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V. Kelly Turner, Ariane Middel, Morgan Rogers, Ruth Engel,
Florian A. Schneider, and Zachary Van Tol

UCLA Luskin Center for Innovation

SITE DESIGN AND HUMAN HEAT BURDEN IN PACOIMA, CALIFORNIA

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On the cover and these pages:
MaRTy cart at Fernangeles Elementary School. Photo by V. Kelly Turner

Acknowledgments

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THIS PROJECT HAS BEEN MADE POSSIBLE BY FINANCING FROM
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We acknowledge the Gabrielino/Tongva peoples as the traditional land caretakers of Tovaangar (the Los Angeles basin and Southern Channel Islands). As a land grant institution, we pay our respects to the Honuukvetam (Ancestors), ‘Ahiihirom (Elders) and ‘eyoohiinkem (our relatives/relations) past, present and emerging.

EXECUTIVE SUMMARY

THIS STUDY EXAMINES how urban design influences the human experience of heat in Pacoima, a neighborhood in the San Fernando Valley region of Los Angeles. The primary metric for heat exposure is Mean Radiant Temperature (MRT), which measures a variety of factors (e.g., sun, surfaces, air, humidity, wind speed) that contribute to that experience, though we also examine Land Surface Temperature (LST; an indicator for the "skin" temperature of the Earth) using estimates from satellite imagery.

We find that the dominance of impervious surfaces like buildings, parking lots and roads, as well as the scarcity of vegetative cover like trees, shrubs and grass, contributes to high LST. In examining MRT using observed and simulated data to evaluate the human experience of heat, however, we find that the primary factor in reducing heat burden is shade. Thus, areas of Pacoima that lack shade leave people vulnerable to extreme heat. This effect is especially noticeable at Fernangeles Elementary School, which has less than 20% shade coverage throughout the day and less than 10% shade coverage during the midday recess period. Fernangeles Elementary is much hotter than its surrounding residential neighborhood across all surfaces (grass, asphalt, concrete, rubber, soil) because it has so little shade. Both the school and residential areas of Pacoima could benefit from increased shade but would also be candidates for a suite of interventions including greening, cool pavements and site-specific building design.

INTRODUCTION

EXTREME HEAT is a major public health and climate justice issue facing Californians. The National Weather Service (NWS) has consistently reported that extreme heat is the leading weather-related contributor to death in the United States (NWS 2021). Local estimates suggest that NWS and state-level reporting, including California, substantially undercount deaths from extreme heat (Los Angeles Times 2021). Exposure to dangerously hot conditions will likely increase in the future with an increased number, length and severity of extreme heat events and extreme heat "seasons" anticipated under climate change (Rockefeller Report). Critically, however, the burden of extreme heat is not shouldered equally among Californians: More deaths are attributed to low-income and communities of color (Los Angeles Times 2021b). Without intervening in what is already a major public health challenge, climate change will undoubtedly exacerbate the uneven impact of extreme heat on Californians. Part of preparing for a hotter future, therefore, includes identifying strategies to reduce the heat burden – how much heat a person is exposed to and associated heat-health impacts – especially in places where heat-vulnerable populations live.

In cities, human heat burden depends on neighborhood microclimate, or local (areas covering up to several hundred square meters) conditions in one area that are different from surrounding areas. At the neighborhood scale, the type and amount of vegetation and how tall and spread out buildings are will create a Local Climate Zone (LCZ) with fairly predictable implications for thermal conditions (Stewart & Oke 2012). Neighborhoods with lots of impervious surfaces like buildings, parking lots and streets, few trees and other green spaces, and with low-rise and dispersed building configurations, tend to experience hot microclimates because heat energy from the sun can easily reach surfaces that capture and slowly re-radiate it into the atmosphere. This type of development causes some neighborhoods to be up to 10 degrees Celsius warmer (as measured by air temperature and land surface temperature). Studies have repeatedly found that low-income and communities of color are exposed to hotter neighborhood microclimates than their counterparts in wealthier, whiter neighborhoods (Harlan et al. 2006; Wilson 2020; Dialesandro et al. 2021). Not only do these communities experience the worst impacts of extreme heat, but they also are categorically some of the hottest neighborhoods in the city.

Site design and the three-dimensional features in a particular setting (e.g., school, park, workplace, street; all less than tens of meters), also contribute to human heat burden outdoors. How a person experiences heat at a particular site depends on humidity, wind speed and heat radiating from nearby surfaces but is primarily moderated by shade availability (Middel and Krayenhoff 2019).

Unshaded areas can be up to 30–50 degrees Celsius (as measured by MRT, a composite indicator for the cumulative heat load experienced by a person) hotter than areas where shade is cast from trees, buildings and shade sails (Middel et al. 2021). While the relationship between shade availability and heat vulnerability is not yet firmly established, the use of tree canopy coverage as a proxy for shade reveals that low-income communities have about 50% less access to shade than wealthier neighborhoods nationally (McDonald et al. 2021, Leahy & Serkez 2021). In some cities, like Los Angeles, disparities are even more pronounced: Throughout the urban area, 18% of trees grow where only 1% of the population lives (TreePeople 2019).

This report examines the relationships between neighborhood and site-scale features and human heat burden. Most U.S. planning efforts that consider the contributions of urbanization to hot conditions in cities have focused on what is frequently referred to as the Urban Heat Island effect (UHI) (Oke 1982, Keith et al. 2020, Turner et al. 2022a). Here, we intentionally do not use UHI to guide our research for reasons that have been discussed in detail by Martilli and colleagues (2020). Most critically, UHI describes *regional* (100s of meters or more) climate patterns that function in different ways from local and hyper-local processes (Turner et al. 2022b). Specifically, we aim to capture the comparative influence of sun *reflecting* (how much sun energy is absorbed by different surfaces and re-radiated as heat) and sun *intercepting* (how much sun is prevented from being absorbed by surfaces) features of sites.

STUDY AREA

WE USE TWO SITES (a residential area and a school) in Pacoima, a neighborhood in the San Fernando Valley region of Los Angeles, as a case study. Pacoima is projected to experience 108 days above 90° F on average between 2035 and 2064, putting it in the 14th percentile of "healthy places" from an extreme heat perspective in the state (HPI 2022). Pacoima sits inland from the Santa Monica Mountains, insulating it from cooling coastal effects. Its land cover is 61% impervious surfaces, so most of the physical neighborhood increases heat. Pacoima is classified as a CalEPA disadvantaged community, meaning that its combined population characteristics and environmental burden place it in the most vulnerable 25% of areas within California (CalEPA 2022). Pacoima's current heat burden, driven by a combination of initial climatic conditions and urban development, means that it will be particularly vulnerable to extreme heat.

Pacoima is also a neighborhood where interventions to mitigate the impacts of heat are possible. It is a Transformative Climate Community (TCC) site, a participant in a California program that invests in community-led development and infrastructure to address environmental and health conditions (SGC 2019). While this report focuses on the contributions of existing urban conditions in Pacoima to human heat burden, it is intended to inform potential future design interventions through TCC and other heat-mitigation programs. It is also part one of a two-part study in which we will assess the potential impact of interventions through local climate scenarios.

Overall, we found that shade is the primary driver of reductions in human heat burden, particularly as it is experienced by humans. Where changes to shade infrastructure are not possible, vegetated land cover can reduce heat, particularly surface temperature and other land use strategies can be employed within a hybrid approach to find the most appropriate intervention for local conditions.

METHODS

IN CONSIDERING how Pacoima's neighborhood microclimate contributes to the outdoor experience of heat, we used two remotely sensed products: 2018 National Agriculture Imagery Project (NAIP; 60-cm resolution) imagery and 2019 Landsat 8 data (30m resolution). We used these data to analyze land cover, greenness and reflectivity of the study area. These metrics can combine to provide an understanding of how the physical neighborhood space absorbs, reflects and shades from incoming solar radiation. We also used Landsat data to calculate neighborhood-wide Land Surface Temperature (Wang et al. 2015). LST as an indicator approximates the "skin temperature" of the Earth at atmospheric levels. It is widely used in heat research as a *signal* of urban heat because it provides full and free coverage for any urban region but is not a replacement for direct measurement of human heat burden.

To more directly assess the experience of heat within Pacoima, we examined two local site designs selected in consultation with TCC Pacoima partners: a residential neighborhood and an elementary school. We collected data at these two sites on July 28, 2021, using mobile human biometeorological (MaRTy) carts, which were developed and deployed by researchers at Arizona State University (Middel and Krayenhoff 2019). MaRTy collects data on a wide range of neighborhood microclimate conditions, including MRT, LST, air temperature (AT), relative humidity (RH), wind speed and direction, solar radiation and albedo (the reflectivity of surfaces).

