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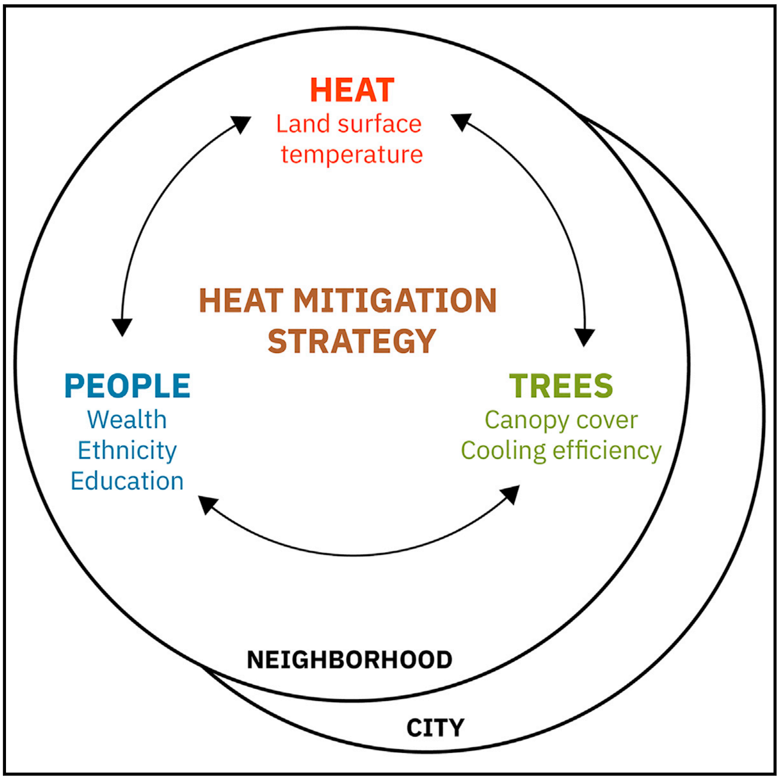
Urban tree canopy has greater cooling effects in socially vulnerable communities in the US

Graphical abstract



Highlights

- Socially vulnerable urban residents live in hotter zones that have fewer trees
- Urban trees have greater cooling efficiency (CE) in socially vulnerable neighborhoods
- We developed tools to facilitate spatial prioritizing heat mitigation strategies
- Heat mitigation solutions must address both distributional and procedural injustice

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In brief

Cities worldwide use trees to adapt to climate-change-associated urban heat. However, how to maximize social and ecological benefits of trees for cooling is poorly understood. We investigate social vulnerability to heat and the cooling capacity of trees in 38 of the United States' largest cities and find that trees have larger cooling effects in socially vulnerable neighborhoods. Increasing tree cover in these neighborhoods will meet the greatest need for cooling and achieve greater cooling capacity, creating socio-ecological win-wins.

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Urban tree canopy has greater cooling effects in socially vulnerable communities in the US

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SCIENCE FOR SOCIETY Cities worldwide face pressing extreme heat events that are becoming a significant climate-driven threat to public health. Tree planting is a common adaptation measure to reduce heat stresses but can create environmental injustice if not properly planned. Information is thus needed regarding who is most vulnerable to urban heat, where they live, and whether they have equal access to trees for cooling. Here, we analyze social vulnerability to heat and the cooling capacity of trees across 38 of the United States' largest cities. We find that socially vulnerable people tend to live in hotter neighborhoods with less tree cover, and planting trees in these neighborhoods have greater cooling effects. It is therefore essential to ameliorate distributional and procedural injustices to ensure that increasing tree cover in these neighborhoods can achieve social and ecological win-wins. We develop tools to facilitate spatial prioritizing neighborhoods in need of heat interventions.

SUMMARY

Cities are home to around half of the global population but face intensified and unevenly distributed heat stresses. Trees are utilized to adapt to urban heat; however, most tree planting is prioritized by either biophysical or social metrics, rather than an integration of the two. It therefore remains unclear how to maximize ecological and social benefits of tree planting in the context of environmental justice. Here, we analyze social vulnerability to heat and the cooling capacity of trees across 38 of the largest cities in the United States. We find that socially vulnerable people tend to live in hotter neighborhoods with less tree canopy. Furthermore, tree planting in such neighborhoods can achieve greater cooling benefits per unit increase in canopy. Increasing tree cover in these neighborhoods will meet the greatest need for cooling and achieve greater cooling capacity, creating social and ecological co-benefits. Adaptation measures must address both the distributional injustices of urban heat and procedural justice in planning and managing nature-based cooling approaches.

INTRODUCTION

Cities are already warmer than their surrounding regions, a result of the well-known urban heat island (UHI) effect.[1,2] Yet, with the synergistic interactions between climate change and urban expansion, cities are expecting more frequent and intense extreme heat events or heat waves, with larger areas exposed to UHI effects.[3–6] Extreme heat increased by more than

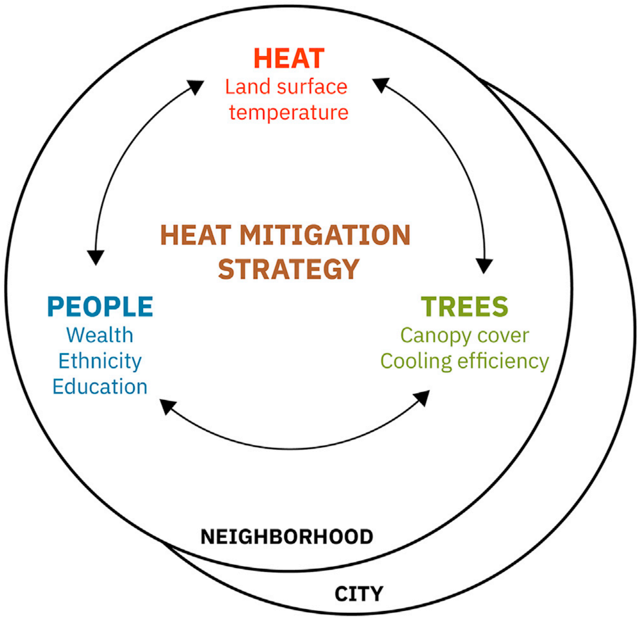

Figure 1. The relationships between urban heat, population, and trees

Excessive urban heat unequally affects urban population, who may have different capacity in heat adaptation and mitigation due to different social-economic characteristics. Addressing the grand challenge of urban heat requires a comprehensive understanding that relates excessive urban heat, people, and the key features of the urban landscape such as urban trees.

