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Evaluating the Impact of Trees on Residential Thermal Conditions in Los Angeles Using Community Science

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As the planet warms, heat-vulnerable communities in cities face increased heat-related risks including lost productivity, reduced learning outcomes, illness, and death. Despite the growing threat of heat, effective approaches to alleviate urban heat are available. Tree planting has received investment in a growing number of cities around the world, but there are significant gaps in our understanding of the cooling potential of trees in the urban context, particularly the impacts on indoor spaces where urban dwellers spend most of their time. Our study engaged community scientists in Los Angeles County, USA to collect data on the impacts of trees on indoor and outdoor thermal conditions in residential sites. Participants created a thermal sensor network that contributed continuous readings for the study period. We mimicked an experimental research design using a difference-in-differences approach where "treehouses" with more trees and "non-treehouses" with fewer trees were compared on hot days (>90°F or 32°C) and non-hot days. We found that on hot days indoor temperatures in treehouses warm less than in non-treehouses, but that trees provide relatively less benefit at night. We also found that exposure to extreme heat reaches dangerous levels in older residences without trees or air conditioning. underscoring the need for swift action to cool heat-vulnerable communities.

Keywords
urban forest, trees, urban cooling, extreme heat, community science

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INTRODUCTION

As the global climate changes, cities around the world are experiencing unprecedented shifts including heat waves that are increasing in intensity, duration, and frequency (Perkins-Kirkpatrick and Lewis 2020). In the Los Angeles (LA) region of California, extremely hot days are projected to be up to 10°F (5.5°C) hotter compared to recent historical trends (Hall et al. 2018). New temperature extremes and compound effects from multiple other stressors portend a future when heat mitigation will be ever-more critical. A recent example of these compounding effects occurred when LA hit 121°F (49.5°C) on September 6, 2020 — its highest-yet recorded temperature. This record was set at the height of the COVID-19 pandemic, when air conditioned public spaces were not widely accessible or desirable, and on the same day the Bobcat Fire began. This wildfire would ultimately burn for three months and scorch over 100,000 acres, producing smoke plumes that heavily impacted the LA area and traveled across the continent and beyond, reaching as far as Europe (Wigglesworth and Cosgrove 2020; Mukherjee et al. 2022).

Extreme heat is the leading cause of weather-related deaths in the United States even before a warming climate is factored in (Karl et al. 2009). Heat disproportionately affects urban low-income communities and people of color, who are more likely to live in urban heat-islands with older housing, limited cooled spaces, and less *urban forest cover* — or UFC, the layer of tree leaves, branches, and stems that provide coverage of the ground when viewed from above (Jesdale et al. 2013; United States Forest Service n.d.). Of the dominant built environment strategies for reducing urban heat — which include trees and other types of vegetation, modifications to the urban environment and building materials, and adding inland urban water bodies — trees reduce heat in a wider variety of situations than other strategies, providing cooling through multiple mechanisms (O'Malley et al. 2015). By countering urban heat, UFC reduces heat-related illnesses and deaths (Vanos et al. 2012; Kalkstein et al. 2022).

Cities around the world have adopted tree planting as a heat-mitigation strategy (Keith et al. 2020), but there are significant gaps in knowledge that stand in the way of optimizing the urban cooling potential of trees. One such area is understanding the effects that trees can have on indoor thermal conditions, and specifically on a room-by-room basis at different times of day. This matters because people spend more than 85% of their time indoors (Kleipeis et al. 2001), and when and where indoor activities occur in the home affects heat exposure and risk (Sailor et al. 2015). Understanding nighttime thermal conditions in a bedroom, for example, is critically important because residents are likely to be in that space for an extended period to rest and sleep.

UFC is understood to change local climate conditions, a service provided primarily through the mechanisms of shading and evapotranspiration. But how exactly do trees cool the environment? Shade from trees blocks direct shortwave radiation from heating surfaces beneath the canopy and can reduce surface temperature up to 72°F (40°C) (Rahman et al. 2020) and maximum summer air temperatures by 0.9-3.6°F (0.5-2°C) (McDonald et al. 2016). *Evapotranspiration* — the combined processes of trees transpiring or "breathing" out water vapor, and of water moving from the earth's surfaces to the atmosphere — reduces the amount of heat available to warm the ambient air around a tree, significantly lowering air temperatures relative to spaces shaded by buildings or other built, dry infrastructure (Park et al. 2021).

Evapotranspiration can reduce ambient air temperatures some 2-14°F (1-8°C) (Rahman et al. 2020; Rahman et al. 2018), though the impacts on nighttime cooling vary (Ruiz et al. 2017).

At the mesoscale of neighborhoods, higher UFC tends to be significantly correlated with cooler temperature (Hoffman et al. 2020), and cooling benefits of UFC increase as trees mature (Taha 2013). In LA, city blocks that have more than 30% UFC are about 5°F (2.8°C) cooler than blocks without trees (Pincetl et al. 2013). Tree cover over LA's streets is the most important cause of land surface temperature variations — accounting for some 60% of variation — compared to factors such as topography and distance from the coast, which account for approximately 30% of variation (Pincetl et al. 2013).

On the microscale of parcels or city blocks, trees impact the microclimate via several processes. In addition to providing shade and intercepting solar radiation, trees can modify wind patterns to disperse trapped heat, and as trees transpire, they convert heat energy from sensible heat to latent heat, releasing energy during the phase transition into water vapor (Streiling and Matzarakis 2003; Steven et al. 1986; Chiang et al. 2018). Cooling at the microscale also impacts energy demand because shade helps air conditioners work more efficiently and reduces building heat gain. Reduced temperature at the microscale also has important implications beyond the microscale. The daily average temperature at which air conditioning use begins in shaded houses is generally higher than in unshaded houses, further avoiding emissions (Akbari et al. 1997; Berry et al. 2013). A tree in Los Angeles avoids the combustion of 40 lbs (18 kg) of carbon annually, exceeding the 10-24 lbs (4.5-11 kgs) it sequesters during the same period (Akbari 2002), thus reducing additional greenhouse gas emissions.

Tree placement and configuration impact these functions at both the mesoscale and microscale. Tree characteristics such as lower canopy height (closer to ground level where humans dwell), greater canopy size, and density of foliage yield greater cooling benefit (De Abreu-Harbich et al. 2015; Rahman et al. 2020; Kong et al. 2017). De Abreu-Harbich et al. (2015) found that tree-planting configurations of two rows of trees, with minimally five to 10 trees per row, improve thermal conditions — an application that is particularly apt in public right-of-way spaces such as streets and sidewalks. Urban morphology also plays a role, with the cooling benefit of UFC increasing where shade from the built environment is less abundant, such as where street canyon geometry is shallow and broad (Coutts et al. 2016).