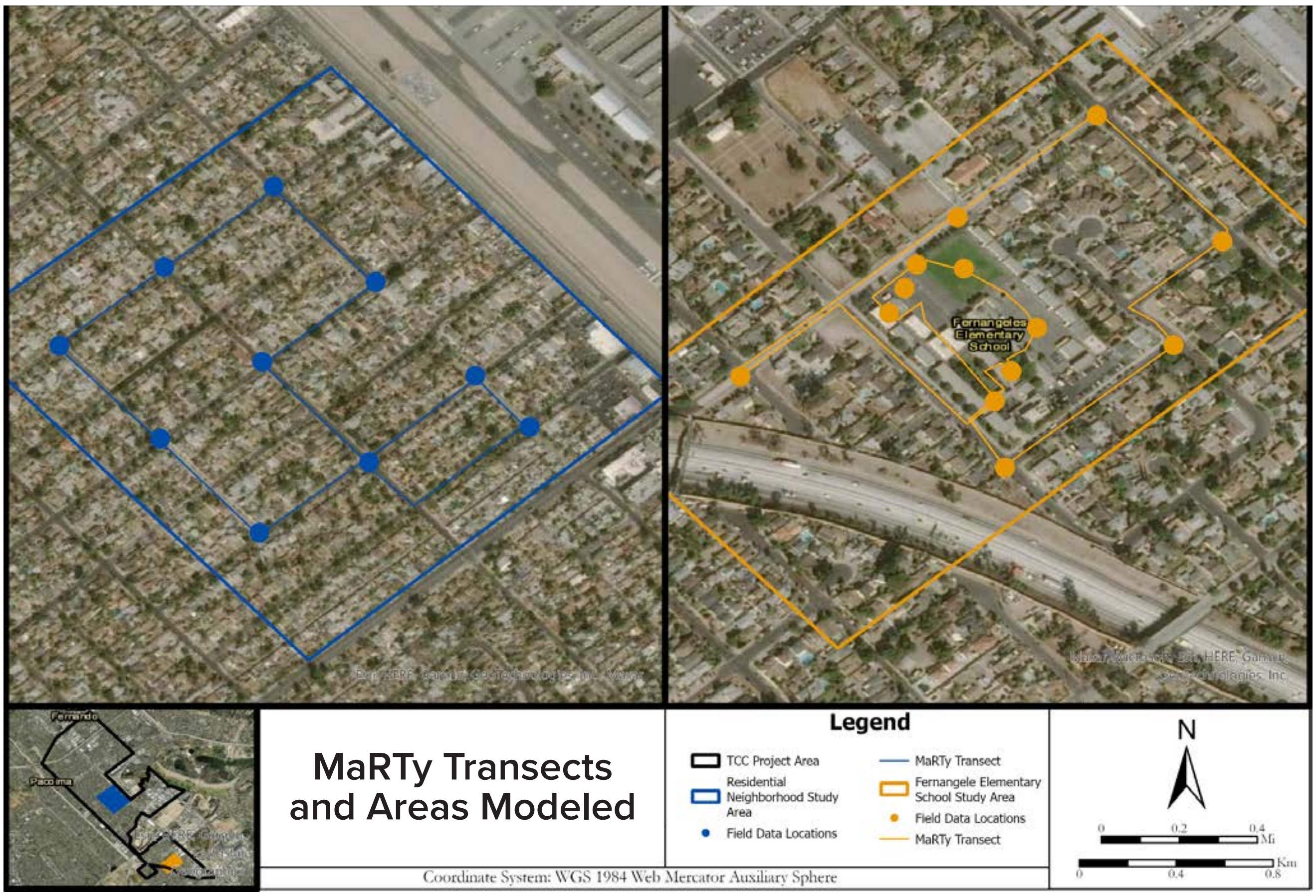
We collected observations along two transect routes using MaRTy on July 28, 2021, from 8 a.m. to 6 p.m. Transect Route 1 consisted of 10 stops in a residential neighborhood in Pacoima and Transect Route 2 consisted of 13 stops in Fernangeles Elementary School and the adjacent residential area (Figure 1). The residential neighborhood transect wound through a homogeneous residential area directly abutting the Whiteman Airpark to the southwest (Figure 1). In land cover, normalized difference vegetation index (NDVI) and albedo, it resembles most of Pacoima, with no particular distinguishing features or LST hot spots. The Fernangeles Elementary School transect included observations taken on blacktop surfaces, on a grass playing field and along residential streets. The transect contains a noticeable area of green vegetation (the playing field) and sits near a high school, church and garden with both green vegetation and barren soil.

At each stop point on the transect route, additional data on the amount of sun exposure/ shade, shade casting features and climate conditions were recorded. Each transect took about 40 minutes to complete. Because small changes in temperature can occur during a one-hour transect, all data were time detrended to correct for minor climatic changes occurring over the observation period.

Finally, we used the microclimate modeling software ENVI-met, which simulates surface-plant-air microscale interactions, to build base models of each transect (Bruse and Fleer 1998, Middel et al. 2014, Simon et al. 2020). We supported the models with 2018 NAIP land cover imagery, LiDAR-derived tree data and Whiteman weather station meteorological data from the date when observations were collected (Whiteman 2021). We validated model performance using "receptors" (field data added to model to compare with simulated data) at each stop point along the transect and calculated the Root Mean Square Error (RMSE) and index of agreement (d) to assess model accuracy (Willmott 1981).

For more information on data and methods, see Appendix A.

FIGURE 1: MaRTy transects and areas modeled in Pacoima Transformative Climate Communities project area

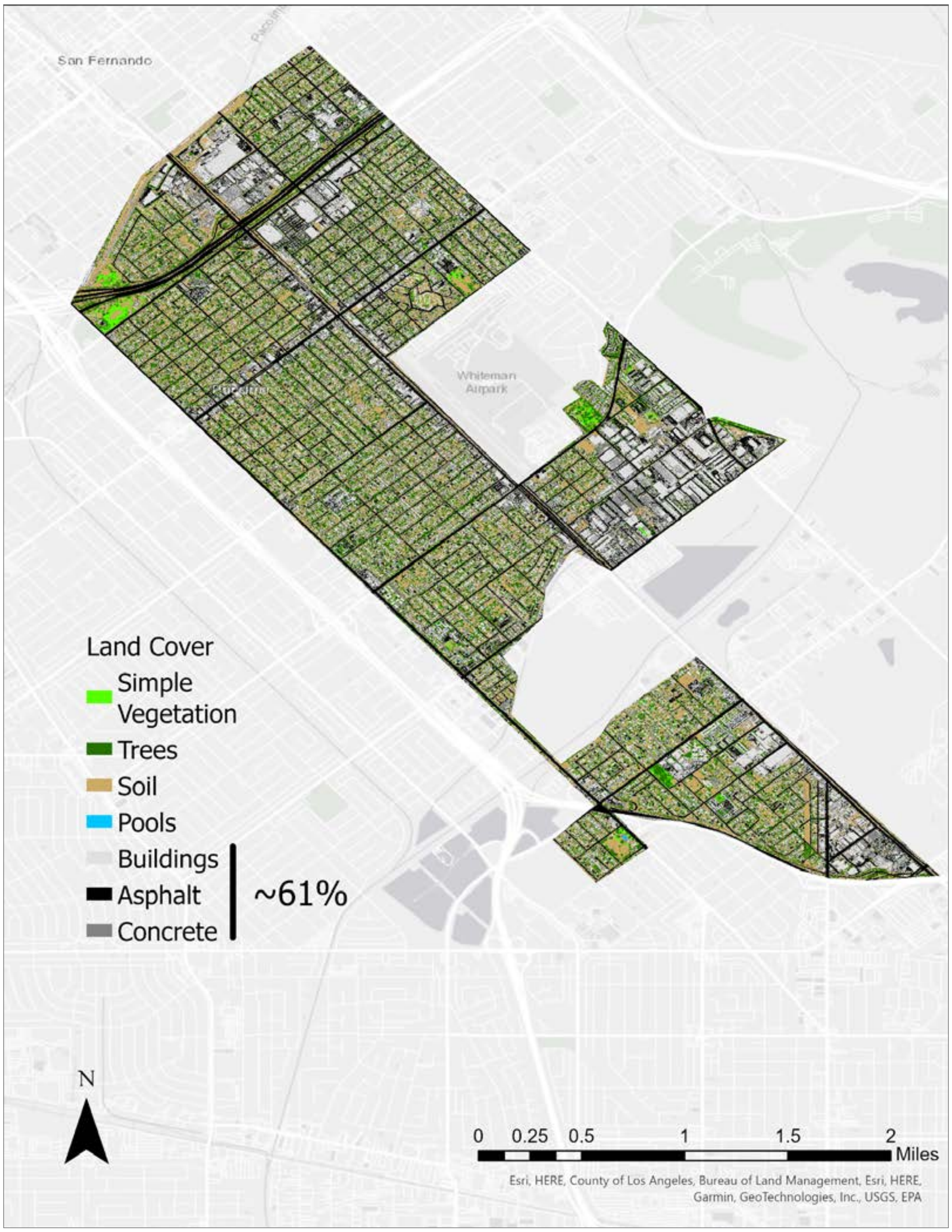


RESULTS

Remote Sensing Observations

Pacoima is approximately 61% impervious surfaces, including buildings, roads, walkways and parking lots. Of non-impervious land, ~22% is barren soil without plants, ~15.5% is tree cover and ~1.5% is low vegetation cover (Figure 2). The impervious cover dominates in several commercial or industrial areas. Notably, the northeast portion of the neighborhood contains large warehouses, an asphalt mixing plant and regional retail centers with large, adjacent parking lots. To the southwest of Whiteman Airpark, a warehouse district houses shipping