1.5 days per year in densely populated regions from 1983 to 2016, and the global exposure of the urban population to a daily maximum wet bulb temperature of 30°C increased almost 200% due to urban population growth and intensified urban warming.[7] UHI is expected to further exacerbate heatwave stress on human health.[8] The heat waves of the past have amply demonstrated that increasing the magnitude and extent of UHI will have significant social, ecological, and technological impacts,[9] posing a grand challenge for cities' ability to achieve sustainability in the context of climate change.[10–12]

In addition to the challenge of increased frequency and intensity of extreme heat, heat also disproportionally affects different urban populations, with the urban poor and people of color being more exposed and having limited capacity to mitigate heat or adapt to extreme heat events.[9,13,14] The disproportionate impact of environmental hazards is a primary concern of environmental justice.[15,16] Climate justice has recently emerged as a new and pressing concern in environmental justice research and practice.[17–19] Cities dominated by multiple forms of inequality have been created in no small part through historical and ongoing planning practices. For example, housing displacement in urban (re)development can force communities to relocate to more hazardous areas, exacerbating uneven distributions of exposure to environmental hazards.[20] Experience of excess heat by vulnerable groups not only exemplifies environmental injustice, but also leads to significant health impacts. Neighborhoods deprived of climate-regulating services, such as from urban green infrastructure, may further perpetuate historical inequalities,[14,17] especially if climate change impacts in cities increase the risk of heat waves in vulnerable communities and thus create new environmental justice challenges.[21,22] For example, MillionTreesNYC had its explicit goal of equalizing urban forest, but still failed to "prioritize low-canopy, low-income communities of color", mainly because parks, which were already unequally distributed, absorbed 83% of the newly planted trees.[23] To address the grand challenge of decreasing disproportionate impacts of heat on vulnerable and historically oppressed urban populations requires a comprehensive understanding of the relationships between excessive urban heat, socially vulnerable populations, and the key features of the urban landscape such as tree canopy that can mitigate heat and heat impacts (Figure 1).[24]

Social vulnerability generally refers to the potential for loss when facing certain environmental hazards. Social vulnerability in the US for example is often associated with racialized status, lower income, or both.[25] Researchers interpret social vulnerability in different ways, from considering it as a social condition that can affect the ability to mitigate or adapt to environmental hazards, to integrating exposure to social condition to estimate risk.[26] A considerable number of studies have confirmed the disproportionate impacts of urban heat and/or extreme urban heat events on urban residents, showing socially vulnerable populations such as the urban poor and people of color living in hotter neighborhoods and exposing them to more extreme heat events.[9,13,14,27,28] Such disproportionate impacts, however, have been discovered for smaller sets or individual cities. It is unclear how general these patterns are at national scales.

Planting of urban trees is one of the most widespread forms of intervention aimed at heat mitigation.[29,30] Similar to urban heat, there are large within-city variations in spatial distribution of urban tree canopy (UTC), with socially vulnerable populations living in neighborhoods with less tree cover,[9,17,31–33] resulting in inequitable provision of the cooling benefits of trees. By considering the relationships between presence of tree canopy and social vulnerability, planting of urban trees in prioritized neighborhoods may achieve greater social benefits.[9,17] Previous studies also discovered that the cooling efficiency (CE) of urban trees, defined as the change in the magnitude of land surface temperature (LST) with one percent unit increase in UTC cover,[34,35] varies in space within and among cities and is affected by biophysical factors such as temperature and wind.[35] However, whether and to what extent UTC can generate greater cooling effects in socially vulnerable neighborhoods is unclear. Consequently, most tree planting is prioritized by either biophysical or social metrics, rather than integrating the two.[9,23] It therefore remains unclear how to simultaneously maximize ecological and social benefits of tree planting in the context of environmental justice. Understanding who is most vulnerable, where they live, and whether they have equal access to benefits of trees for cooling is a critical starting point for prioritizing urban heat interventions in planning and policy at several levels of governance.

Here, we conducted a continental scale cross-city comparison of the 38 largest cities in the U.S. We quantify the associations between LST and social and biophysical characteristics for each city and compare the direction and strength of the associations among cities. We examine the cross- and within-city spatial heterogeneity of the CE of urban trees and investigate how it relates to the social differentiation and biophysical variation of neighborhoods. We focused on these US cities because they, like many cities worldwide, continue to struggle to address long-standing issues of uneven development, environmental degradation, and systemic racism.[31,36] We use US Census block groups (BGs), which are essentially the neighborhood scale, as the unit of analysis. The result shows that people who are more socially vulnerable tend to live in hotter neighborhoods with less tree canopy, and that tree planting in these neighborhoods achieved greater cooling benefits per unit increase in canopy. By spatially explicitly locating neighborhoods in need of heat mitigation from an environmental justice perspective, spatial analysis and maps of heat, tree canopy, and social indicators can provide useful tools for spatially prioritizing potential heat mitigation strategies and interventions.

RESULTS

Method summary

We address two main questions: 1) Is there a generalizable relationship between urban heat and social vulnerability within cities at a national scale? 2) In what physical and social conditions does the cooling capacity of trees have the greatest environmental and social impact? To answer the second question, we test two hypotheses: 1) increasing the UTC will have a greater cooling effect in hotter neighborhoods that have fewer trees and 2) the presence of socially vulnerable populations predicts locations in which trees will have greater cooling effects (Figure 1). We do not suggest that being socially vulnerable is a cause of cooling effectiveness, but rather that it is part of a bundle of social indicators that are associated with places in American cities that are densely inhabited, poorly resourced, historical disenfranchised, and are little connected to municipal power structures.[37] Such places are structurally vulnerable to heat as an outcome of multiple social conditions and their physical manifestations.[28,38] (Figure S1).

This study focused on the 38 most populous cities in the continental United States as of the 2010 census (see experimental procedures). These cities are widely distributed across the US and encompass coasts and interior and northern, southern, eastern, and western regions, representing many climate zones and geographic locations (Figure S1). The total population of these cities ranged from 305,704 (Pittsburgh, PA) to 8,175,133 (New York, NY) in 2010, with median household income ranging from $27,349 in Cleveland, OH to $79,405 in San Jose, CA (Table S1). The percentage of the population identifying as white ranged from 10.61% in Detroit to 80.84% in El Paso, and proportion of people having a high school degree ranged from 41.78% in Fresno to 65.91% in Seattle (Table S1). These cities were very racially diverse (Table S2).