Climate type and latitude also influence the impact of UFC on regulating temperature and the relative contribution of each UFC cooling mechanism, as a meta-analysis of the cooling traits of trees by Rahman et al. (2020) found. In hotter and drier climates — including California's semiarid Mediterranean climate — the magnitude of the shading effect is stronger than it is in high latitude locations because there is greater benefit to intercepting radiation in low and mid latitudes, which receive more intense solar radiation. In wetter climates and those with more evenly distributed precipitation regimes, the magnitude of cooling via evapotranspiration is more significant than it is in drier climates, though shade is still the dominant mechanism regardless of climate or latitude (Rahman et al. 2020).

Despite the cooling benefits of trees, the energy, ecosystem, and health protection services that trees provide are not free from tradeoffs and understanding these tradeoffs can help maximize benefit and reduce risk (Figure 1). For instance, when considering the microclimate effects of trees in urban areas, trees can provide cooling through shading of buildings during hot weather but can increase the need for wintertime heating, and can also have a wind shielding effect that reduces mixing and dilution of pollutants that contribute to poor air quality (Taha 2013). In hot weather, cooling impacts from shade and transpiration peak during summer afternoons, when evaporation levels are at their highest — an important function on hot days (McPherson and Simpson 2003). However, lower wind speed by trees can produce more conductive heat gain on surfaces in the built environment — a phenomenon that can be beneficial in cool weather but detrimental during hot weather (Huang et al. 1990). While shading and reduction of solar radiation by building-adjacent trees and vegetation reduce temperature, trees can raise humidity outdoors and indoors (Huang 1987; Akbari 2002). Increased humidity in dry climates or during dry heat waves can promote improved *thermal comfort* — a subjective condition in which an individual is satisfied with their thermal environment and does not have an impulse to change it (Djongyang et al. 2010) — but it can have the opposite effect in humid climates or during humid heat waves (Zhou et al. 2020). Careful consideration of the placement of trees can help mitigate these tradeoffs. Decision-making tools such as the i-Tree suite of tree planting calculators can reveal building interactions, air temperature impacts, and forecast the effects of land cover changes produced by planting trees, from a single tree to planting campaigns at the neighborhood or city level (i-Tree n.d.).

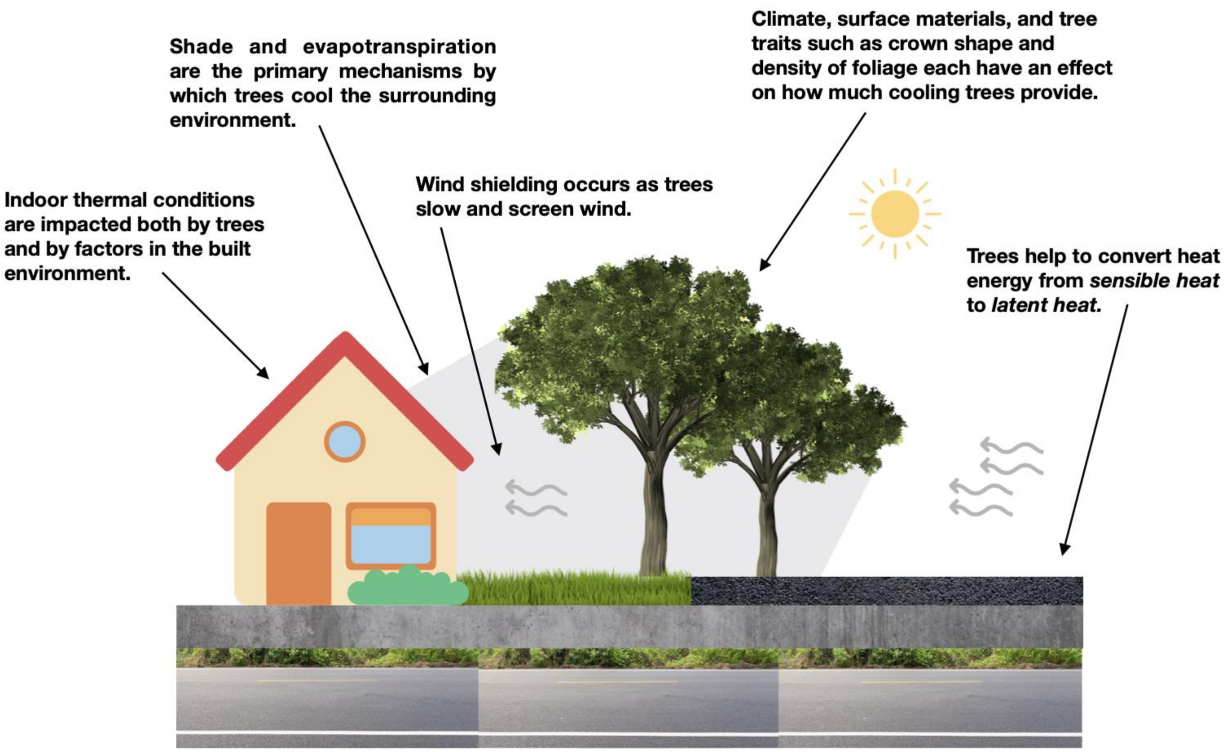

Figure 1. Impacts of UFC on thermal conditions at the microscale. The figure shows multiple mechanisms through which trees affect the microclimate.

While exploring these functions holistically can help address these tradeoffs, much of the existing literature explores the benefit of trees solely on outdoor conditions. Studies on the indoor impacts of trees make up a small portion of the literature (Wolf et al. 2020). This is relevant because outdoor conditions may not be a good predictor of indoor conditions, as a multitude of factors in the built environment — such as cavity wall insulation, rate of heat loss or gain of windows, and albedo of roof, pavement, and wall materials — modulate indoor heat exposure (Baniassadi et al. 2018). Fewer still are studies that consider impacts on the microscale rather than the meso or macro scale, those that use empirical observations rather than modeling (Wang et al. 2014), or those that evaluate thermal conditions by room or by time-of-day activity.

This study seeks to contribute to this limited body of knowledge by answering the question: What is the impact of trees on indoor and outdoor residential temperature and thermal conditions? We hypothesized that indoor thermal conditions for residential parcels with trees would be improved on hot days, and that parcels with trees would have lower peak temperatures on hot days compared to residences without trees. Overall, we found that homes with trees experienced *relatively* less warming on hot days than homes without trees, and living rooms (but not bedrooms) in residences with trees had cooler *actual* temperatures during the hottest times of the day. We also found that trees provide relatively less benefit at night, a finding that is consistent with other studies but warrants further investigation for its potential impacts on public health. Our study presents new empirically-derived, spatially and temporally granular data supporting the daytime heat-protective function of trees in an urban environment during hot weather in residential sites, and presents research methods that can serve as a foundation for future studies.