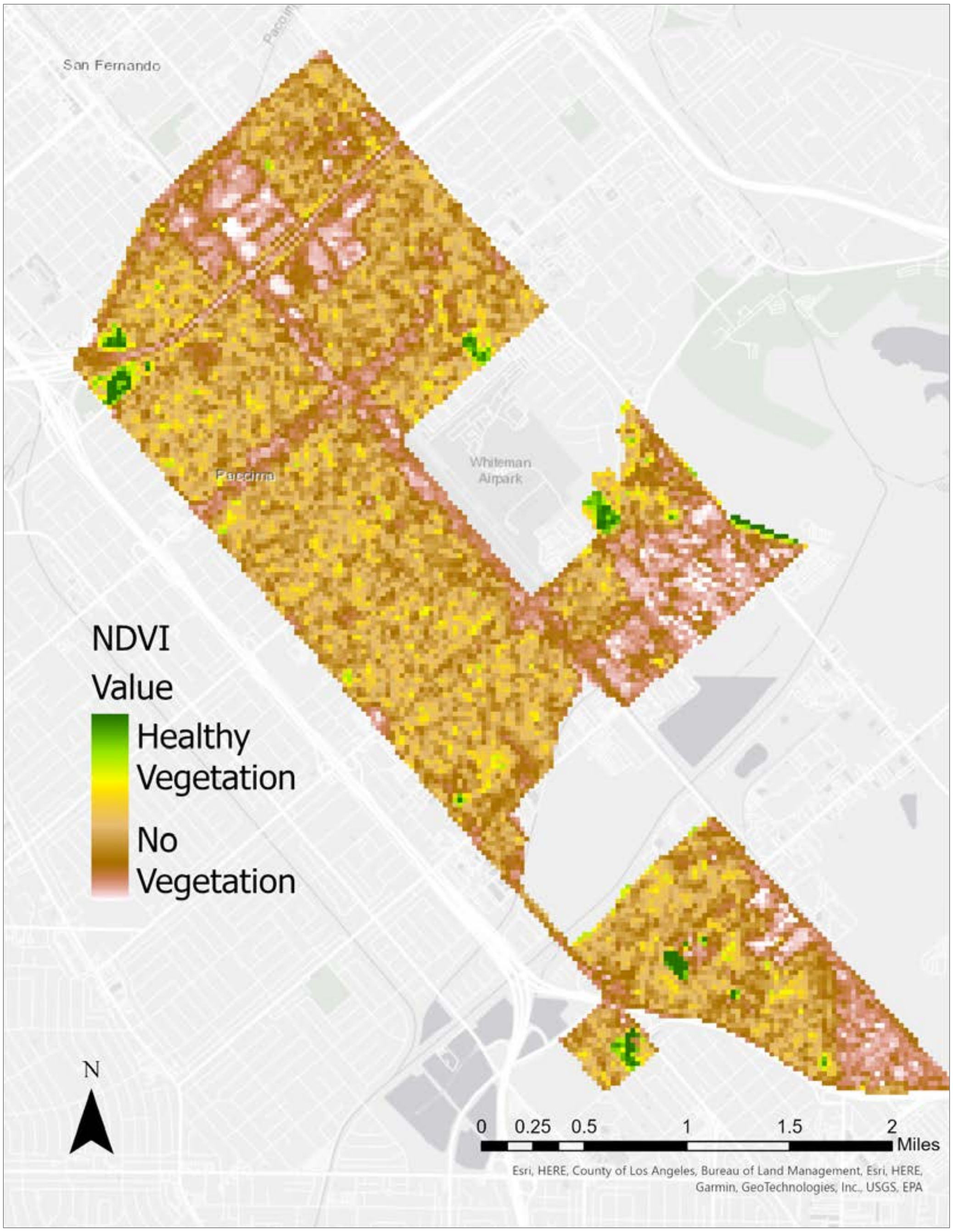
FIGURE 2: **Land cover in Pacoima**



and logistics centers and a film studio. While trees are dispersed in residential areas, grass is concentrated in several small parks (Figure 2).

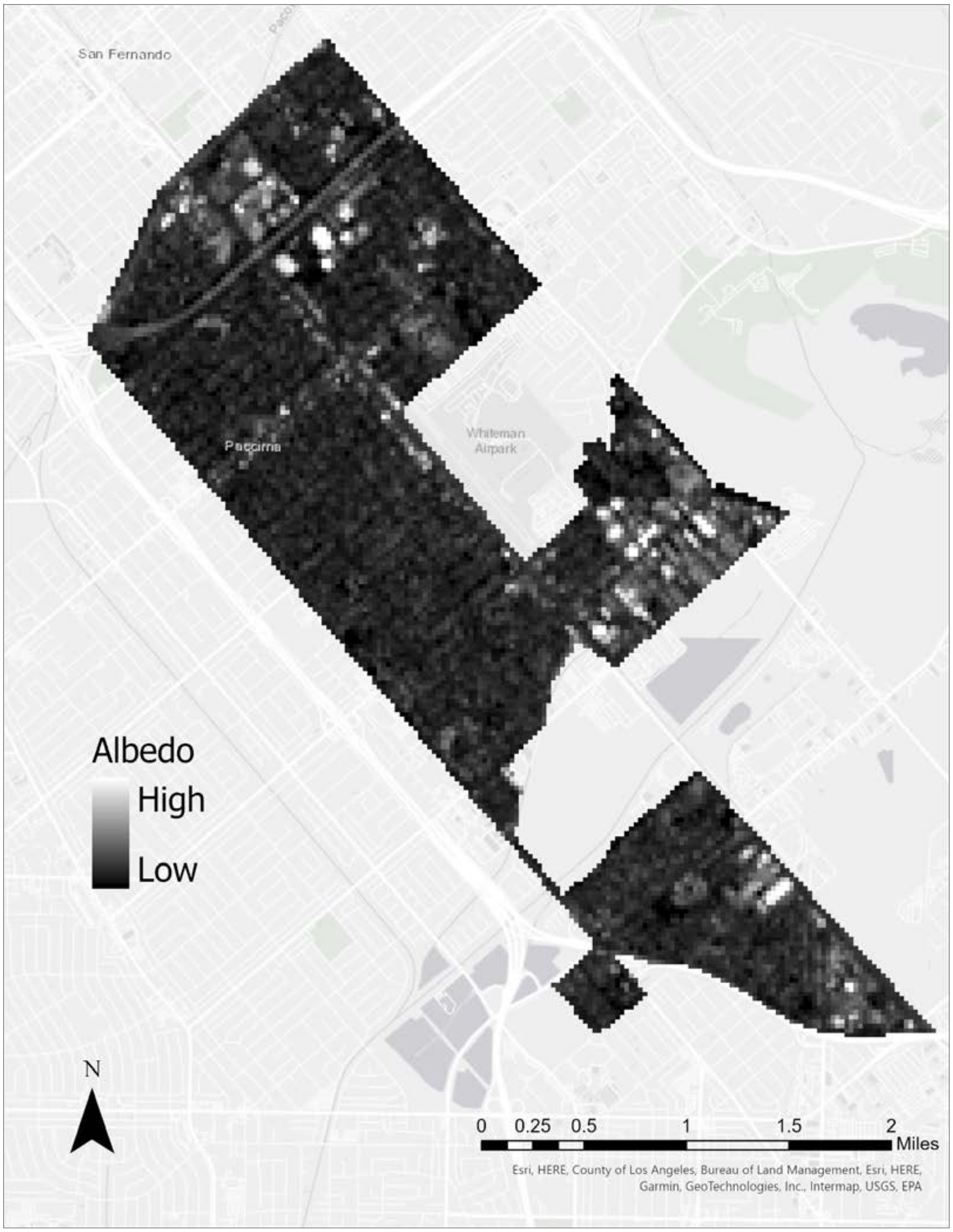
We examined greenness in Pacoima via the NDVI, a metric in which zero and below means no vegetation, around 0.2 is barren soil or dry vegetation, 0.4 indicates green vegetation and 0.6 indicates irrigated green vegetation. While NDVI ranged from -0.06 to 0.86, most of the NDVI values were clustered in the lower end of that range, indicating that Pacoima has low vegetation cover on the whole. The only true high-range NDVI areas are within isolated parks or recreation centers (Figure 3).