We use social vulnerability to describe social condition, which influences the community's ability to respond to, cope with, and recover from excess heat.[26] We consider race, income, and education as indicators of social vulnerability. The three indicators are generally agreed to be the major factors that influence social vulnerability[26,39] and have been repeatedly used in studies assessing in particular social vulnerability to heat.[40,41] We use race as a critical indicator of social vulnerability because it is correlated with differential exposure to environmental hazards including excess heat as well differential access to political power and representation that may affect the adaptive capacity to excess heat.[37,42] For example, black and brown residents have been shown to have higher exposure to climate extremes including heat and flooding.[18,43] We examine income because it is shown in many studies to correlate with differential resilience and ability to adapt to excess heat.[44,45] For example, low-income populations often have less access to air conditioning and other economic resources important to coping and adapting to heat sources.[17,43] Education is also a critical component of social vulnerability as well, because it can indicate differential access to knowledge and information. For example, lower education levels may constrain the ability to understand warning information and thus act in ways that decrease exposure.[46,47] We used the 2010 US Census data for the three indicators of social vulnerability so that the year in which the social variables were collected would approximately matches that of 2011 for the UTC data (see experimental procedures).

Income, race, education, and urban heat

Results show that urban populations with more people of color, lower income, and less education tend to live in hotter neighborhoods that have less tree canopy cover. Results were generally consistent across the 38 largest American cities at a national scale (Figure 2). Spatially, LST, tree canopy, and the three social variables had large variation in space (Figure 3). Neighborhoods having higher LST tended to also have lower tree canopy coverage, higher proportions of people of color, and lower household median income and education levels. The variation of LST was significantly related to spatial variation in tree canopy cover and the social variables considered (Figure 3).

The negative relationship between the percentage of cover of tree canopy and LST was significant in all 38 cities except for Tucson, Arizona (Figure 2), indicating that urban trees have significant cooling effects within cities. The percentage of cover of tree canopy generally was strongly negatively correlated with LST, with 31 cities having correlation coefficients with absolute values greater than 0.5, and five cities with absolute values of correlation coefficients greater than 0.8.

The percentage of the population classified according to US Census categories as people of color, which we recognize is limited and even problematic in how race is represented and does not fully account for complexity in racial and ethnic identity, was positively correlated with LST in general, suggesting that neighborhoods with a higher proportion of people of color tended to be hotter. The percentage of people of color population had a significantly positive correlation with LST in 26 cities, with values of the correlation coefficient ranging from 0.13 to 0.68. The relationship was not significant in 10 cities and was significantly negative in two cities, Pittsburg, PA and Saint Louis, MO. Compared with the relationship between the other two social variables of income and education, as described below, the relationship between the percentage of the population identified as people of color and LST within a city was more variable among the 38 cities.

Household median income was significantly and negatively correlated with LST, indicating that poorer urban populations tend to live in hotter places. Among the 38 cities, four had relatively strong negative correlations ($r < -0.5$), 15 had moderately

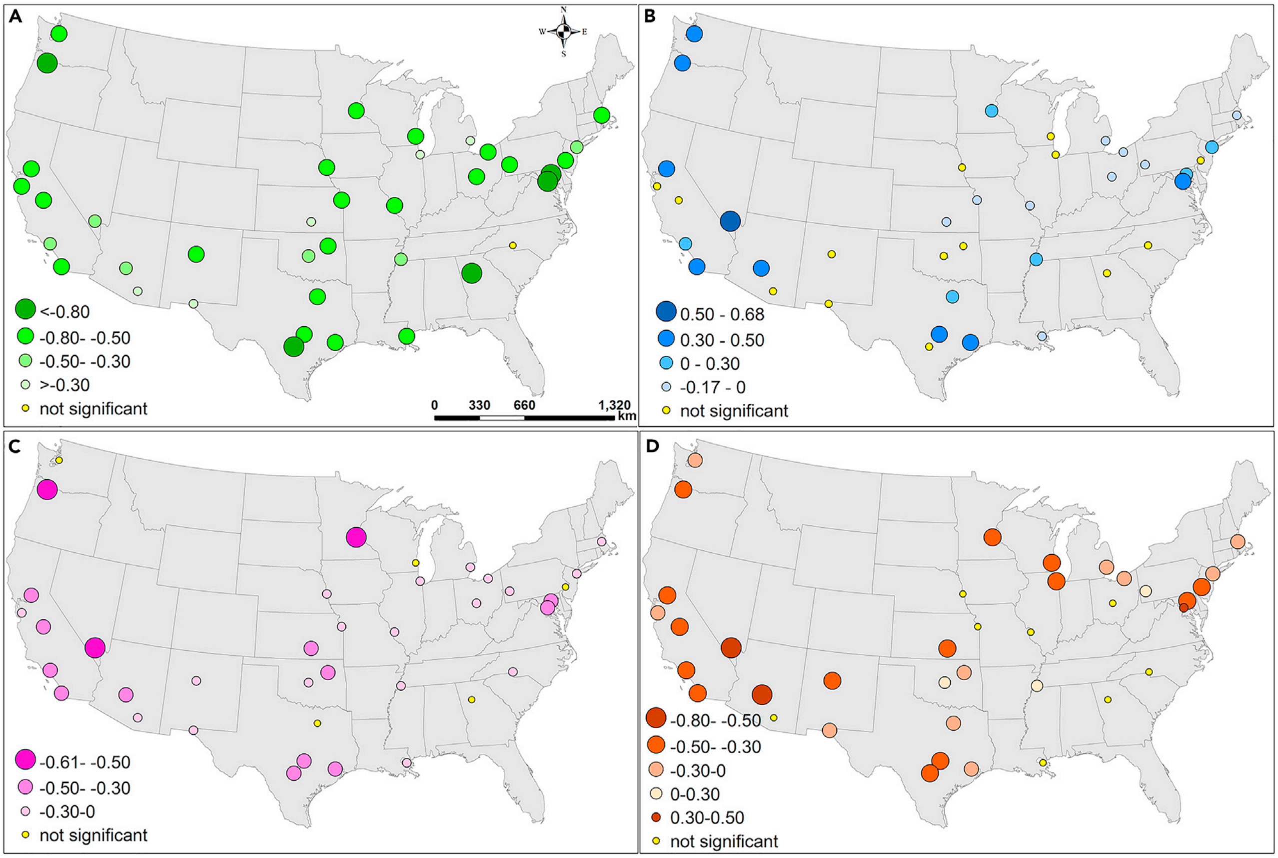

Figure 2. Relationships between LST and tree canopy, and the three social variables

(A) LST was significantly and negatively related to the percentage of cover of tree canopy (A) for all the 38 cities except for Tucson, Arizona.