MATERIALS AND METHODS

Difference-in-differences

Conducting empirical research to compare the impact of the presence or absence of trees on thermal conditions of houses is complicated by confounding variables and the likelihood that these two groups of houses differ on other dimensions that might affect temperatures independent of trees, such as building materials, insulation, solar radiation and building orientation. Behavioral factors can also have an influence on thermal conditions. For example, households that live with higher UFC are likely to have greater wealth (Schwarz et al. 2015) and might therefore be more likely to have better-insulated homes. While randomized experiments are one way to control for confounding factors, such studies are costly and difficult to design and execute because such an experiment would ideally plant mature trees that provide benefits immediately. Young trees take time to grow and realize cooling benefits, and households randomized into the treatment group might migrate; as new residents move in, the experiment would be contaminated in non-random ways such as adaptive investments being made — for example, different behaviors than the original tenants, or the addition of a new air conditioning system.

To address these shortcomings, we use a difference-in-differences (DD) quasi-experimental approach. DD is a statistical technique that uses observational data to mimic an experimental research design by assigning two groups to either a control or treatment group

(Angrist and Pischke, 2008), and is a technique recommended for evaluating the effectiveness of varying strategies for reducing the health impacts of extreme heat (Dwyer et al. 2022). DD enables the evaluation of non-experimental conditions by designating data to either belonging to the control or treatment group. The DD approach captures the spirit of differential changes over time across these two groups, where one group is more exposed to a particular treatment (in our case, trees) at a given point in time (Angrist and Pischke 2008). As shown in Table 1, in our study the two groups were *residences with low or no tree canopy cover* (the control group, which we refer to as "non-treehouses") and *residences with moderate or high canopy cover* (the treatment group, which we refer to as "treehouses"). We calculated the differences in temperatures in each group during hot days ≥90°F (≥32°C) and non-hot days <90°F (<32°C). The model assumed that homes with trees experience a relatively larger cooling effect from trees on hot days and, therefore, have a relatively smaller increase in indoor temperatures on hot days compared to control sites. We did this by calculating the effect of the independent variable (trees) on the dependent variable (temperature) over the study period in the two groups.

Table 1. Definitions for terms used in the study. "UFC" refers to the parcel's urban forest cover.

Term	Definition
Treehouse	A participating residence for which the parcel UFC is ≥18%*
Non-treehouse	A participating residence for which the parcel UFC is <18%*
Hot day	A day with a maximum daily temperature ≥ 90°F (32°C)**
Non-hot day	A day with a maximum daily temperature < 90°F (32°C)**

* *L.A. County's average UFC is 18%*

** *Temperature recorded at the National Weather Service Los Angeles Downtown/USC weather station*

Community scientist recruitment

The project scope, which was written before the COVID-19 pandemic — called for interested members of the public living in Los Angeles County to host thermal sensors in their homes and allow study personnel to visit their home to install the sensors and download the data several times during the project period. To accommodate necessary social distancing requirements of the pandemic, we modified the scope. Rather than recruit members of the public at large, we conducted recruitment among frequent and regular volunteers of the LA-based environmental organization TreePeople, which was the prime recipient of the research grant. This modification provided the opportunity for a more hands-on community science approach involving participants in installing sensors, downloading and transmitting data, and troubleshooting sensor issues. This more active level of involvement warranted recruitment of vetted TreePeople volunteers.

Recruitment took place in July and August 2020 with the assistance of TreePeople's community engagement staff, who maintain lists of the organization's approximately 8,800 regular volunteers (L. Rodriguez, personal communication, July 11, 2022). An email explaining the study and the requirements for participation was sent to volunteers who live in two areas: Watts (south central Los Angeles County) and the Gateway Cities (southeast Los Angeles County). These neighborhoods were selected because of their limited resilience to heat waves, measured by low UFC and lower-than-average air conditioning availability (Galvin et al. 2019; Fraser et al. 2017).

Interested individuals were asked to fill out an application. Twenty-nine applications were received and screened, and eight households were ultimately selected, though one of the participating households was ultimately excluded from the study for neglecting to install the sensors. Selection criteria included:

- **Parcel urban forest canopy**: half of selected participants had a UFC lower than the LA County average of 18%, while the other half had moderate or high UFC above the average. UFC was determined by using the Los Angeles Tree Canopy Map Viewer (available at tinyurl.com/treeviewer).
- **Building vintage**: we sought older buildings built prior to the adoption in 1978 of California's Title 24 building energy efficiency standards.
- **Air conditioning access and use**: to minimize the potential of misleading data readings skewed by the use of air conditioning, we sought homes that either had no air conditioning, or homes with window units but no central air conditioning. We asked applicants with window units how often they typically use AC when very hot out (never, rarely, sometimes, always), and we sought participants who reported never, rarely, or sometimes.
- **Geographic location**: we selected sites that were clustered around one heat-vulnerable part of the county to allow for use of one official reference weather station.
- **Tech-savvy participant**: we asked applicants to rate their technological savvy so we could recruit participants who would be able to accurately install the sensors and download and transmit collected data.

Participating households were provided detailed instructions on how and where to install the sensors. Data downloads were requested from the participants every two weeks in order to be able to identify data collection issues such as a unit malfunction or battery problems. The study received an exemption from UCLA's Institutional Review Board, and participants were asked to sign a consent form advising them of the voluntary nature of the project. Participants received a $100 gift card at the conclusion of the project.

Data collection occurred at study sites in Southeast Los Angeles (Table 2). Relative to other parts of LA County, this region has some of the highest concentrations of impervious surfaces coupled with low UFC. This is a working-class area that is approximately 70% Latino/a, 7% Black, and 7% Asian, and has an average annual household income ranging between $40,000 for Maywood and Huntington Park to about $60,000 in Downey, which is low for LA County (Los Angeles Times 2021). The environmental justice mapping tool CalEnviroScreen assigns this area a pollution burden of between the 65th percentile in Downey and the 95th to 100th percentile in Maywood, South Gate, and Huntington Park (Office of Environmental Health Hazard Assessment 2020).

Table 2. Descriptions of study sites, including neighborhood, building vintage, parcel and neighborhood UFC, and housing type.

