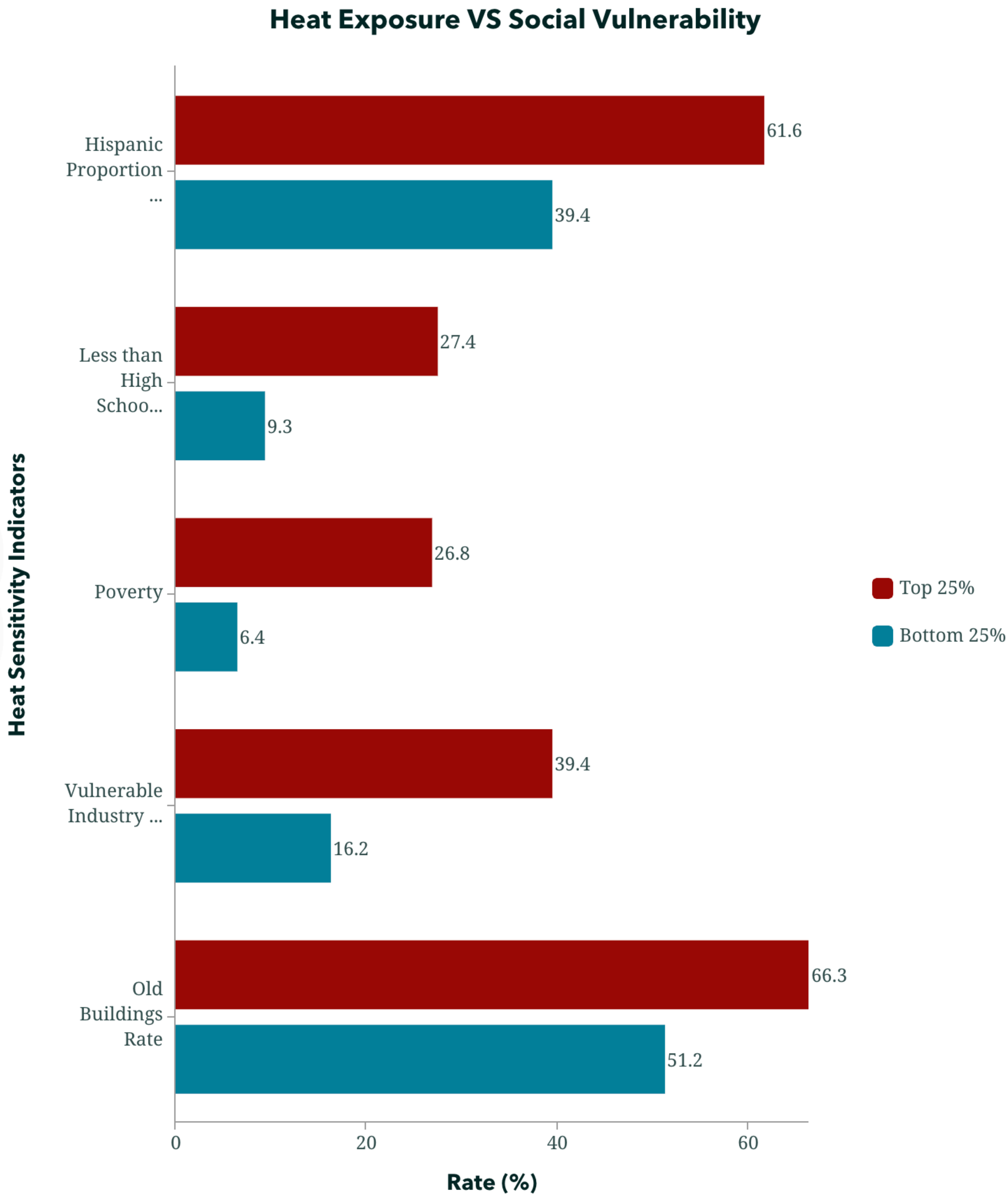
Source: San Bernardino County Parcel Layer and San Bernardino Property Characteristics File

BUILDING COUNT

Key Takaways:

+ The Building Count map shows the total number of buildings in each census tract, with higher counts shown in red and dark orange, representing denser urban areas, and lower counts shown in yellow and light orange, indicating less developed zones.

+ Areas with higher building densities tend to experience greater increases in extreme heat days, suggesting a clear urban heat island effect where concentrated development amplifies local temperature extremes.