(B–D) Percentage of people of color (B), household median income (C), and education level (D) were all significantly and negatively related to LST in most of the American cities, indicating that populations with higher proportions of people of color, lower income, and having lower education levels live in hotter places.

strong negative correlations ($-0.5 < r < -0.3$), while only five had no significant relationship (Figure 2). Similarly, the proportion of the population possessing a high school diploma had a significantly negative correlation with LST, suggesting that urban populations with lower educational attainment tend to live in hotter places.[48] Among the 38 cities, two had relatively strong negative correlations ($r < -0.5$), 16 had moderately strong negative correlations ($-0.5 < r < -0.3$), and eight had no significant relationship (Figure 2).

Greater cooling effects in hotter neighborhoods

UTC has a greater cooling effect in hotter neighborhoods with fewer trees. The CE of the UTC had large cross- and within-city variation. Previous studies have also shown the occurrence of cross-city variations in the CE of the UTC in American cities.[35] Results demonstrate a novel finding that there are large, within-city variations in CE at the neighborhood scale (Figure 4). This variation was significantly related to the biophysical and social characteristics of the neighborhood. In addition, we extend the analysis to a larger roster of large US cities with national scale implications. The CE of the canopy was significantly correlated with LST for most of the cities (31 out of 38), mostly in a positive direction (26 out of the 31 significant instances), suggesting that the UTC generally has a greater cooling effect in hotter neighborhoods (Table 1). The CE of the canopy, however, generally had a significantly negative relationship with its percentage of cover (Table 1), suggesting that the UTC had a greater cooling effect in neighborhoods with fewer trees, which are also generally hotter.

Greater cooling effects in vulnerable neighborhoods

Overall, we found that UTC has a greater cooling effect in socially vulnerable neighborhoods. The CE of the UTC tended to be greater in neighborhoods having a higher proportion of people of color and people with lower income and education levels (Figure 4; Table 1). CE had a significantly negative correlation with median household income in 21 cities, suggesting that UTC had a greater cooling effect in neighborhoods with a lower income. In contrast, only eight cities had significantly positive relationships. Similarly, CE generally had a negative correlation with the level of education, suggesting that UTC had a greater cooling effect in neighborhoods having a higher proportion of people with less educational attainment. CE had a significantly negative correlation with the proportion of people having a high school degree in 23 cities, with 11 cities having a moderate or strong correlation. Only six cities had a significantly positive, though marginal, relationship between CE and level of education. Additionally, CE generally had a positive correlation with the percentage of people of color in a neighborhood, suggesting that UTC