FIGURE 3: Normalized difference vegetation index in Pacoima



NDVI is a unitless measure of greenness. The highest values signify trees and show healthy grass and low values show impervious surfaces. Albedo, or the reflectivity of surfaces, is an important component in understanding heat: Low-albedo surfaces are dark-colored and they absorb incoming solar energy and slowly re-radiate it as heat, while high-albedo surfaces are light-colored and reflect solar energy as heat more quickly. Most of Pacoima consists of dark-colored, low-albedo, asphalt surfaces (Figure 4). Specific areas of higher albedo values are generally light-colored warehouse roofs, designed to reflect heat so as to keep the warehouse space cooler. The combination of predominantly impervious surfaces, low

FIGURE 4: Albedo in Pacoima



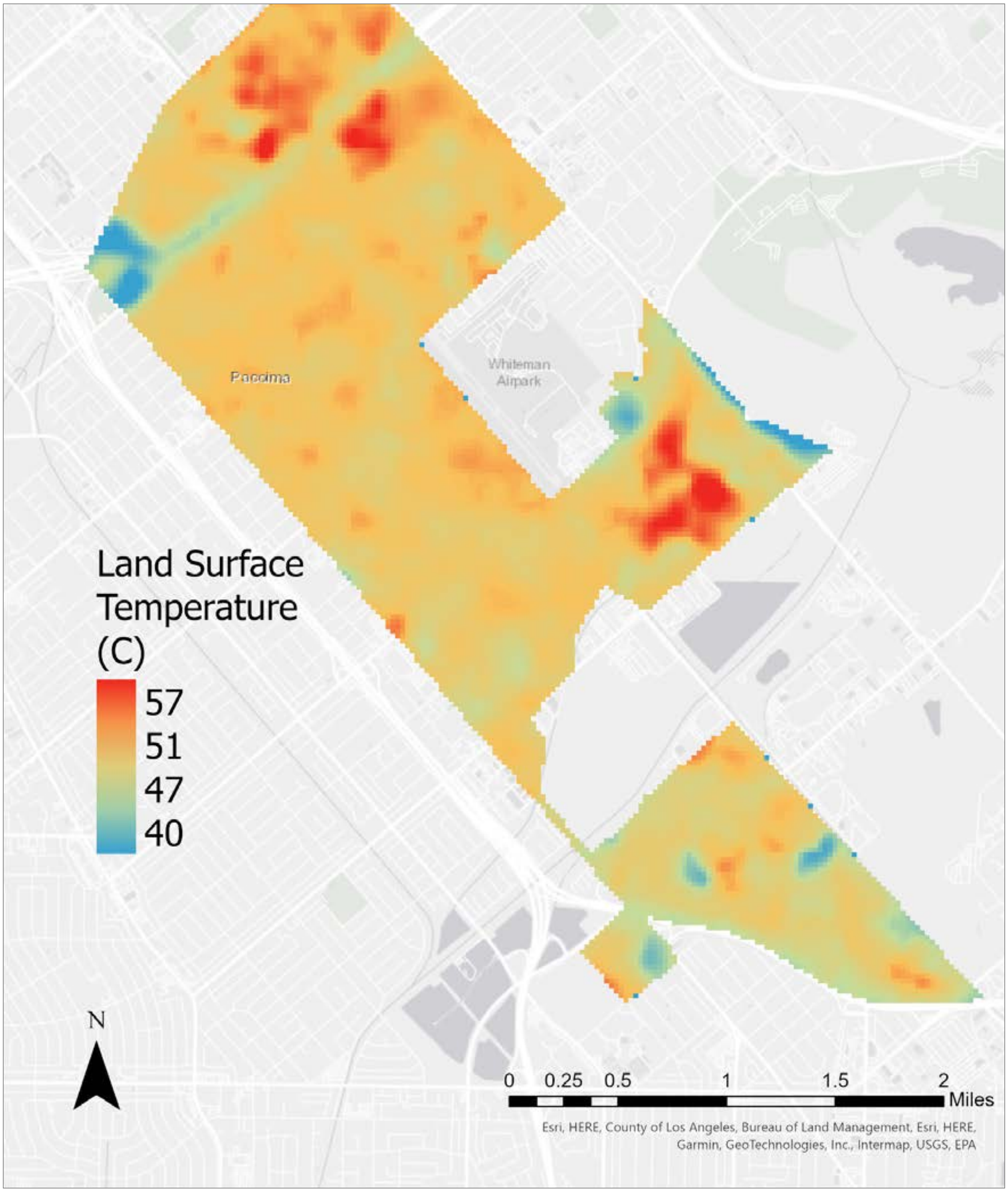
NDVI and low albedo indicates that there is a substantial amount of ground cover absorbing and re-radiating heat throughout the day.

Across the neighborhood, average LST at 6 p.m. ranged from 39 to 56 C, with most of the values falling approximately between 49 and 51 C (Figure 5).

MaRTy Field Observations and ENVI-met Simulations

Highly impervious industrial areas displayed higher LST and parks had lower LST. Summertime LST is usually warmer than AT and this held true in Pacoima: Average AT for the day was 32 C with a relative humidity of

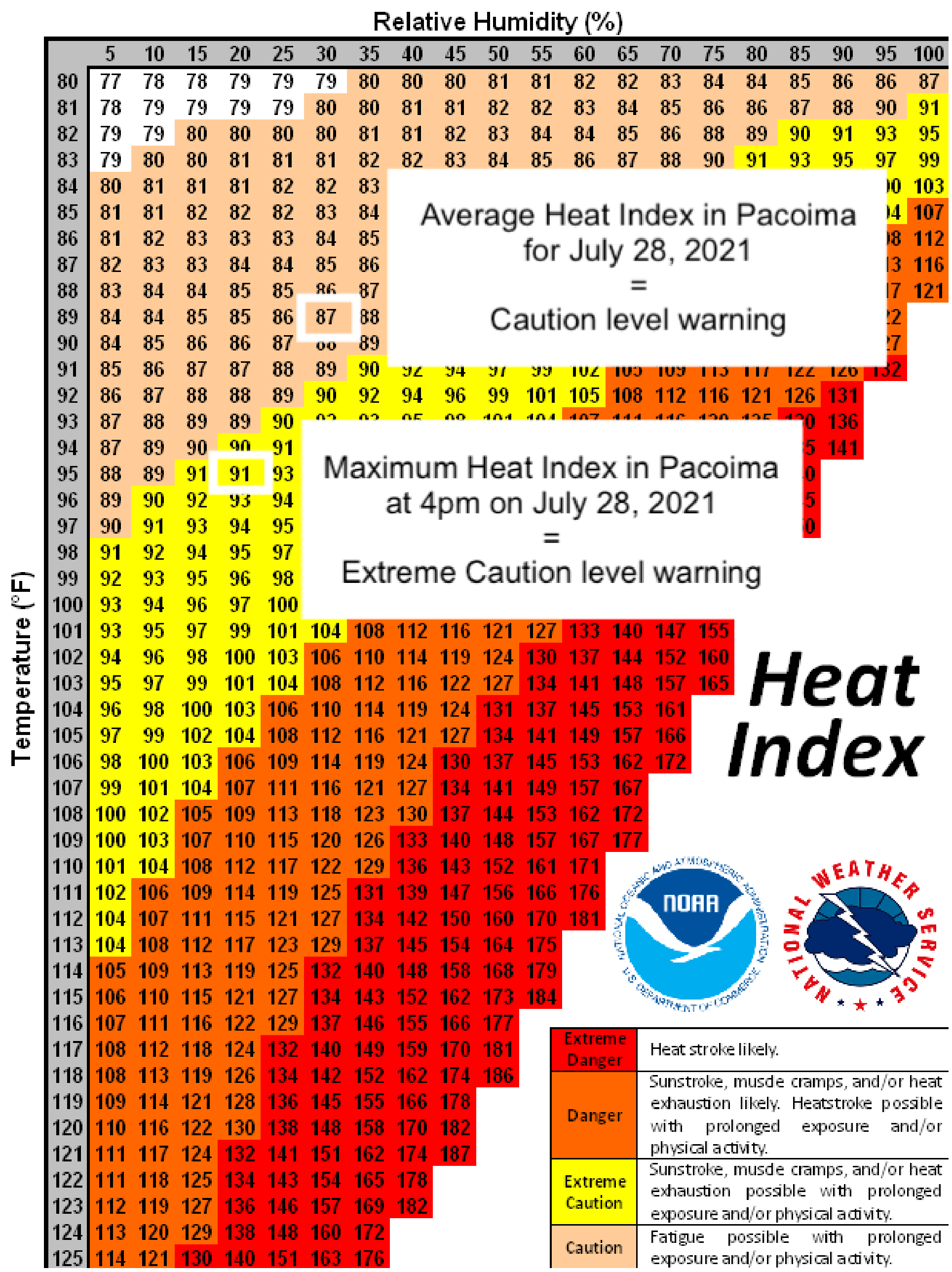
FIGURE 5: Land surface temperature in Pacoima



29%. This temperature and humidity threshold places Pacoima within the National Weather Service's (NWS) Heat Index "Caution" Warning that day based on average AT. However, we also observed a maximum AT at 4 p.m. of 35.0 C with a corresponding relative humidity of 21%, placing Pacoima in the NWS Heat Index "Extreme Caution" Warning (Figure 6).