Heat Exposure VS Social Vulnerability
Heat Sensitivity Indicators
Hispanic Proportion ...
61.6
39.4
Less than High Schoo...
27.4
9.3
Poverty
26.8
6.4
Vulnerable Industry ...
39.4
16.2
Old Buildings Rate
66.3
51.2
0
20
40
60
Rate (%)
Top 25%
Bottom 25%

The bar chart on the left shows how heat exposure is correlated with certain demographic characteristics. Specifically, it compares the top 25% of census tracts with the highest heat exposure to the bottom 25% with the lowest heat exposure across several social vulnerability indicators.

Each horizontal pair of bars represents one indicator of social vulnerability—factors that can influence how communities experience and recover from extreme heat. The red bars show the average rates for the top 25% (areas most exposed to heat), and the blue bars show rates for the bottom 25% (least exposed).

HEAT EXPOSURE: ADAPTIVE CAPACITY + SENSITIVITY

HEAT EXPOSURE AND SOCIAL VULNERABILITY

Key Takaways:

+ **Hispanic Proportion:** Areas in the top 25% for heat exposure have a much higher Hispanic population share (61.6%) than those in the bottom 25% (39.4%), suggesting racial and ethnic disparities in heat risk.

+ **Less than High School Education:** The share of adults without a high school diploma is nearly three times higher in the most heat-exposed areas (27.4%) compared to the least exposed (9.3%).

+ **Poverty:** The poverty rate is more than four times higher in the most heat-exposed block groups (26.8%) than in the least exposed (6.4%), linking socioeconomic disadvantage to heat vulnerability.

+ **Vulnerable Industry Employment:** People working in heat-sensitive industries (like construction or agriculture) are more common in highly exposed areas (39.4% vs. 16.2%).

+ **Old Buildings Rate:** Older housing, which often lacks efficient cooling, is also more prevalent in high heat exposure areas (66.3%) compared to low exposure areas (51.2%).

These differences suggest that communities facing the greatest heat exposure also tend to have higher concentrations of vulnerabilities, amplifying their overall risk from extreme heat events.

SECTION 4

HOW VULNER
EVALUATING H

ABLE ARE WE?
HEAT IMPACTS

EVALUATING HEAT IMPACTS

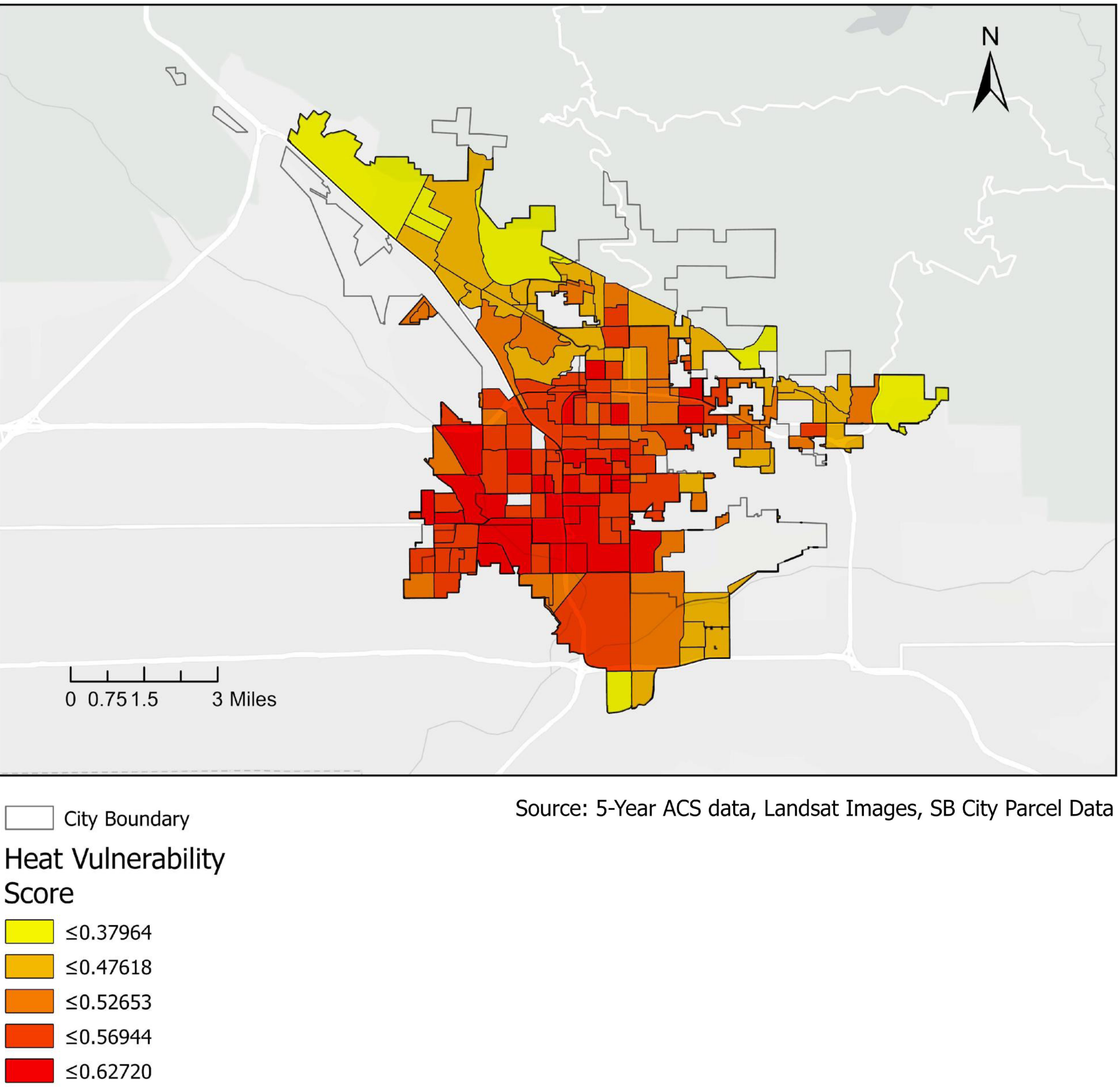
HOW VULNERABLE ARE WE?