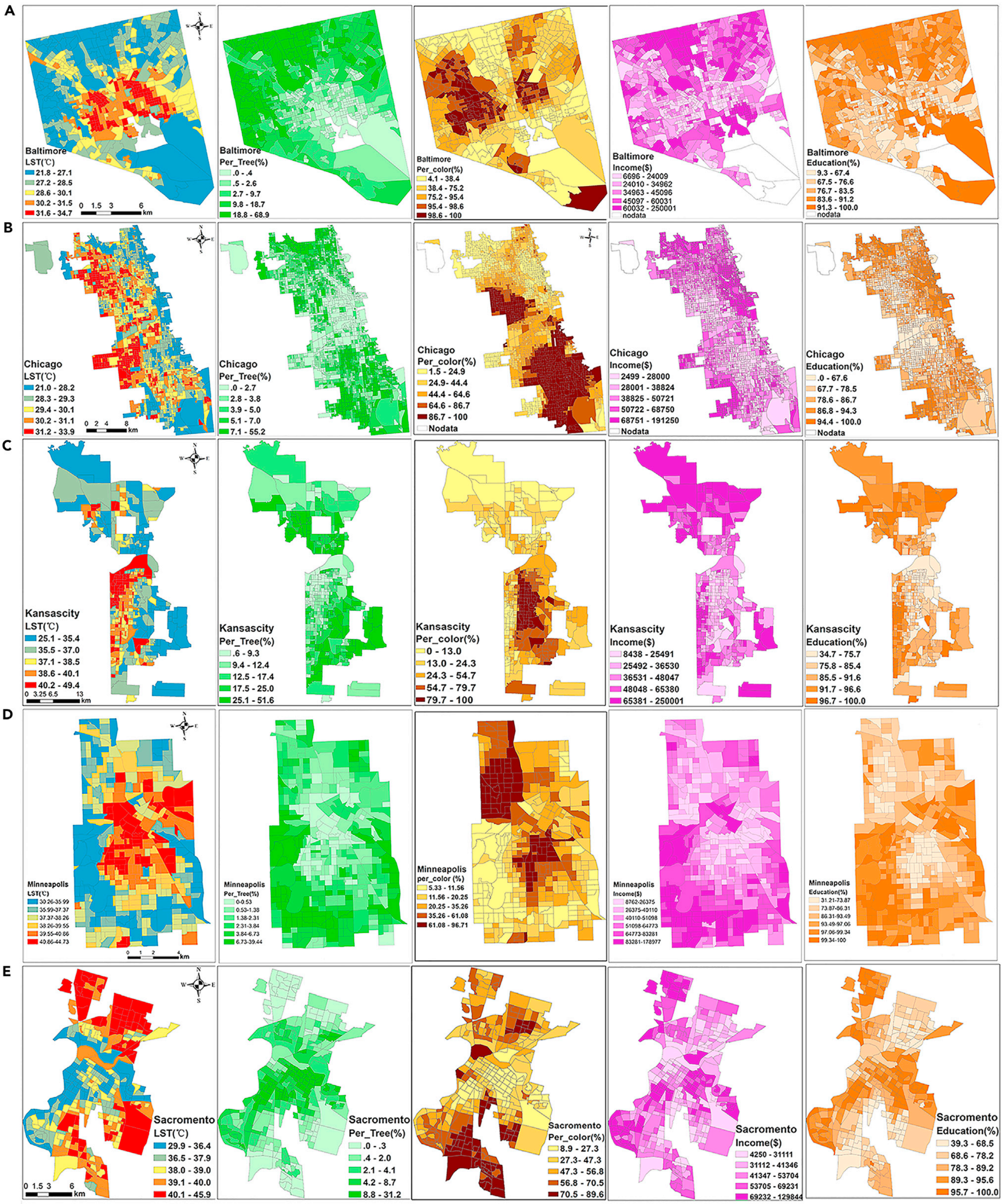

Figure 3. Examples from five of the 38 study cities

(A–E) The spatial distribution of LST, percentage of tree canopy, percentage of people of color, household median income, and education level at the neighborhood (BG) scale is shown from left to right for each of the five cities —Baltimore, Maryland (A), Chicago, Illinois (B), Kansas City, Missouri (C), Minneapolis, Minnesota (D), and Sacramento, California (E). Maps show that neighborhoods having higher LST tend to also have lower tree canopy coverage, higher proportions of people of color, and lower household median income and education levels.

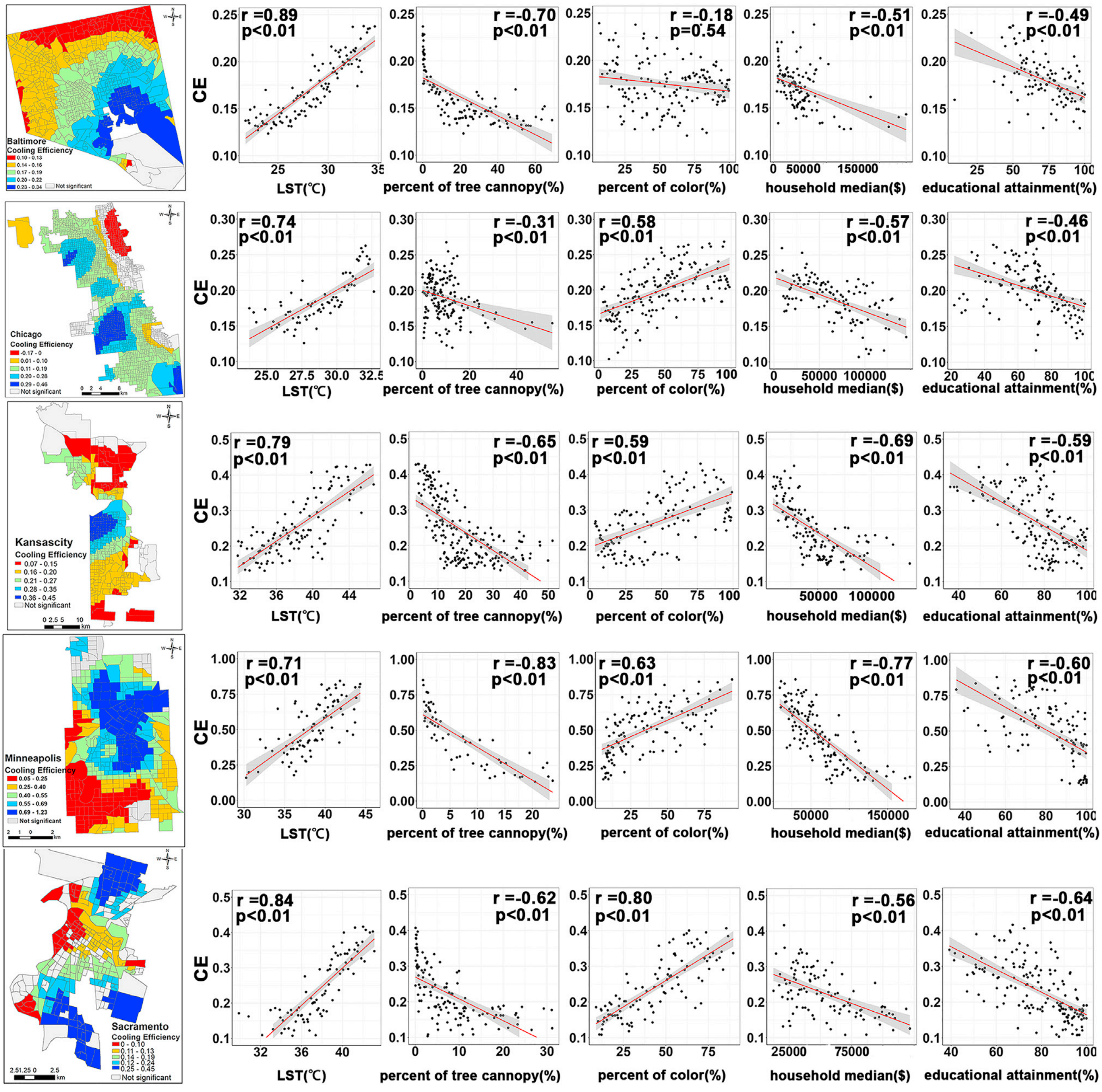

Figure 4. CE of tree canopy in the five example cities

The maps show that CE varies in space, and the scatter plots show that the cooling effect of urban trees, measured by CE, tends to be greater in hotter neighborhoods having a higher proportion of people of color and people with lower income and education levels.

had a greater cooling effect in neighborhoods with a higher proportion of people of color and thus represents distributional injustice of heat impacts. A majority of cities (30 out of 38) had a significant relationship between CE and the percentage of people of color, and most (23 out of 30) were positively correlated (Table 1). Although the associations between CE and the three social variables were usually not very strong, most of them were significant at the 0.01 level. The fact that the social variables were significantly correlated with CE, but could only explain a relatively small amount of variations in CE in some of the cities, is likely because the CE of urban trees can be affected by many social and ecological factors such as characteristics of urban trees (e.g., tree species, height, and leaf area index) and its surrounding environments (e.g., radiation and ambient temperature and pollutants such as ozone) and management practices such as irrigation.[1,35,49]

Locating neighborhoods in need of heat mitigation

Maps of LST, UTC, and social variables clearly demonstrate that hot neighborhoods within large American cities are also