Study site	Neighborhood	Decade built	Parcel tree cover	Neighborhood tree cover	Housing type
Non-treehouse 1	Central-Alameda	1910s	10%	13%	Duplex
Non-treehouse 2	Bell Gardens	1940s	4%	11%	Single-family home
Non-treehouse 3	Huntington Park	1960s	7%	12%	Single-family home
Non-treehouse 4	South Gate	1940s	9%	13%	Duplex
Treehouse 5	Huntington Park	1960s	23%	12%	Duplex
	Tree mix: a mix of mature fruit trees exceeding 20-25' in height				
Treehouse 6	Downey	1940s	72%	16%	Single-family home
	Tree mix: predominantly mature broadleaf deciduous exceeding 35' in height; mature fruit trees and shrubs				
Treehouse 7	Maywood	1930s	40%	12%	Multi-unit apartment building
	Tree mix: predominantly mature broadleaf deciduous exceeding 35' in height				

Data collection

Each participating household was given three Kestrel DROP thermal data loggers with instructions for installing the sensors, connecting them to an iOS or Android device via the Kestrel LINK app, and downloading and transmitting the data. Kestrel DROP sensors have been successfully used in other research studies, including a study on the spatial-temporal dynamics of people's interaction with the urban environment (Li et al. 2019); a study that measured above-canopy meteorological profiles using unmanned aerial systems (Prior et al. 2019); and a comparative study of personal temperature exposure assessments (Bailey et al. 2020). Our study used Kestrel DROP D2HS Heat Stress Monitors for indoor installations and Kestrel DROP D3FW Fire Weather Monitors outdoors.

Three devices were installed at each site: in the bedroom, in the living room, and in a shaded location on the exterior of the home, under an eave. Instructions for installation were written based on a literature review of similar studies using weather sensors, and included directions to place the sensor: at a height of 40-50 inches (100-125 cm) above the floor; on an interior wall that is not exterior-facing and does not have a window or door leading out; and away from sources of heat, sources of light, direct sunlight, or heating/cooling vents. Participants were instructed to install outdoor sensors in fully shaded locations. As a precaution, all outdoor sensors were placed in a light-colored upside-down paper cup to shield them in the event of direct sun exposure. Homes considered to have moderate to high UFC were given a fourth data logger to install in the canopy of a tree, but in order to compare sensor location data between the two groups, tree sensor data were ultimately excluded from the analysis.

Thermal readings were collected between September 1 and November 15, 2020, for a total of 76 days of data collection. The study period included occurrences of air masses known to cause higher human mortality under the Spatial Synoptic Classification (SSC). The SSC classifies each day into an air mass type based on air temperature, dew point, cloud cover, and surface air pressure (Sheridan 2002), and is widely used to analyze the impact of climate on human health (Dixon et al. 2016; Hondula et al. 2014). We focused on the two most deleterious air masses: Moist Tropical Plus (MT+), which is excessively hot and humid, and Dry Tropical (DT), which produces the hottest and driest conditions (Sheridan and Kalkstein 2004). Table 3 shows average long-term frequencies of DT and MT+ air masses in LA and occurrences during the study period, recorded at the nearest-available weather station at Los Angeles International Airport (LAX) for which frequency data were available.

Table 3. Frequencies of deleterious air masses over a long-term average and for the study period (September-November 2020)* recorded at the LAX weather station. Dry Tropical (DT) produces the hottest and driest conditions, and Moist Tropical Plus (MT+) is excessively hot and humid.

Month	DT Avg. Freq.	DT Study Period	MT+ Avg. Freq.	MT+ Study Period
September	3% (0.9 days)	6.7% (2 days)	1.2% (0.4 days)	- (0 days)
October	6.6% (2 days)	3.2% (1 day)	0.6% (0.2 days)	6.4% (2 days)
November	15.6% (4.7 days)	13.3% (4 days)	0.5% (0.2 days)	- (0 days)

Source: Sheridan SC (2022) Spatial Synoptic Classification, version 3. http://sheridan.geog.kent.edu/ssc3.html

***Long-term average frequencies are 1944-2022 and reported monthly rather than daily. Table thus includes entire month of November.**

Half-hourly readings were collected by the Kestrel sensors throughout the study, yielding 48 readings per sensor per day. Readings included temperature, relative humidity, heat stress index, and dew point. The total number of half-hourly readings for each site (bedroom, living room, and outdoor) was over 20,000 per sensor. The sensor network was in place in time to capture the hottest day recorded to date in Los Angeles County, which occurred on September 6, 2020.

Daily highs for the study region were obtained from the National Oceanic and Atmospheric Administration's National Centers for Environmental Information. The reference weather station used for the study was the Downtown/USC (KCQT) located just west of the study area.

Data analyses

We used Stata statistical software (StataCorps 2019) and applied a difference-in-differences model to compare the change in temperature between hot and non-hot days in treehouses versus non-treehouses. We estimated the following basic model via ordinary-least-squares regression:

$$INDOOR_{it} = CLOSE_i + \gamma\ HOT_t + \beta\ CLOSE_{it} \times HOT_t + e_{it}$$

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where *INDOORit* represents the temperature of one of two indoor rooms (bedroom or living room) in household *i* on day *t*. *HOT* is an indicator for whether the temperature at the reference weather station was ≥90°F (32°C), *CLOSE* is an indicator for whether the household *i* is a treehouse within the protective reach of UFC, and *e* is an error term. *CLOSEi* captures the average indoor temperature for treehouses on non-hot days, which also accounts for the possible fixed differences in indoor temperature between households that might be spuriously correlated with proximity to trees. The parameter γ captures the change in indoor temperature on non-hot days in non-treehouses that are far from trees. β is the difference-in-differences parameter that captures the difference in indoor temperatures for treehouses versus non-treehouses on hot days.

Behavioral responses might mitigate the effect of the trees and are naturally captured in the parameter β. For example, households without trees might rely on fans or air conditioners more to bring the household temperature down on hot days. Therefore, the model captures the net effect on indoor temperature for the study sites. However, the estimate does not capture the overall societal benefit of trees since the study does not capture energy expenditures, most likely leading to an underestimate of the benefits of trees.

RESULTS AND DISCUSSION

The difference-in-differences for bedroom temperatures (Figure 2) shows that over the entire study period, the average temperature in bedrooms of treehouses was actually 2.1°F (1.2°C) *higher* on the baseline non-hot days. There are a host of reasons why this could be the case, including building materials and solar radiation as a function of the orientation of the bedroom relative to the rest of the house. This fact alone does not diminish the potential of urban cooling by trees, and it underscores the aptness of the DD research design. More importantly, the data show that on average, bedrooms in treehouses are 5.0°F (2.8°C) warmer on hot days than on non-hot days, and that bedrooms in non-treehouses are 6.1°F warmer on hot days than on non-hot days. The difference between the two groups of homes being 2.1°F (1.2°C) on non-hot days and shrinking to 1.0°F (0.5°C) on hot days suggests that trees have a 1.1°F (0.6°C) dampening effect in the heat. Without trees, we would expect that treehouses would be warmer and expose residents to even higher temperatures.