Our heat-vulnerability framework comprises three dimensions:

(i) heat exposure, (ii) heat adaptivity capacity, and (iii) heat sensitivity measured by socioeconomic factors (e.g., poverty, race/ethnicity, age, income, and the share of outdoor workers).

The map here summarizes the heat vulnerability score based on heat exposure, people's adaptive capacity to deal with this heat, and the sensitivity of certain popula-

HEAT VULNERABILITY SCORE



Source: 5-Year ACS data, Landsat Images, SB City Parcel Data

HOW DO WE KNOW

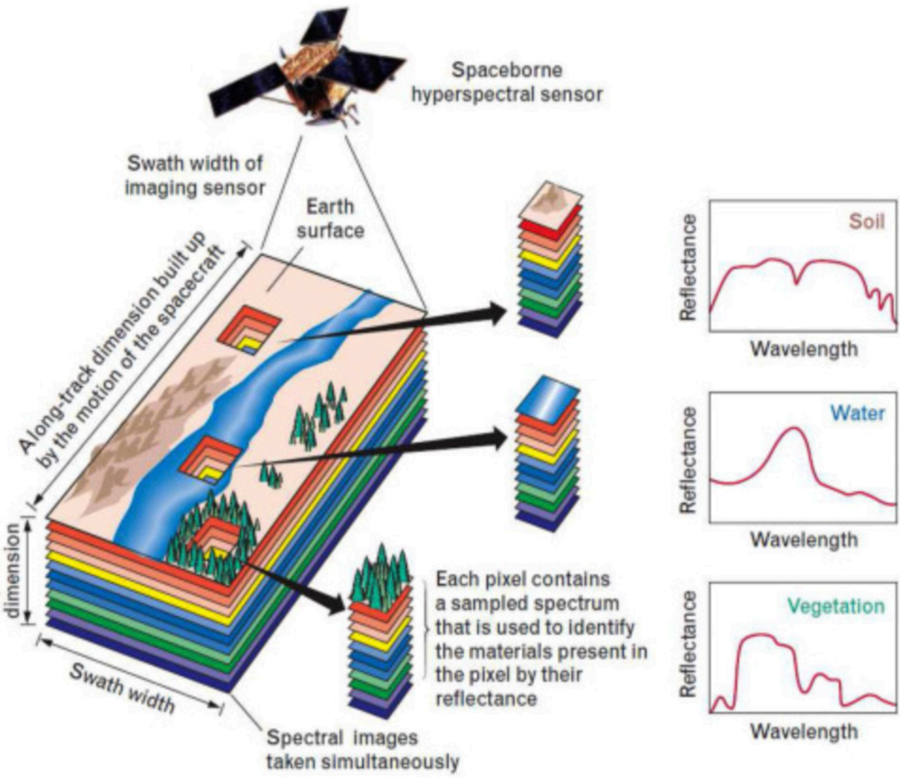
APPENDIX :

METHODS

V WHAT WE KNOW?