Table 1. Correlation coefficients between CE and social and ecological variables

City	State	PTree	LST	Color	Income	Education
Albuquerque	New Mexico	−0.17**	0.42**	0.12*	0.049	−0.022
Atlanta	Georgia	0.27**	−0.24**	0.43**	−0.21**	−0.30**
Austin	Texas	0.06	0.12*	−0.14**	0.23**	0.22**
Baltimore	Maryland	−0.56**	0.60**	−0.18**	−0.05	−0.23**
Boston	Massachusetts	−0.17**	0.12**	−0.08	−0.10*	−0.02
Charlotte	North Carolina	−0.03	0.01	0.27**	−0.23**	−0.23*
Chicago	Illinois	−0.07**	0.54**	0.37**	−0.27**	−0.44**
Cleveland	Ohio	−0.09**	0.20**	0.23**	−0.19**	−0.13**
Columbus	Ohio	−0.25**	0.30**	0	−0.13**	0.007
Dallas	Texas	−0.02	0.43**	0.03	0.04	0.02
Detroit	Michigan	−0.17**	−0.005	−0.22**	−0.17**	−0.28**
El Paso	Texas	0.05	−0.36**	0.09	0.24**	0.14*
Fresno	California	−0.34**	0.25**	0.61**	−0.54**	−0.61**
Houston	Texas	0.03	−0.02	0	0.03	−0.01
Kansas City	Missouri	−0.52**	0.56**	0.26**	−0.29**	−0.35**
Las Vegas	Nevada	−0.15**	−0.25**	−0.27**	0.14*	0.08
Los Angeles	California	−0.12**	0.21**	0.13**	−0.17**	−0.23**
Memphis	Tennessee	0.05	0.37**	−0.12**	0.22**	0.23**
Milwaukee	Wisconsin	−0.09**	0.18**	0.47*	−0.34**	−0.34**
Minneapolis	Minnesota	−0.17**	0.50**	0.46**	−0.55**	−0.40**
New Orleans	Louisiana	−0.20**	0.15**	−0.22**	0.05	−0.07
New York City	New York	−0.006	0.28**	0.17**	−0.13**	−0.044**
Oklahoma	Oklahoma	0.86**	0.31**	−0.32**	0.25**	0.24**
Omaha	Nebraska	−0.17**	0.09	0.45**	−0.41**	−0.46**
Philadelphia	Pennsylvania	−0.39**	0.52**	0.28**	−0.31**	−0.24**
Phoenix	Arizona	−0.20**	0.20**	−0.05	0.11**	−0.08*
Pittsburgh	Pennsylvania	−0.16**	0.16**	0.13**	0.04	−0.24**
Portland	Oregon	−0.19**	0.35**	0.25**	−0.23**	−0.49**
St. Louis	Missouri	−0.17**	−0.17**	−0.27**	0.32**	0.28**
Sacramento	California	−0.53**	0.66**	0.59**	−0.15**	−0.45**
San Antonio	Texas	−0.16**	0.17**	0.20**	−0.19**	−0.26**
San Diego	California	−0.08*	0.27**	0.25**	−0.14**	−0.31**
San Jose	California	−0.24**	0.28**	0.12**	−0.36**	−0.35**
Seattle	Washington	0.21**	0.006	0.15*	0.16**	−0.19**
Tucson	Arizona	0.04	0.31**	−0.37**	−0.09	0.26**
Tulsa	Oklahoma	−0.11	−0.09	0	0.05	−0.08
Washington, D.C.	District of Columbia	−0.40**	0.44**	0.01	−0.05	−0.11**
Wichita	Kansas	0.04	−0.09	0.01	0.03	0.003

Correlation coefficients between CE and percentage of cover of tree canopy, LST, percentage of people of color, median household income, and education attainment for the 38 cities (* significant at the 0.05% level; ** significant at the 0.01% level).

those where high proportions of vulnerable persons live. Vulnerability can be indexed based on race, median household income, and levels of educational attainment.[13,28,37,50] For example, Figure 5 shows all BGs in five widely distributed cities—Baltimore, Maryland, Chicago, Illinois, Kansas City, Missouri, Minneapolis, Minnesota, and Sacramento, California—that have higher than average LST and the social indicator of race, and lower than average levels of the social indicators of income and education. These neighborhoods are potentially the most vulnerable to excess heat and have relatively high LST.[9] Our findings suggest that such neighborhoods are where heat mitigation and intervention strategies should be applied to alleviate potential negative health impacts of heat (Figure 5). The quantitative thresholds, set as the average value here, can, of course, be chosen differently based on different community-based scenarios or practical sustainability goals.[9] Still, such spatial analysis can explicitly locate neighborhoods in need of heat mitigation and thus can provide effective tools for spatially prioritizing potential heat mitigation strategies and interventions.