We observed typical diurnal (day-to-night) trends for AT on both transects and found little variation between them. Within the Residential Neighborhood transect, AT ranged from 24.5 to 35.0 C, with an average of 32.0 C (Figure 7). These values were consistent with local weather station observations. In the Fernangeles Elementary School transect, observed AT ranged

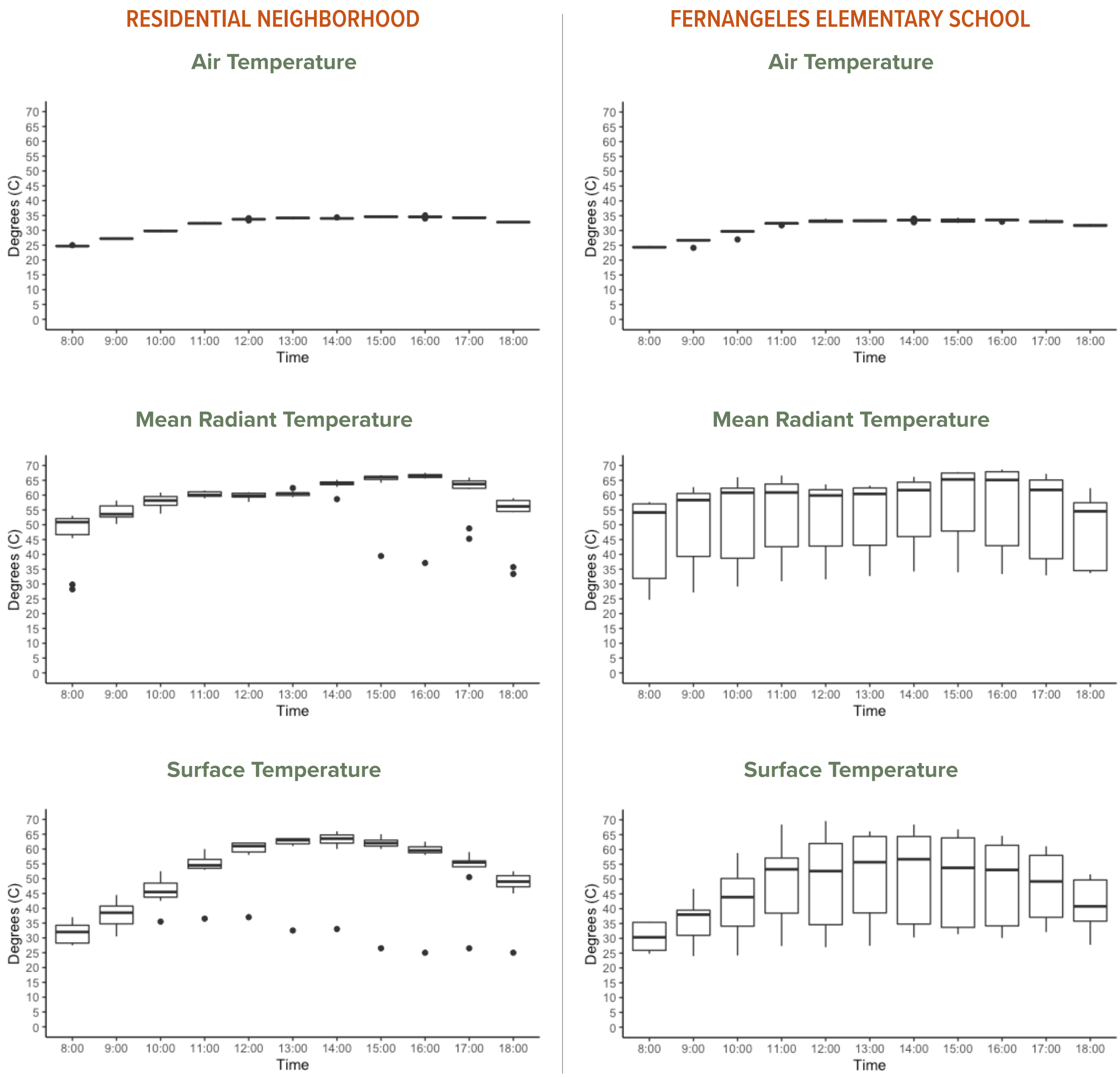
FIGURE 6: National Weather Service average and maximum heat index values for Pacoima on July 28, 2021



from 24.1 to 34.4 C, with an average of 31.4 C. We found more variability in LST due to the more diverse land use conditions: In the Residential Neighborhood, LST varied from 25.0 to 66.0 C, and around Fernangeles Elementary it ranged between 24.0 and 73.9 C. The higher range in the Fernangeles Elementary School transect is due to the large blacktop and grass surfaces as well as the more varied shade conditions from buildings and trees than were present in the Residential Neighborhood transect.

We also observed Mean Radiant Temperature. In the Residential Neighborhood transect, MRT ranged from 28.2 to 67.6 C, with an average of 58.3 C (Figure 7). In the Fernangeles Elementary

FIGURE 7: Diurnal trends by climate variable in a Pacoima residential neighborhood and Fernangeles Elementary School, July 28, 2021



School transect, MRT fell between 24.7 and 68.2 C, with an average of 53.6 C. We observed a wider range of MRT temperature readings in the Fernangeles Elementary School transect due to more heterogeneous land use and design characteristics in the site that created both sun-exposed and shaded conditions. Observations in the Residential Neighborhood transect were primarily sun-exposed asphalt sites.

Shaded area measurements for MRT and ST averaged ~30.0 C cooler than sun-exposed areas in our simulation, regardless of land cover type. The lowest observed MRT values correspond to locations that were either shaded by trees or buildings. These locations were approximately 22.0 to 33.0 C cooler than fully sun-exposed locations (Figure 8).

Some differences in MRT between sun-exposed land cover types were observed. Areas with sun-exposed concrete, asphalt and soil land cover had the highest average MRT of ~60 C. Sun-exposed soil, which has a higher albedo than asphalt, had the highest maximum MRT value overall at ~85.0 C (Table 1). Sun-exposed rubber in the playground at Fernangeles Elementary school had the highest MRT across the day, ranging from 57.1 to 68.2 C with an average MRT of 64.1 C (Table 2). Meanwhile, asphalt shaded by a tree ranged from 22.4 to 27.7 C, with an average MRT of 37.7 C – more than 40% cooler than the sun-exposed rubber. All shaded surfaces had lower MRT values than sun-exposed areas.

FIGURE 8: Mean radiant temperature trends by surface cover type and sun-exposed versus shaded aggregated across both sites (MaRTy observations)

Note: 17:00 and 18:00 readings for Asphalt Shaded by Tree & Building due to sun exposure at those hours skew the data.

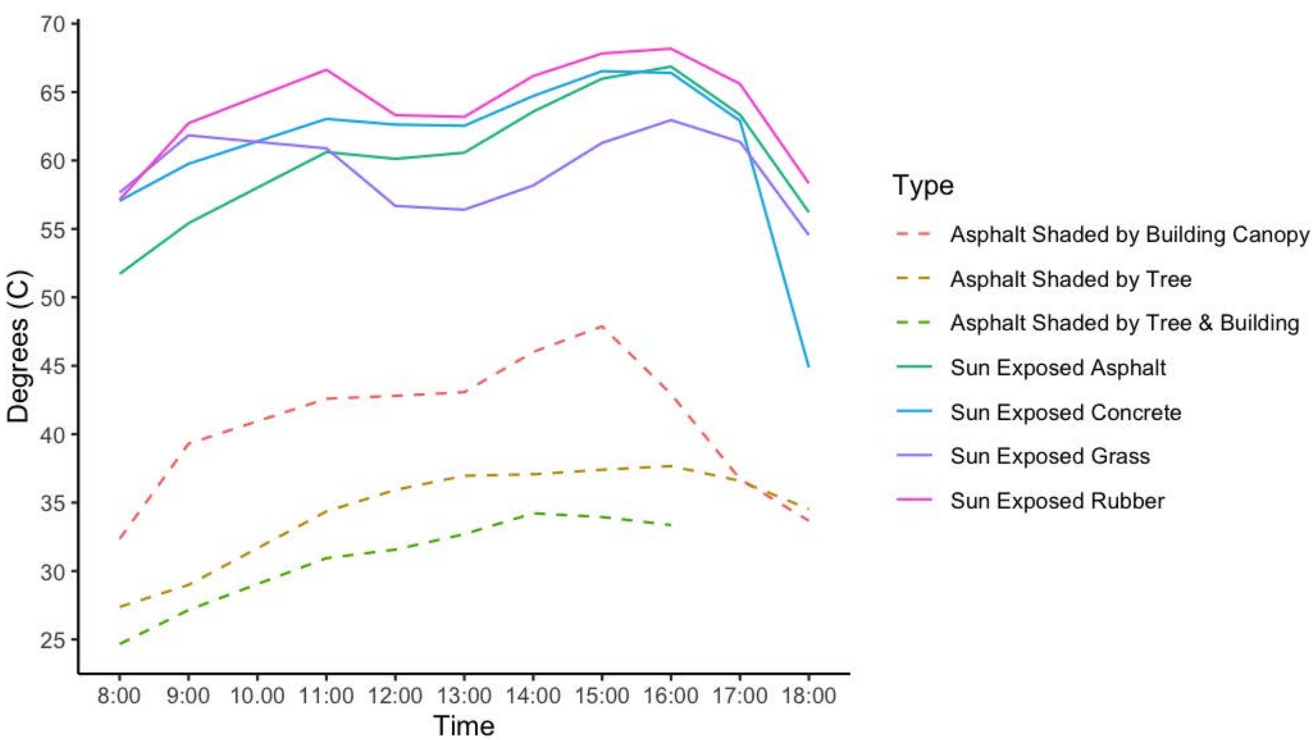


TABLE 1: **Summary statistics of simulated air temperature (AT), mean radiant temperature (MRT) and surface temperature (ST) by surface cover type and shade versus sun exposed. All temperatures in degrees Celsius.**