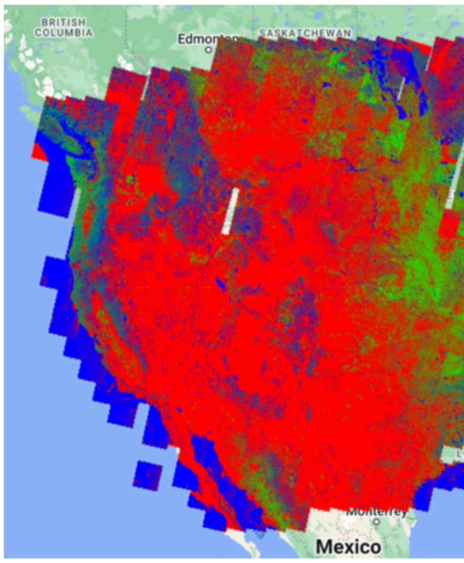
SMALL VEGETATION PATCH DETECTION

Because San Bernardino City lies in a summer-dry, semi-arid climate, vegetation is relatively sparse in summer and the built-up area is extensive. Consequently, conventional satellite products and national land-cover datasets (e.g., the U.S. NLCD) have difficulty detecting small vegetation patches (<1,000 square feet). To address this, we applied spectral unmixing to the original satellite imagery, decomposing mixed pixels to recover sub-pixel vegetation signals and to track their changes over the past two decades.



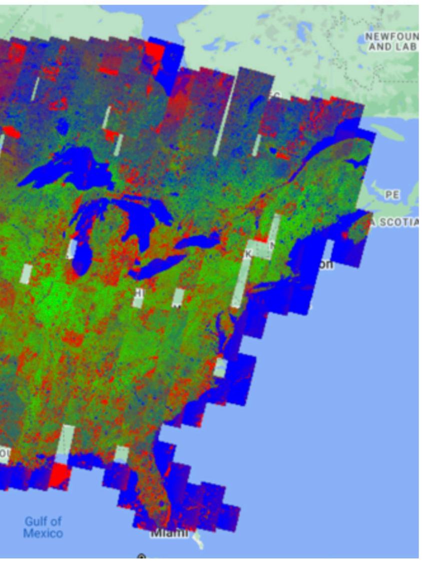
CROSS VALIDA
AND ROBUSTI

To improve the reliability and robust
results, we ran the analysis at two sp
nardino city extent and across the U
maintain a summer-season greennes
over the 20-year period.



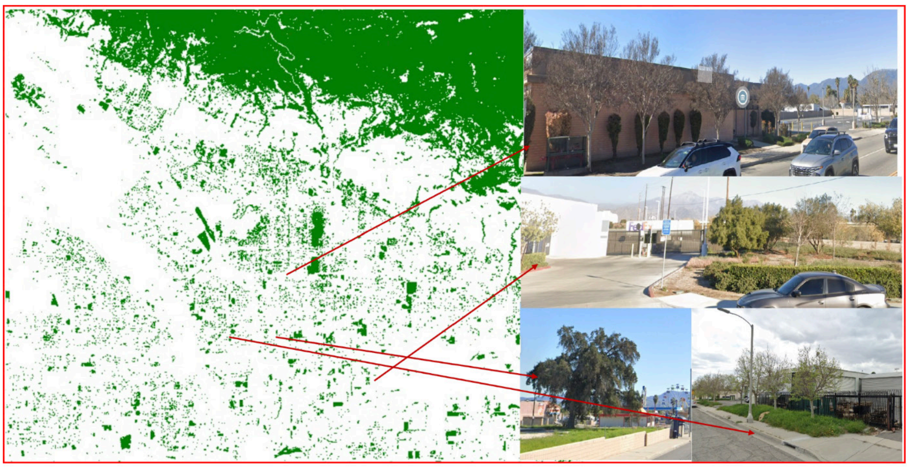
ATION
NESS

tness of our spectral unmixing
patial scales—within the San Ber-
United States—to calibrate and
s threshold that remains stable



RESULTS AND VALIDATION

Following spectral unmixing, we identified fine-scale green spaces within the city that are not typically resolvable in standard remote□sensing imagery. We validated a subset of these detections using Google Street View imagery and found that the unmixing approach successfully captures sparse street trees, roadside shrubbery, and greenbelts at the margins of built-up areas, as illustrated.



STAYING COOL, STAYING CONNECTED

RISING HEAT:
UNDERSTANDING EXPOSURE AND VULNERABILITY IN THE CITY OF SAN BERNARDINO

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