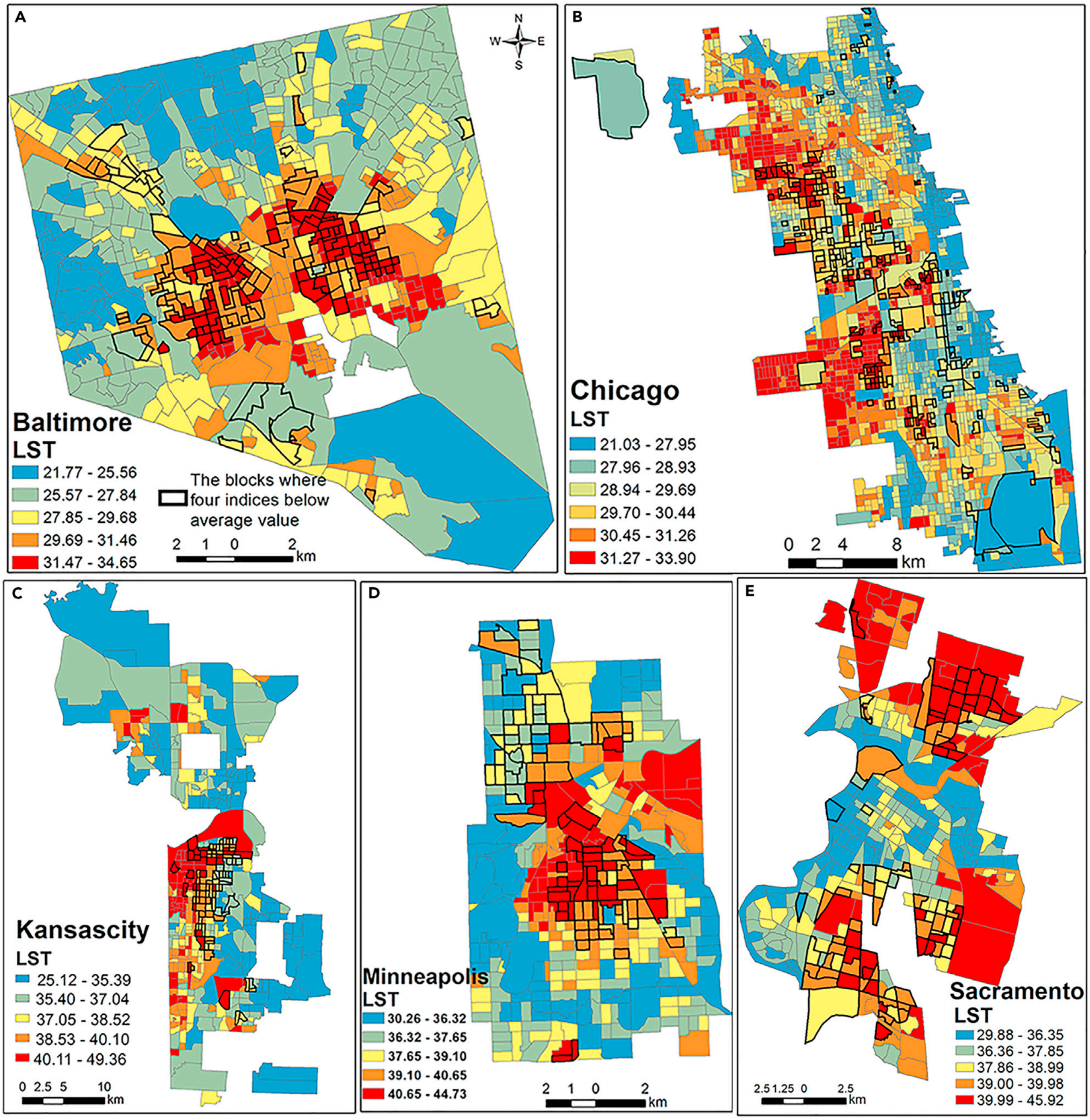

Figure 5. Locating neighborhoods in need of heat mitigation

(A–E) Maps show the spatial distribution of LST and neighborhoods (outlined in black) having higher than average LST and lower than average levels of the selected social indicators for the five cities—Baltimore (A), Chicago (B), Kansas City (C), Minneapolis (D), and Sacramento (E). These maps demonstrate that hot neighborhoods within a city are also where high proportions of vulnerable persons live.

DISCUSSION

Intensification of urban heat island effects and an increase in heat waves are among the most likely outcomes of climate change for urban dwellers worldwide.[3,11] Mitigating heat in urban areas is a pressing concern for urban policy, planning, design, and community action throughout the world.[11] Mitigation in all these contexts requires understanding the relationships between people, heat, and the trees that constitute one of the most proposed nature-based mitigation tools in cities around the world, regardless of the climate context. We examined the relationships among social characteristics, urban heat, and the capacity of trees to mitigate heat in the 38 most populous cities in the U.S at both between- and within-city scales, using the most extensive US data set yet assembled and analyzed. We found strong consistency among American cities in the relationships between surface temperature, presence of tree canopy, CE of tree canopy, and social vulnerability to heat. However, it is worth noting that these relationships do not explore the mechanisms that might link social characteristics aggregated to the neighborhood scale with the processes of tree canopy CE. Indeed, further research on such detailed mechanisms is a pressing research need, especially considering the exceptions to the general trends that appear in some cities. Future research can focus on the potential mechanisms connecting the medium-scale social variation with the proximal causes of LST and CE across neighborhoods.

We have discovered strong relationships across 38 widely distributed cities throughout the US, between tree canopy coverage, race, income, and education and the variable of LST as an indicator of heat stress. Although relationships between trees, heat, and social variables have been discovered for smaller sets or individual cities, this study confirms the importance of such relationships across the entire nation and among cities ranging in population from 300,000 to over 8 million. In American cities, populations with lower income, higher proportions of people of color, and lower education levels live in hotter places with less tree canopy. Within cities, there is variation in social vulnerability relative to high temperatures and presence of tree canopy. Neighborhoods with more people of color and lower income represent a case of distributional injustice[51] and require particular attention because they have low tree cover, high LSTs, and they lack economic and educational resources. These results suggested unequal adverse impacts of urban heat on different urban residents, with greater burdens in neighborhoods with higher proportions of people of color, who also had lower capacity of heat adaptation and mitigation due to lack of economic and educational resources. For example in Sacramento, the 127 neighborhoods that had higher LST than the mean LST of the city also had lower medium household income ($42,387 versus $48,393) and lower level of education attainment (72.2% versus 79.5%), but higher percentage of color (58.7% versus 47.2%).

We also discovered that the CE of the tree canopy is a powerful factor for within-city heat mitigation. There are large, within-city variations in CE at the neighborhood scale, which were not only related to biophysical factors such as temperature and abundance of tree cover, but also correlated with the social characteristics of neighborhoods. Urban trees tend to have greater cooling effects in hotter neighborhoods with fewer trees that lack economic and educational resources and are thereby more socially vulnerable to extreme heat. Therefore, increasing tree cover in socially vulnerable neighborhoods will not only meet the greatest need for cooling in these areas, but also achieve greater increases in cooling per unit canopy increase, creating social and ecological win-wins. These results suggest a potential ecological and social win-win if urban tree planting advances distributive and procedural justice. However, such findings can only be discovered by integrated social-ecological approaches.