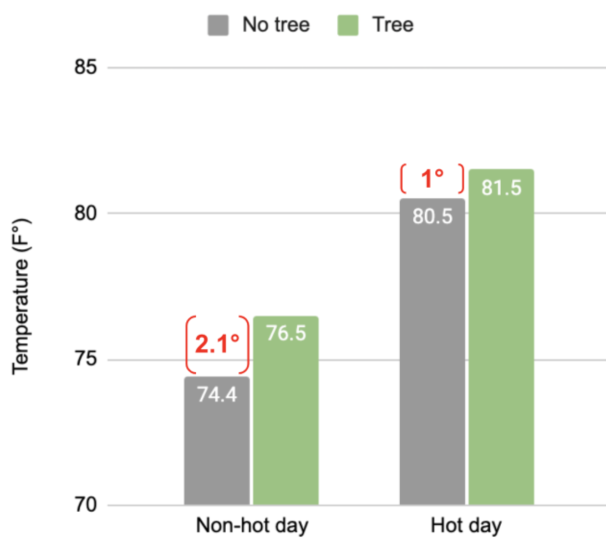

Figure 2. Average bedroom temperatures on hot and non-hot days for treehouses and non-treehouses.

When we look at the data by hourly averages throughout the study period, we see that the difference in temperatures between treehouses and non-treehouses is smaller at all times of day on hot days than it is on non-hot days (Figure 3), suggesting a temperature attenuation effect by trees on hot days. The fact that the benefits extend to nighttime hours is particularly beneficial to public health, because while occupants are sleeping the body seeks to recuperate after the day's heat exposure. Notably, indoor temperatures peak around 5:00pm, approximately 3 hours after outdoor peak temperatures (Figure 7), as heat continues to be retained and conveyed even after outdoor temperatures begin to cool off.

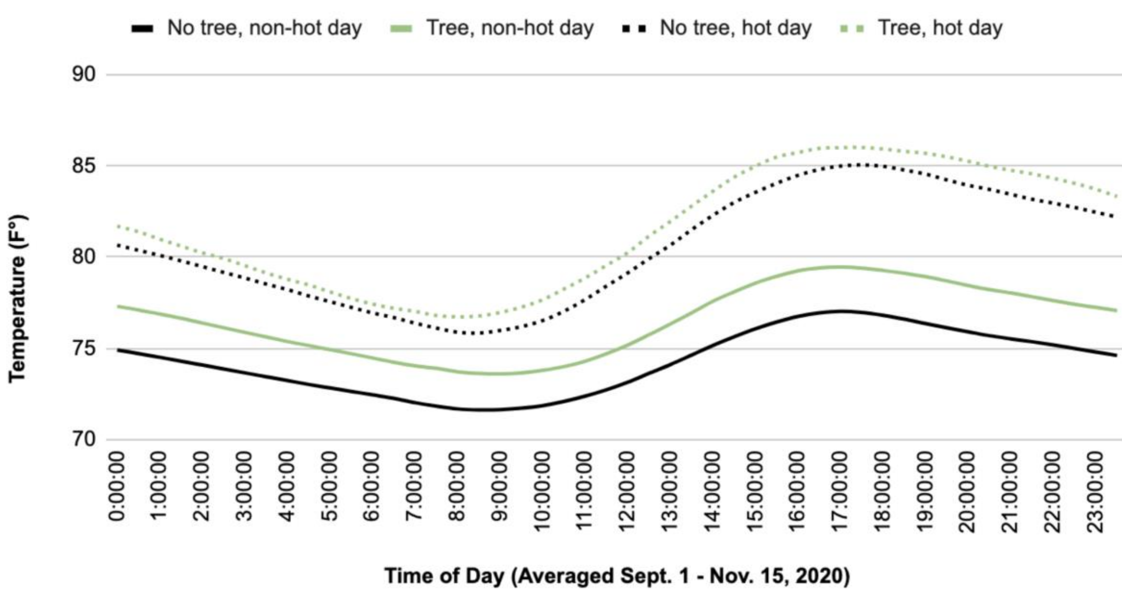

Figure 3. Hourly average temperatures for bedrooms on hot and non-hot days for treehouses and non-treehouses.

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Figure 4 shows that the effects of trees on living room temperatures are similar to those in bedrooms. Living rooms in treehouses are 1.2°F (0.7°C) warmer on non-hot days and 0.2°F (0.1°C) warmer on hot days relative to non-treehouses, implying a DD of approximately 1.0°F (0.5°C). The estimated effect for the living room is similar to the estimate for the bedroom, indicating the benefits of trees are not confined to one area of the house.

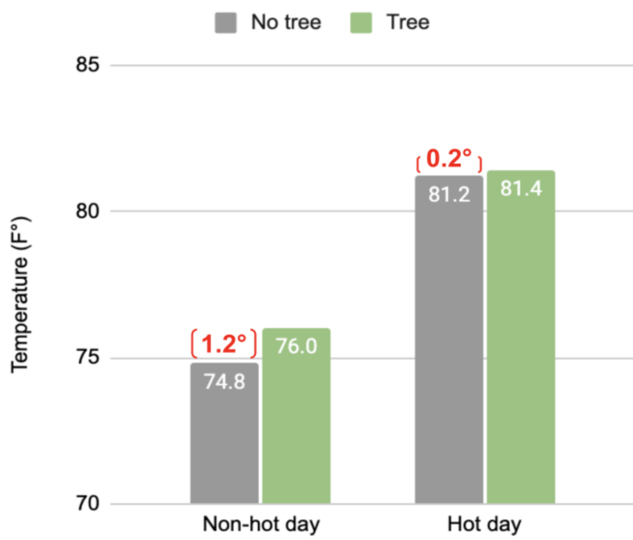

Figure 4. Average living room temperatures on hot and non-hot days for treehouses and non-treehouses.

Considering hourly averages (Figure 5), we see that temperatures in treehouses increase by a lesser amount on hot days and that actual temperatures in non-treehouses exceed those in treehouses as daily temperature increases between about 11:00am and 6:00pm. This implies that trees have an even larger cooling effect during daytime hours, when temperature is on the rise. This switch is not observed in bedrooms and is likely attributable to factors in the built environment such as building materials, insulation, solar radiation or building orientation.