Land Cover Type	Shade | Sun Exposure	Variable	Minimum	Mean	Maximum	SD
Asphalt	Full Shade	AT	19.9	30.0	35.4	3.4
Asphalt	Partial to Full Sun Exposure	AT	20.1	31.3	35.9	2.7
Concrete Pavement	Full Shade	AT	19.9	30.5	35.7	3.2
Concrete Pavement	Partial to Full Sun Exposure	AT	19.9	31.2	35.9	2.8
Grass	Full Shade	AT	24.9	30.6	35.0	3.1
Grass	Partial to Full Sun Exposure	AT	24.8	31.1	35.2	2.8
Soil	Full Shade	AT	19.9	30.3	35.6	3.1
Soil	Partial to Full Sun Exposure	AT	19.9	31.1	35.7	2.7
Asphalt	Full Shade	MRT	15.6	29.5	55.0	7.3
Asphalt	Partial to Full Sun Exposure	MRT	21.7	60.3	81.5	6.2
Concrete Pavement	Full Shade	MRT	15.1	31.0	63.8	7.6
Concrete Pavement	Partial to Full Sun Exposure	MRT	21.6	63.5	83.8	6.6
Grass	Full Shade	MRT	17.6	30.1	55.1	6.3
Grass	Partial to Full Sun Exposure	MRT	23.5	53.8	69.9	7.7
Soil	Full Shade	MRT	15.5	31.5	63.3	7.2
Soil	Partial to Full Sun Exposure	MRT	21.6	62.9	85.0	8.1
Asphalt	Full Shade	ST	23.7	34.6	55.2	6.5
Asphalt	Partial to Full Sun Exposure	ST	27.2	48.2	58.9	6.9
Concrete Pavement	Full Shade	ST	23.6	34.5	54.7	6.0
Concrete Pavement	Partial to Full Sun Exposure	ST	26.5	45.8	56.6	6.6
Grass	Full Shade	ST	20.8	30.3	46.5	5.0
Grass	Partial to Full Sun Exposure	ST	22.7	39.1	55.6	7.2
Soil	Full Shade	ST	20.1	30.3	51.1	5.0
Soil	Partial to Full Sun Exposure	ST	21.9	40.5	60.1	7.3

TABLE 2: **Summary statistics of MaRTy-observed mean radiant temperature by site type. All temperatures in degrees Celsius.**

Site Type	Minimum	Mean	Maximum
Asphalt Shaded by Building Canopy	32.4	40.6*	47.9*
Asphalt Shaded by Tree	27.4	34.4	37.7
Asphalt Shaded by Tree & Building	24.7	33.2	54.1
Sun Exposed Asphalt	51.7	60.3	66.9
Sun Exposed Concrete Pavement	44.9	61.2	66.5
Sun Exposed Grass	54.5	59.4	63.0
Sun Exposed Rubber	57.1	64.1	68.2

**The Asphalt Shaded by Building Canopy site was sun exposed at 17:00 and 18:00 hours, which is why both the mean and maximum are higher than expected.*

In the Fernangeles Elementary School transect, modeled results showed that MRT was lowest around buildings and trees due to the shade they produced. In the Residential Neighborhood Transects, there were lower MRT values overall due to the clustering of buildings and street trees – in the Fernangeles Elementary School transect, buildings were more spread out and there was less tree cover, so there was less shaded area (Figure 9).

FIGURE 9: Mean radiant temperature simulation results for a residential neighborhood in Pacoima and Fernangeles Elementary School

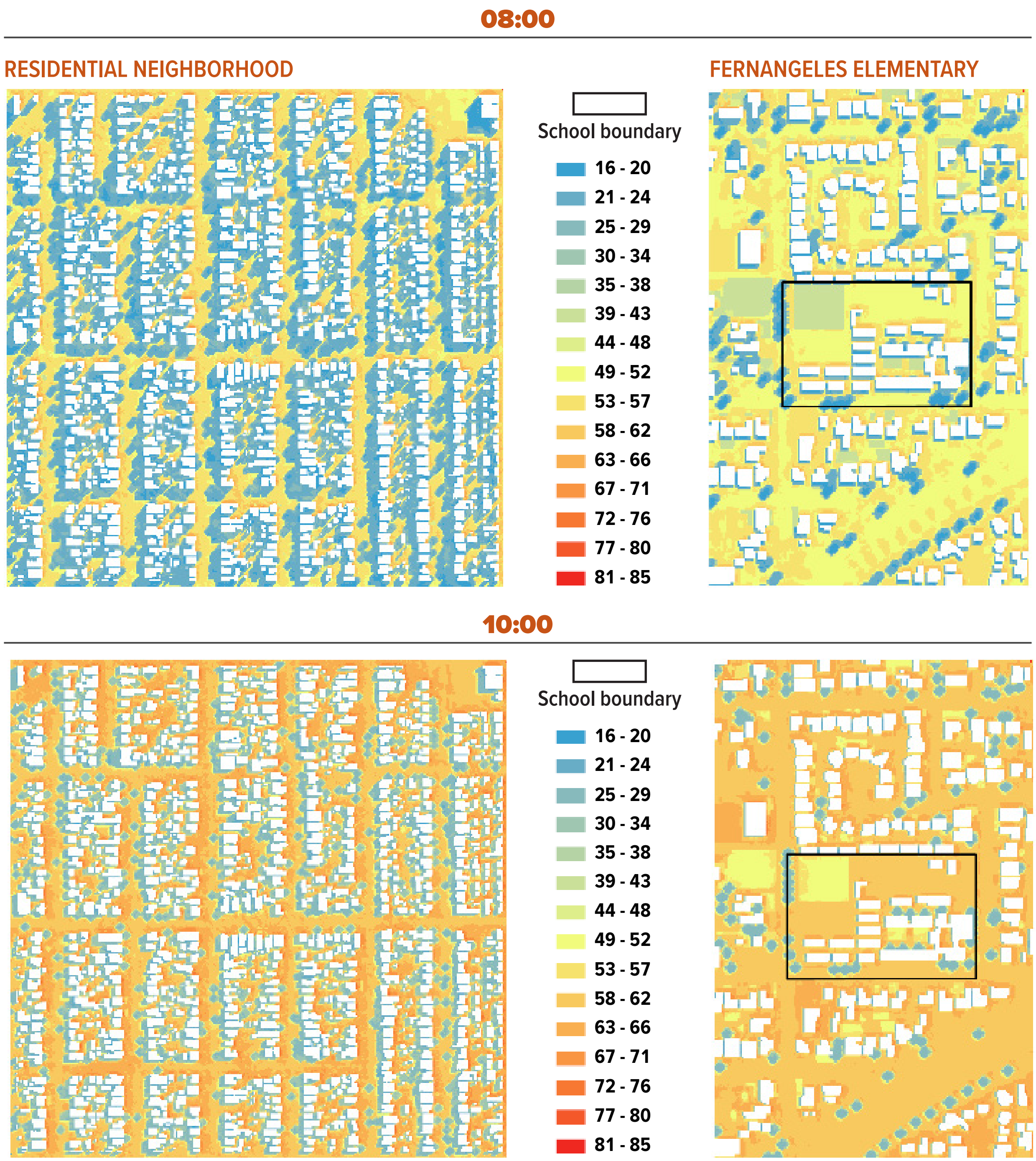


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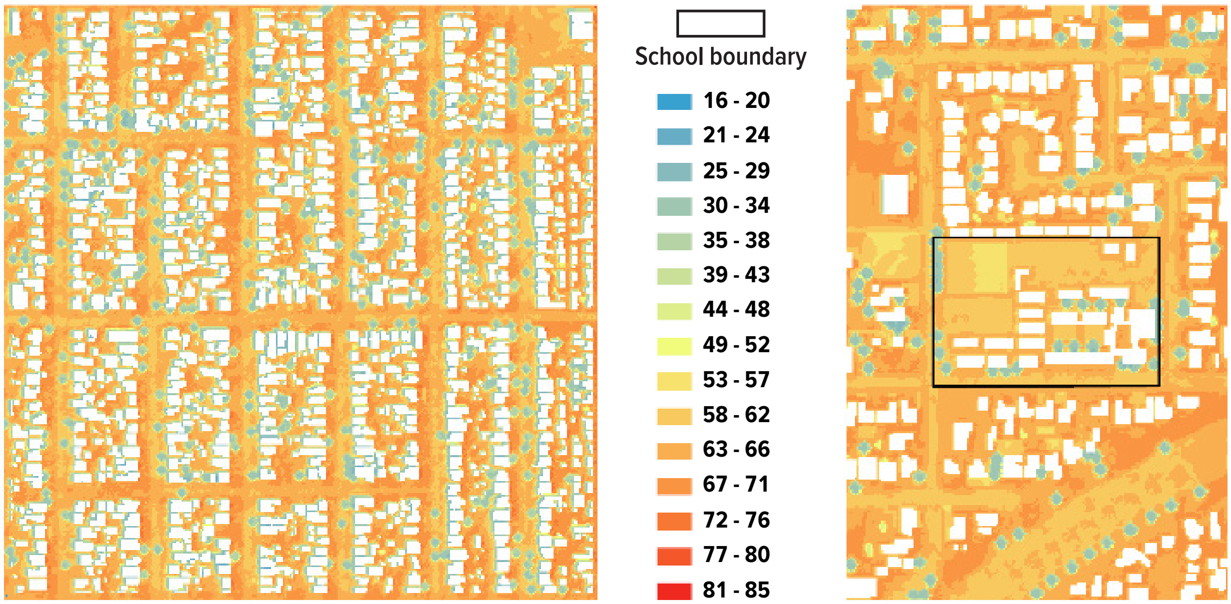
FIGURE 9 (continued): Mean radiant temperature simulation results for a residential neighborhood in Pacoima and Fernangeles Elementary School