Additionally, by integrating spatial analysis and maps of heat, tree canopy, and social indicators, we developed effective tools that can spatially explicitly locate neighborhoods in need of heat mitigation. Such tools can facilitate spatially prioritizing heat mitigation strategies. However, researchers and practitioners have highlighted that simply improving distributional justice in urban greening initiatives without also seriously addressing procedural and recognition justice by directly involving communities in planning, decision-making, and implementation processes may have a limited impact on multiple dimensions of this environmental justice approach.[17,18,52]

The social variables we have employed represent a bundle of disadvantages associated with well-known processes of racial segregation, restricted access to housing markets, and marginal positions in urban power networks.[42] These indicators do not imply that vulnerable residents are responsible for the heat stress and sparse tree canopies in their neighborhoods. The bundle of disadvantages is ‘‘baked in’’ the legal, cultural, economic, and cultural structure of many American cities.[42,53] It is likely to affect many things that constrain the amount of UTC in impoverished neighborhoods. These include such things as limited tree planting space in small private yards and sparse public parcels; limited access to power or capital for planting and maintaining trees; restricted knowledge acquisition about urban environmental benefits and hazards; and local fear of displacement or hazards associated with trees themselves.[54,55] Consequently, the spatial distribution of existing urban tree canopies in different neighborhoods under investigation not only reflects the effects of present or recent greening initiatives, politically and/or civically driven, but is also legacy resulted from the legal, cultural, and economic structure of different cities.[32,56,57]

Using the three cities, Baltimore, MD, New York, NY, and Phoenix, AZ as case studies, our analysis showed that in spite of the differences in demographic structure, proportional cover and spatial distribution of urban tree canopies, and social characteristics, they share the reality that people of color have been segregated and discriminated against in employment and the environmental burden in all the three cities from the early days (see details in Notes S1–S3). For example, racial segregation has a long history in Baltimore, and a variety of discriminatory practices have resulted in accumulated deprivation in the neighborhoods occupied by Black residents. Although some discriminatory practices no longer occur, the legacies of these slightly persist. Tree cover is one such legacy. There are ongoing legacies of this segregation, disinvestment, and exclusion from decision making in the three cities, and these patterns are represented in the environmental justice patterns across US cities.[58,59]

Alleviating current unequal distribution requires a deep understanding of such legacies. Furthermore, tree planting is also a complicated process. Our study took a step to identify places where trees are needed to mitigate urban heat the most, which by no means guarantees new trees would be welcomed by local people. In contrast, perceived safety issue, cost for maintenance, increased rent or housing prices, or aesthetic preference can all discourage tree planting practice. Therefore, procedural justice that involves all stakeholders and makes sure every voice is heard, is as, if not more, important than the target of distributional justice. Procedural justice is thus crucial to equitable planning and outcomes.[33,60,61] Heat mitigation strategies in socially vulnerable neighborhoods thus require attention not only to biophysical factors surrounding heat risk, but also to bringing affected communities into the assessment and decision-making processes.[22,52,61,62] Planning and implementation of tree planting must account for communities' financial and time resources and address their perceptions of the risks associated with tree planting and maintenance.[55,63]

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Ganlin Huang (ghuang@bnu.edu.cn).

Material availability

This study did not generate new unique materials.

Data and code availability

The original data generated during this study are available at Mendeley Data, https://data.mendeley.com/datasets/hxrtddggsx/2.

LST, UTC, and social data. We used LST data derived from the thermal infrared (TIR) band (10.40–12.50 μm) of Landsat-5 Thematic Mapper (TM) images with a spatial resolution of 120 m. We used a total of 34 TM images, most of which were acquired in the summer of 2010 (June, July or August) to coincide with the year the census data were collected. All the images were acquired on sunny, calm days with clear-sky conditions at approximately 10:30 a.m. local time. We first converted the digital number of the TM TIR band to the top-of-atmospheric (TOA) radiance. We then calculated the surface-leaving radiance from TOA radiance. This was carried out by removing the effects of the atmosphere in the thermal region. Finally, we calculated LST based on surface-leaving radiance using the Planck function. More details about the calculation of LST can be found in Zhou et al.[64]

We used the National Land Cover Database (NLCD; 2011 Edition) tree canopy product to calculate the percentage of cover of tree canopy for each BG. The NLCD tree canopy product has a single layer of tree canopy coverage, with pixel values ranging from 0 to 100%, representing the proportion of 30 * 30 m cell covered by tree canopy.[64,65] Social variables used in this study include the percentage of population identified as a person of color, the joint proportion of all people of color represented by difference, median household income, and the percentage of people having a high school degree. We calculated all social variables at the census BG level. All social data are collected from the 2010 US Census.

Statistical analysis

BG, a census-based geography, was used as the unit of analysis in this research. A GIS data layer of census BG was created for each city, and the BG boundary layer was used as the common boundary for all geospatial operations and statistical analysis. We calculated the mean LST, the percentage of cover of tree canopy, and the three social variables for each BG.

The Pearson's correlation analysis was used to examine the relationship between LST and the percentage of cover of tree canopy, and the three social variables. It was also used to examine the relationship of CE of urban trees with LST, the percentage of cover of tree canopy, and the three social variables. To better illustrate the relationships of CE with the percentage of cover of urban tree canopies, LST, and the three socioeconomic indicators, we calculated the mean CE at certain increments of the variables for each variable, for example, 0.5% increment of UTC cover from 0% to 100% (see Figure 4).[66,67]

We used geographically weighted regression (GWR) to estimate the within-city spatial variation of CE of urban trees. Using a GWR model, we calculated the local coefficient of the relationship between LST and the percentage of cover of tree canopy for each BG (Figure 4). The absolute value of the local coefficient was used to measure the CE of UTC, that is, the magnitude of decrease in LST with a 1% increase in tree canopy cover. GWR is based on the assumption that spatial data are often nonstationary, and thereby the relationships between variables are affected by spatial structures of the data and can vary spatially.[68,69] The outputs of GWR included local coefficient, whose absolute value was defined as the local CE of urban trees, local coefficient of determination (i.e., R^2), and local t-value, the significance test result.[68,69] All the GWR analysis was conducted using ArcGIS^{TM} 10.1. It is worth noting that the output coefficients of the GWR model (i.e., CE) are local coefficients.[68,69] Therefore, it is statistically valid to conduct the correlation analysis on CE with the percentage of cover of UTC, LST, and indicators of social vulnerability, even though the percentage of cover of UTC and LST were used to calculate CE in the GWR models.[70] Basically, what we did here was first obtain the local coefficients (i.e., CE) by regressing y (i.e., LST) on x (i.e., percentage of cover of UTC), and then to regress local coefficients on x and other indicators again. In other words, we took the derivative of y with respect to x and then took the derivative (of the first-order derivative) with respect to x again.[70] By doing this, we examined the feature of the second-order derivative.[68] Therefore, this is not a circular argument.[70]

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2021.11.010.

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AUTHOR CONTRIBUTIONS

W.Z. and G.H. conceived the study. W.Z., G.H., J.W., and J.W. led the data compilation and the data analysis, and W.Z., G.H., S.T.A.P., and T.M. wrote the manuscript with the input of all the other authors.

DECLARATION OF INTERESTS

The authors declare that they have no competing interests.

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