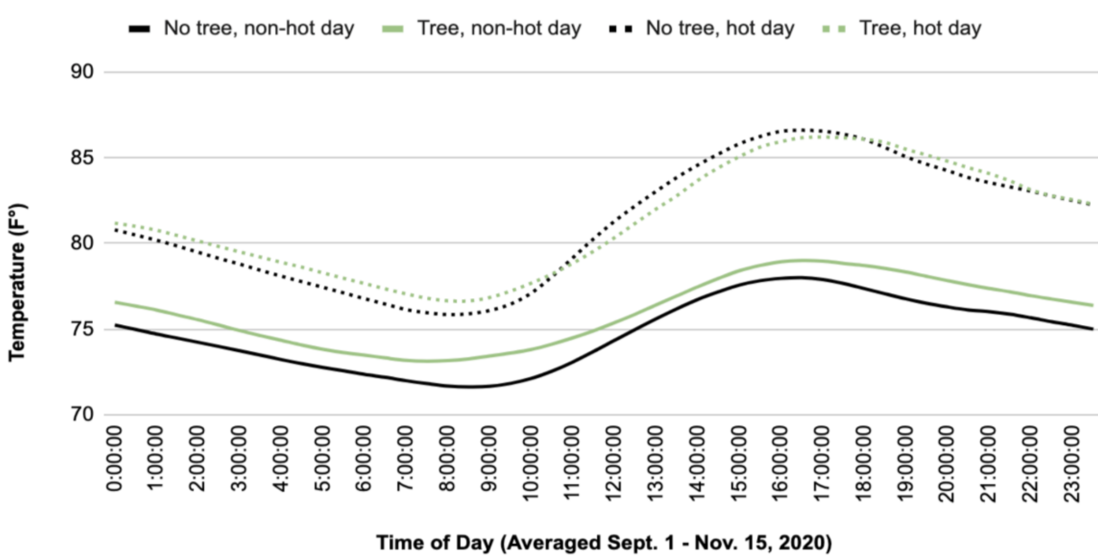

Figure 5. Hourly average temperatures for living rooms on hot and non-hot days for treehouses and non-treehouses.

As with the indoor readings, Figure 6 shows that average outdoor temperatures recorded over the study period are warmer at treehouses than at non-treehouses. In contrast with indoor temperatures, we see that eave temperatures in treehouses actually rise by a greater amount than eaves in non-treehouses during hot weather. On average, eaves at treehouses are 10.5°F warmer on hot days than on non-hot days, whereas non-treehouse eaves are 9°F warmer on hot days than on non-hot days. The difference between the two groups of homes is 1.1°F on non-hot days and grows to 2.6°F on hot days, suggesting that treehouses are actually warming 1.5°F *more* outdoors on hot days. There are a variety of site-specific reasons that could account for this unexpected phenomenon, and while we cannot conclusively ascribe this differential to any specific factors given the data at hand, we expect that average outdoor temperatures in treehouses would grow even more significantly if trees were absent. This suggests that the findings above, which already support a cooling benefit of trees, might be understated.

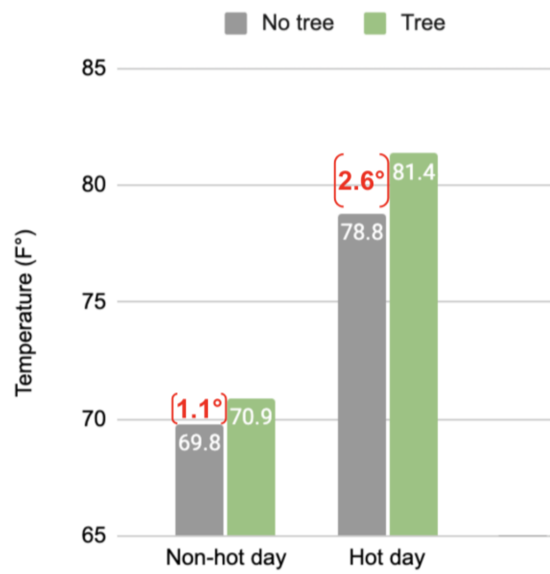

Figure 6. Average outdoor temperatures on hot and non-hot days for treehouses and non-treehouses.

Figure 7 illustrates the varying time-of-day effect of trees on outdoor temperatures and indicates that trees have a considerable daytime cooling effect and a lesser effect during the night. Outdoor temperatures are higher on average at treehouses than those observed at non-treehouses during the cooler parts of the day. Importantly, we see that the relationship switches during peak temperature hours (between about 12:00pm and 5:00pm), when outdoor temperatures at treehouses are cooler. This occurs both during hot and non-hot days, though the differential at the coolest part of the day is larger on hot days.

These observations suggest different possibilities: a) trees provide some, albeit relatively less, cooling at night than during the day, or b) trees trap heat and have a warming effect at night. A reduced cooling benefit at night is attributable to the fact that while the mechanism of evapotranspiration operates during nighttime hours, cooling from shade is not actively at play at night, apart from residual thermal benefits accrued during the daytime (McPherson and Simpson 2003). Relative warming at night may be attributable to factors such as wind shielding (Huang et al. 1990) and longwave radiation emitted from the ground being reflected by the tree back down to the ground due to limited "sky view factor" (Souch and Souch 1993; Taha et al. 1991). Disentangling these two competing hypotheses is difficult given the small number of study sites, but the first hypothesis seems more likely since the literature suggests the benefits of trees are largest during the hottest part of the day and more tempered during the cooler part of the day (McPherson and Simpson 2003; Rahman and Ennos 2016).

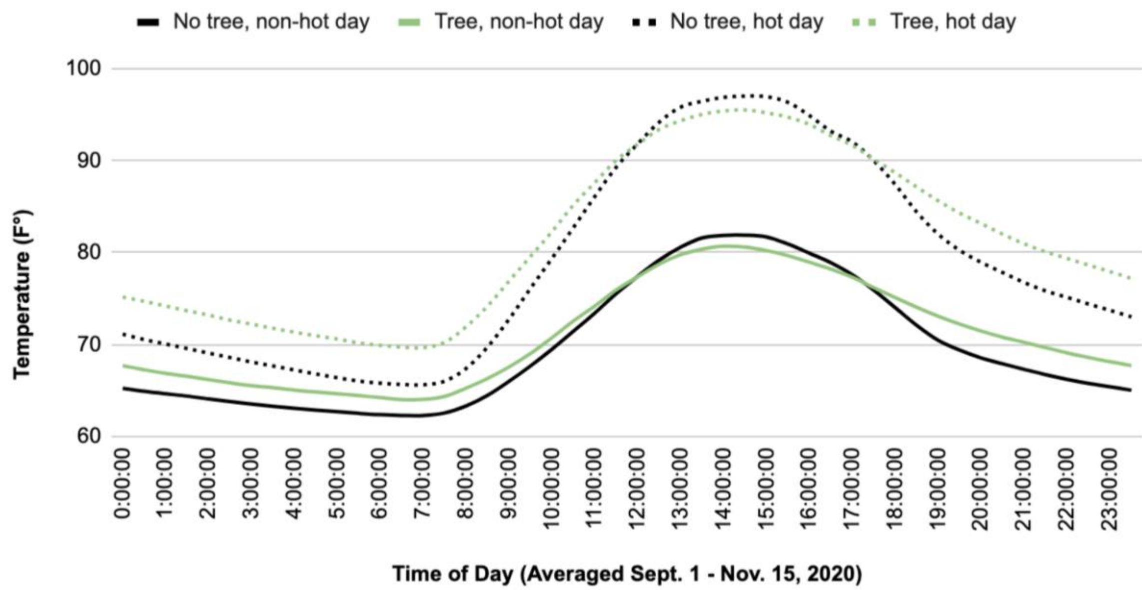

Figure 7. Hourly average outdoor temperatures on hot and non-hot days for treehouses and non-treehouses.