12:00

RESIDENTIAL NEIGHBORHOOD

FERNANGELES ELEMENTARY



14:00

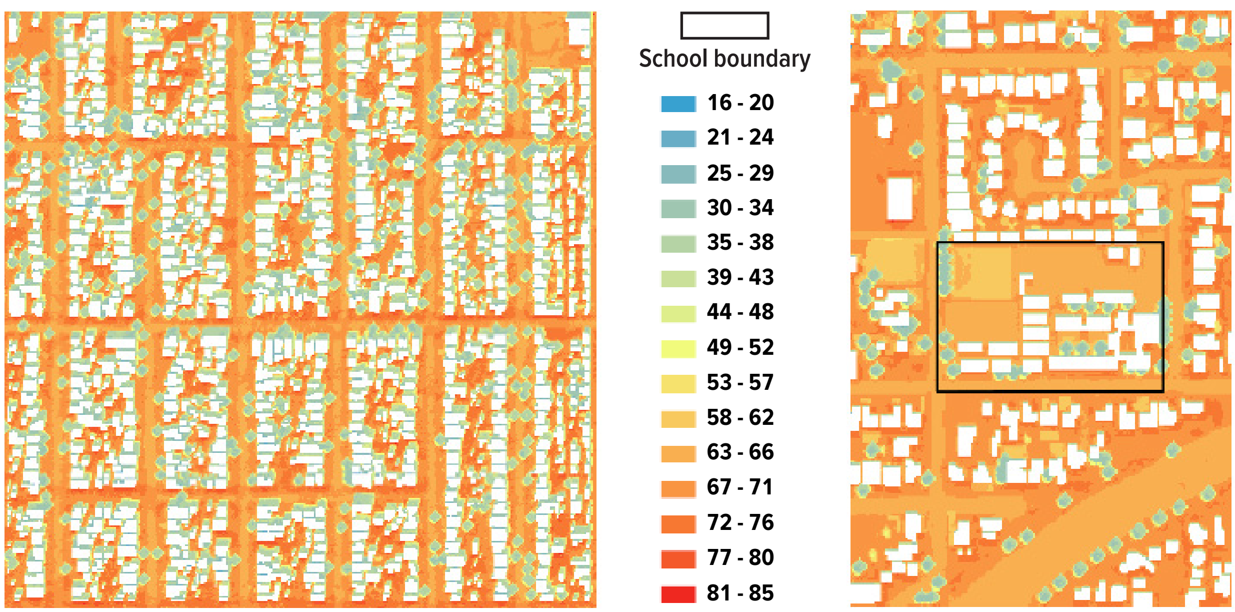


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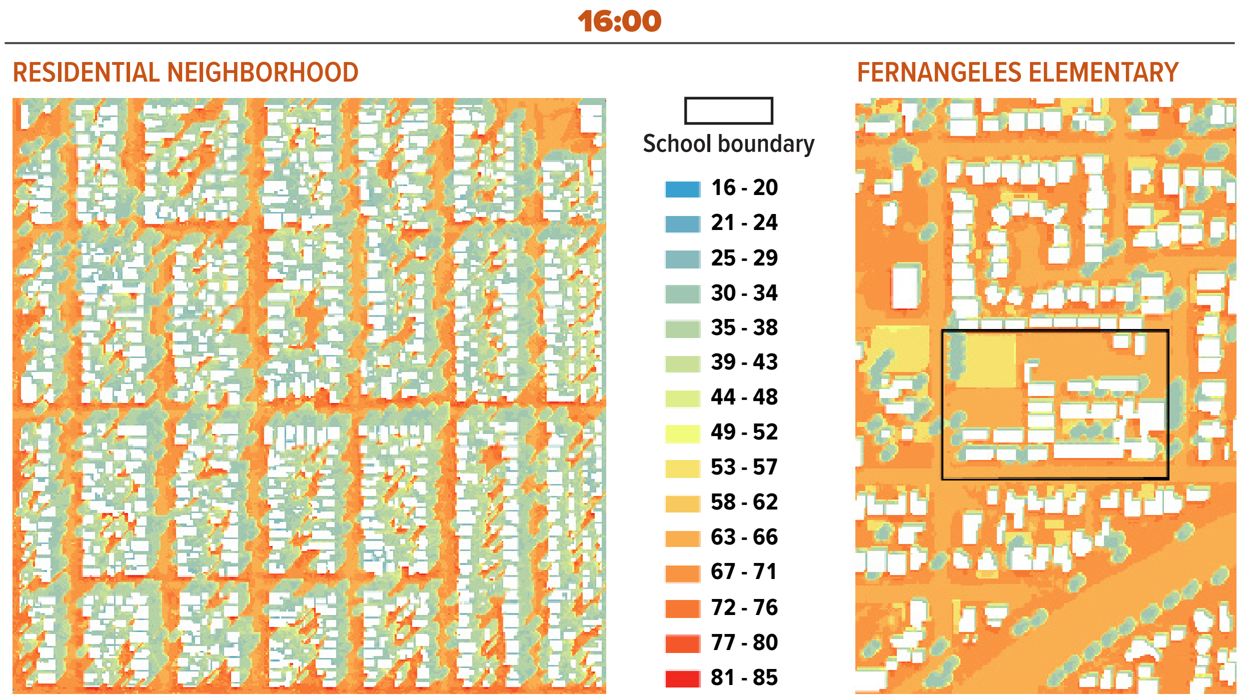
FIGURE 9 (continued): Mean radiant temperature simulation results for a residential neighborhood in Pacoima and Fernangeles Elementary School



Air Temperature, which is affected by larger regional climate patterns, rarely varies at the site scale. As expected, there was little variation in AT across site area, between land cover types and level of sun exposure (Figure 10). The minimum AT for all land cover types was 24.0 C; the average was 31.0 C, and the maximum was 33.0 C (Table 3).

FIGURE 10: Air temperature trends by surface cover type and sun-exposed versus shaded aggregated across both sites (MaRTy observations)

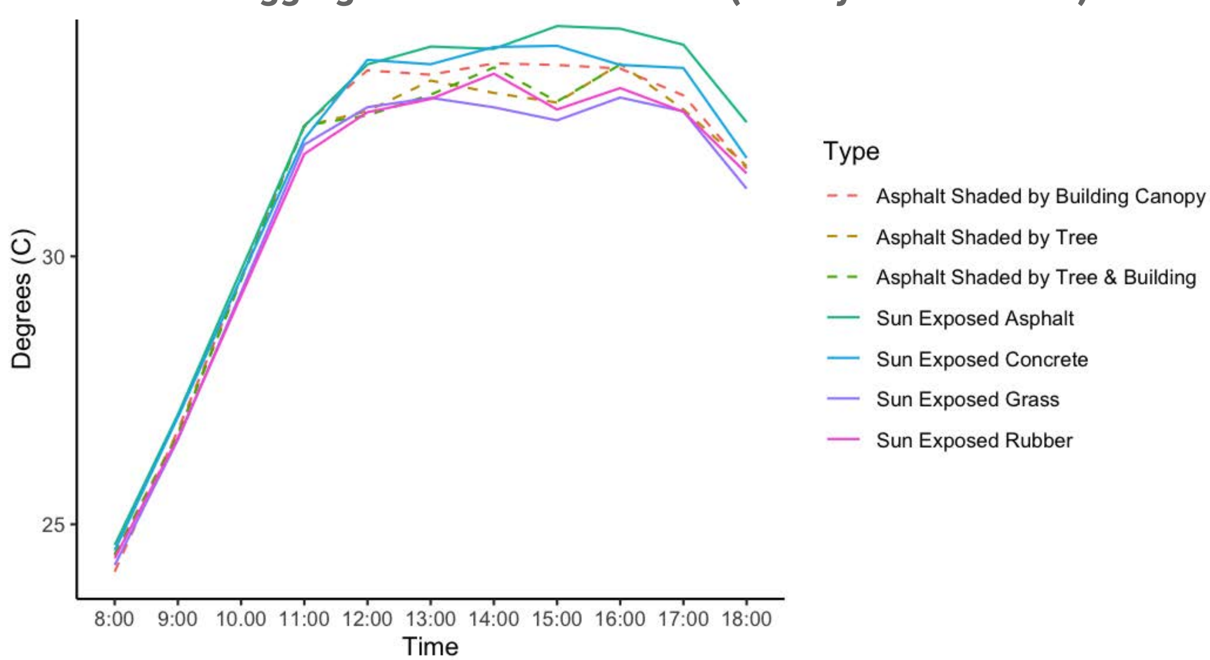


TABLE 3: **Summary statistics of MaRTy-observed air temperature by site type. All temperatures in degrees Celsius.**

Site Type	Minimum	Mean	Maximum
Asphalt Shaded by Building Canopy	24.1	31.4	33.6
Asphalt Shaded by Tree	24.5	31.2	33.6
Asphalt Shaded by Tree & Building	24.4	31.2	33.6
Sun Exposed Asphalt	24.6	31.8	34.3
Sun Exposed Concrete Pavement	24.5	31.6	33.9
Sun Exposed Grass	24.2	31.0	33.0
Sun Exposed Rubber	24.4	31.0	33.4

In comparing LST across different land cover types and levels of sun exposure, sun-exposed rubber was, once again, the hottest surface, reaching up to 73.9 C with an average surface temperature of 59.3 C. Sun-exposed rubber's average LST was 5.0 C hotter than sun-exposed asphalt, 10.1 C hotter than sun-exposed concrete and 26.4 C hotter than sun-exposed grass (Table 4). In terms of LST and in contrast to afternoon MRT, lower-albedo paved surfaces were consistently warmer than higher-albedo ones.