Table 4. Regression analysis for indoor and outdoor temperatures on hot and non-hot days for treehouses and non-treehouses (robust standard errors in parentheses).

Variable	Bedroom	Living room	Eave
Moderate / High tree cover	2.138 (.241)	1.237 (.197)	1.1963 (.211)
Hot day >90F	6.129 (.965)	6.433 (.946)	9.069 (1.152)
Tree x Hot day	-1.111 (.276)	-1.046 (-1.046)	1.351 (.304)
Constant	74.377 (.650)	74.759 (.630)	69.751 (.699)
Sample size	25,596	25,326	20,695

Table 4 presents the overall study average temperatures in table format and shows the estimates for the dependent variable (temperature), which are identical to those previously shown in Figures 2, 4, and 6. Standard error calculations for the regression analyses are in parentheses. Bedrooms in non-treehouses are 6.1°F warmer on hot days than non-hot days (*Hot day >90F*).

Bedrooms in treehouses are an average 2.1°F warmer than non-treehouses on non-hot days (*Moderate / High tree cover*), but temperatures in treehouse bedrooms increase by 1.1°F *less* than they do in non-treehouses (*Tree x Hot day*), once again pointing to indoor temperature modulation impacts of trees. The standard error is 0.28, and the estimates are statistically significant ($p = 0.0000$). The number of observations varies due to variations in thermal sensor performance over the 76-day study period.

While a DD of 1.1°F (0.6°C) may appear small, we consider these findings to be conservative. This study was intentionally conducted in neighborhoods that have low UFC in order to yield data about the parcel-level function of trees, excluding the influence of neighborhood-level UFC. Even where the parcel had high UFC, as is especially the case with treehouse 6 and 7, we can expect no additional UFC benefit to come from neighborhood-level UFC, because all neighborhoods have less than the LA County average of 18%. The study thus inherently understates the cooling benefit of large-scale planting efforts that are documented in studies such as Kalkstein et al. (2022), Hoffman et al. (2020), and Pincetl et al. (2013). We also note that hourly averages reveal insights about the cooling performance of trees at different times of day and night — details which are not discernible when looking only at the overall study averages.

In addition to contributing new empirical evidence of the benefits of trees on indoor thermal conditions, our study also quantified exposure to extreme heat, which we found to reach dangerous levels in older residences without trees or air conditioning. At various points in the study, each of the homes recorded indoor temperatures that could be harmful to residents with underlying health conditions, and occasionally recorded temperature that could be dangerous even for healthy individuals. When on September 6, 2020 the LA neighborhood of Woodland Hills reached 121°F (49.5°C), LA County surpassed its previous record high of 119°F (48.3°C) set during California's historic 2006 heat wave (Wigglesworth and Cosgrove 2020). On that record-breaking day, the daily high for our study's reference weather station at Downtown/USC was 111°F (43.9°C). The hottest of our study sites that day — a residence in Huntington Park with no trees or air conditioning — reached dangerously high temperatures: 110.3°F (43.5°C) outdoors at 2:00pm; 107.4°F (41.9°C) at 4:00pm in the living room; and 99.7°F (37.6°C) at 6:00pm in the bedroom. Such extreme temperatures are risky even for healthy people, and sustained exposure can prove deadly.

Other studies can help us understand the findings and variations we observed in the present study. Kong et al. (2017) used modeling to show that trees planted in higher-density configurations are more effective at cooling not only outdoor but also indoor spaces, and that a dense canopy and large crown are some of the most advantageous characteristics for promoting cooling. Our study included treehouses with varied canopy characteristics and we would thus expect varied findings — for example, Treehouse 6 has a parcel-level UFC of 72% composed of mix of broadleaf trees, fruit trees, and shrubs of varying canopy density, while Treehouse 5 has a UFC of 23% composed primarily of mature fruit trees which have less dense canopies. A future study could replicate these methods with a larger sample of study sites and include analysis of thermal impacts correlated with canopy characteristics.

Another study relevant in our context, published by Sailor et al. (2021), modeled the impacts on indoor and outdoor conditions by simulating UFC and built environment albedo modifications in single-family homes in Los Angeles. The researchers modeled the combined effects of varying combinations of UFC and albedo on temperature and dew point at 3-hour intervals. Mitigation cases included one focused on increasing albedo more than UFC, another which increased UFC more than albedo, and two cases that tested moderate and high albedo and UFC.

In general, Sailor et al. found that the albedo-dominated case performed better than the UFC-dominated case during daytime hours, while the UFC case performed better at night, likely because higher albedo produces greater effects when solar radiation intensity is high, whereas UFC effects of cooling are influenced both by solar radiation and by ambient temperature and humidity. However, results varied with air mass type. Indoor air temperature reductions were greatest during daytime hours under humid moist tropical+ (MT+) conditions, likely because the mechanisms of shading by trees and of reflecting solar radiation by high-albedo surfaces do not interact with humidity in the way that the mechanism of evapotranspiration does. Indoor temperature responded more favorably to the UFC-dominated case during nighttime hours, regardless of air mass type.

Sailor et al. (2021) provide findings that are useful for discussion for our purposes. The relative performance of albedo- versus UFC-dominated cases points to the impacts that shade and evapotranspiration produce since the potential cooling benefits provided by higher albedo surfaces are achieved by a totally different mechanism — reflecting solar radiation. Sailor et al.'s findings also allow a discussion of how the UFC-dominated case performs at different times of day, both indoor and outdoor. The lower range of their modeled temperature reductions is on par with what we see in the empirical data we collected, but with no empirical data to validate their model, it is not possible to conclude whether their model overstates the results of the tested scenarios. The fact that their UFC-dominated cases tended to perform better at night relative to albedo-dominated cases only tells us how the two interventions performed comparatively, and while this finding seems to conflict with our study finding (that trees provide greater cooling benefit in the daytime), the Sailor et al. study did not include a UFC-only scenario so we cannot draw a direct comparison. Sailor et al. also assumed widespread mitigation via UFC and albedo throughout the city, not at the parcel level — further limiting our ability to draw direct comparisons.

Among the rare studies that use combined field measurements and modeled simulations to investigate both indoor and outdoor thermal conditions is a study by Morakinyo et al. (2016) of two buildings in Nigeria. Using empirical data as well as modeling, the study assessed summer thermal impacts in a building shaded by trees and an unshaded building. The researchers found lower indoor temperatures in the tree-shaded building compared to the unshaded building, but also found that modeled results overestimated the cooling effects by as much as 2.7ºF (1.5ºC) over observed measurements (Morakinyo et al. 2016), highlighting the importance of empirical observations, and suggesting that results of the Sailor et al. study might be overstated. Morakinyo et al. (2013) conducted a study similar to their 2016 study which investigated the effects of trees on indoor and outdoor air temperature and found that shaded buildings had indoor-outdoor temperature differences of no more than 4.3ºF (2.4ºC) for the shaded building, while the unshaded building differences were roughly twice that, peaking at 9.7ºF (5.4ºC). We observed a similar pattern on hot days in our study, though our findings were of a lesser magnitude. Yet even when small, the temperature reductions observed in shaded sites in both our study and the Morakinyo study may be sufficient to improve public health outcomes (Jay et al. 2021; Kalkstein et al. 2022).

Altogether, our study findings point to the benefits of UFC during the daytime but raise important questions about potentially limited nighttime effects. The findings also confirm one of the two original hypotheses (that indoor thermal conditions for residences with trees nearby will be improved on hot days), but did not confirm a second hypothesis (that sites with trees will have lower actual peak temperatures on hot days compared to sites without trees). The difference-in-differences approach shows a *relative* improvement in treehouse temperatures, but not an *absolute* improvement. That is, though treehouse temperatures generally increased by a lesser amount than non-treehouses, actual temperatures were sometimes higher, demonstrating how nuances in the built environment influence the microclimate and thus how heat is experienced differently in the urban environment.

LIMITATIONS

This study has some limitations. The grant that supported this research was written and awarded prior to the COVID-19 pandemic. Recruitment was originally meant to occur through door-to-door canvassing. With agreements in place, the plan was for study team personnel to enter each household to install the data loggers and then visit the homes approximately every two weeks to check on the devices, download collected data, and troubleshoot any issues. This plan was not possible given the realities of social distancing, and our methods changed. Instead, installation instructions were provided to residents who served as community scientists on the study. Study personnel were in frequent communication with residents to obtain photos of sensor installations and data downloads.

Community science, also known as citizen science or participatory monitoring, has gained popularity in recent years because it offers a cost-effective way to collect data across large spatial and temporal scales and brings positive experiences and learning opportunities for volunteers (Aceves-Bueno et al. 2017). In the case of this pandemic-era study, community science made it possible for the research to proceed. However, a community science approach raises questions about accuracy, and in the case of this study, special measures had to be taken to ensure correct sensor placement (confirmed via photos submitted by study participants) and accurate data collection. Candidates interested in participating in the study were screened to ensure they had a thermal sensor-compatible iOS or Android device and were asked how strongly they agree with the statement “I consider myself technologically savvy with the use of mobile applications.” Selected participants were provided detailed instructions for installing the devices and downloading the data, and were asked to submit photos of the installed devices. Remote troubleshooting support was available to them from study personnel. These and other measures rely on participants being committed and responsive. In practice, we learned that participants are not all equally committed and communicative. For instance, the community scientist nature of the project led to data downloads occurring sporadically, at times causing a delay in identifying and troubleshooting sensor issues. In another instance, we learned too late that one of the participants failed to install the sensors provided, even after signing an agreement and receiving frequent communications from the study team throughout the course of the study. This led to a sample of seven homes rather than eight.

Another limitation is that a key modeling assumption — that the baseline temperature on non-hot days is not influenced by the tree canopy, or that it is influenced to a lesser degree than on hot days — might be violated because UFC can trap heat in cooler temperatures under certain conditions. Though the magnitude of this warming effect may be small, it would likely lead to overestimating the benefits of trees since it would lead to finding a relatively smaller differential between hot and non-hot days in treatment sites relative to control sites. We attempt to address the magnitude of this bias by considering the mechanics of cooling and warming by trees, and how these are influenced by time of day. Trees provide cooling through the processes of shading and transpiration, both of which are maximized during daylight hours, when temperatures tend to be highest (Rahman and Ennos 2016). Conversely, trees can have a warming effect at night, as wind is reduced and shielded, preventing dispersion of accumulated heat (Huang et al. 1990). However, the magnitude of daytime cooling is understood to exceed that of nighttime warming, with one study finding that trees provide up to 8.1°F (4.5°C) of daytime cooling while providing only 1.8°F (1°C) of nighttime warming (Taha et al. 1990). We therefore expect any warming effects to have a minimal influence compared to the cooling impacts observed over the course of the study.

Other limitations also exist. Adaptive responses, like use of air conditioning, were not closely accounted for in this study. It is possible that households that lacked cooling from trees may have relied on fans or window air conditioning units more regularly than houses with trees, and it thus possible that the indoor benefit of trees is understated in the analysis. To mitigate this concern, prospective study participants with central AC were excluded because of the relative ease and automation of controlling indoor climate with central systems, and we selected participants who either have no AC or have window or wall units only, which they self-reported to use infrequently. To further address this limitation, a future study could collect daily energy use data or otherwise monitor adaptive responses such as AC use.

Lastly, the small sample size meant that we could not test whether site characteristics, such as housing type, tree type, and tree distance may have impacted cooling by trees. For example, houses where trees are planted on the west-facing wall or in front of windows would be expected to see larger benefits from trees, but with the limited sample size and high variability in built environment characteristics between study sites, aggregating observations into the two study groups (treehouses and non-treehouses) proved to be the most conservative and defensible approach. With these limitations in mind, we offer this as a proof-of-concept study that can serve as the foundation for a larger future study.

CONCLUSIONS

This study contributes new empirically-derived support for the heat-protective function of trees in an urban environment. We found that on average, indoor temperatures in treehouses warm 1.0-1.1°F (0.5-0.6°C) *less* on hot days compared to non-treehouses. These temperature benefits extend to all times of the day, which is critical from a public health perspective, with cooling benefits peaking during daytime hours. Even modest reductions in peak temperatures can translate to improved public health outcomes: UFC and albedo modifications that produce just a 1-2°F (0.5-1.1°C) reduction in peak heat wave temperatures could reduce heat-related deaths 10-20% (Kalkstein et al. 2022).

Such temperature reductions can help improve heat-related public health outcomes and reduce public health costs among heat-vulnerable communities, which is of critical importance as the study also finds that exposure to extreme heat can and does reach dangerously high levels — up to 107.4°F (41.9°C) indoors in older residences without trees or air conditioning. Sustained exposure to such heat is a reality for many residents in LA and other cities who lack access to coping strategies, emphasizing the need for swift action to cool heat-vulnerable communities.

Future research could involve a larger-scale study involving dozens or hundreds of sites segmented by neighborhood and site characteristics. This would enable a deeper exploration of tree and housing type characteristics. Additionally, incorporating household-level energy data for the study period could enable quantification of the impacts of trees on energy demand. Such an analysis could be linked both to in situ sensors, such as the ones used in this study, and remote-sensed temperature data. Further investigation of thermal impacts of different canopy types and of the daytime vs. nighttime effects of trees on thermal conditions are other critical areas that should be explored, especially in the context of how exposure to heat at different times of day and in different rooms of the house impacts public health outcomes.

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