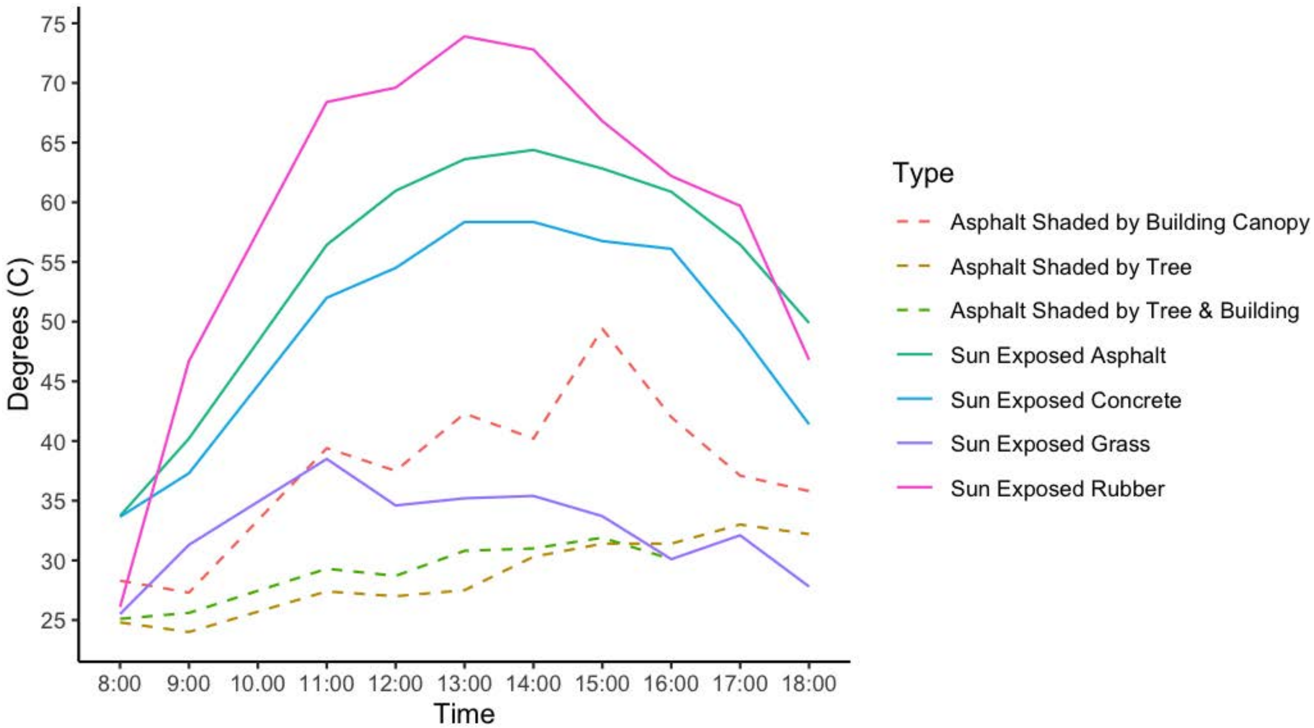
TABLE 4: **Summary statistics of of MaRTy-observed surface temperature by site type. All temperatures in degrees Celsius.**

Site Type	Minimum	Mean	Maximum
Asphalt Shaded by Building Canopy	27.3	37.6*	49.4*
Asphalt Shaded by Tree	24.0	28.5	33.0
Asphalt Shaded by Tree & Building	25.1	31.0	42.8
Sun Exposed Asphalt	33.7	54.3	64.4
Sun Exposed Concrete Pavement	33.7	49.2	58.4
Sun Exposed Grass	25.5	32.9	38.5
Sun Exposed Rubber	26.1	59.3	73.9

**This site was sun exposed at 17:00 and 18:00 hours, which is why both the mean and maximum are higher than expected.*

The coolest LST averages were at asphalt sites shaded by a tree (38.5 C) and shaded by a tree and building (31.0 C). The disparity between the two shaded sites is partially due to sun exposure at the site shaded by a tree and a building beginning at ~18:00, which increased the average. Asphalt shaded by building canopy was also much cooler than all sun-exposed sites except for sun-exposed grass, which was cooler throughout the afternoon (Figure 11, Table 4). Refer Appendix B to see diurnal trends by site.

FIGURE 11: **Surface temperature trends by surface cover type and sun-exposed versus shaded aggregated across both sites (MaRTy observations)**



MRT observations showed that the grass field in Fernangeles Elementary had a lower MRT throughout the day compared to other sun-exposed surfaces but nevertheless was warmer than asphalt, grass, or pavement shaded by buildings or trees (Figure 8).

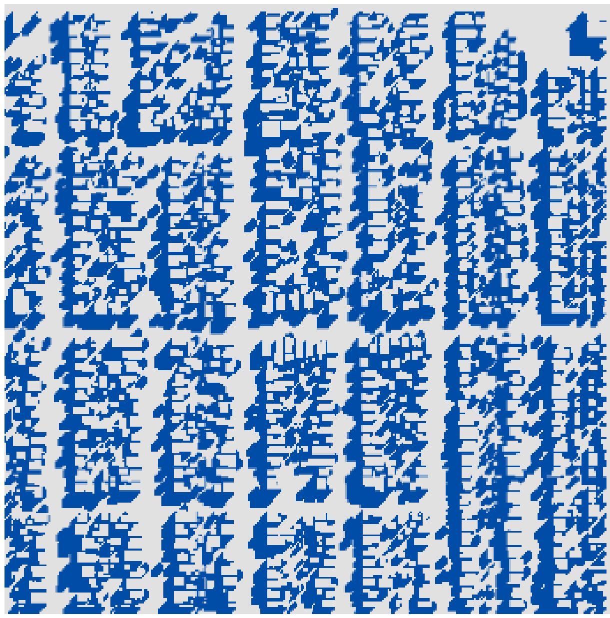
Notably, Fernangeles Elementary has very little shade, accounting for the high simulated MRT and ST values (Figure 12). The Fernangeles Elementary area has one shade canopy over picnic tables that is not included in the model; including that area, the school has less than 20% shade coverage throughout the day and less than 10% shade coverage during the midday hours when students are outside for recess. Accordingly, the mean simulated MRT for Fernangeles Elementary at 12:00 was >60 C (Figure 13).

FIGURE 12: Shade analysis in residential neighborhood and Fernangeles Elementary School and surrounding neighborhood

Full Shade | Partial to Full Sun Exposure | Fernangeles Elementary School

Shade at 08:00

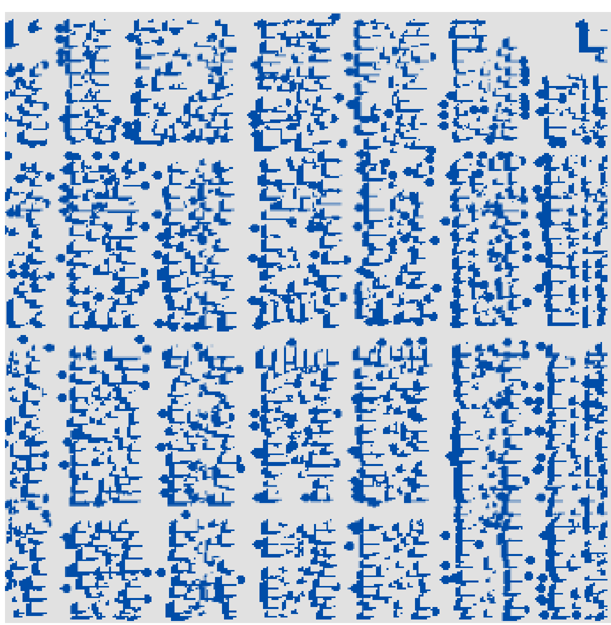
45% of Area Shaded



15% of Area Shaded

Shade at 10:00

27% of Area Shaded



8% of Area Shaded

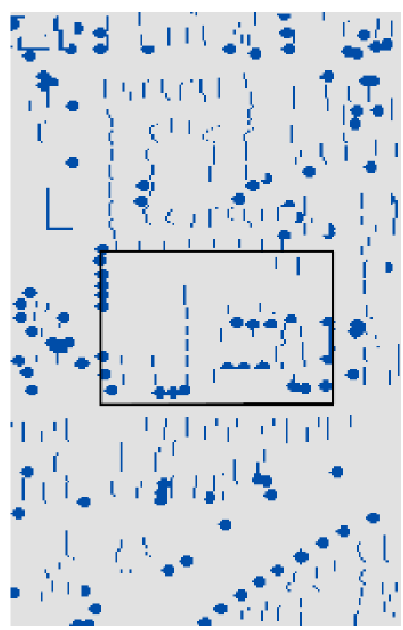


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FIGURE 12 (continued): Shade analysis in residential neighborhood and Fernangeles Elementary School and surrounding neighborhood

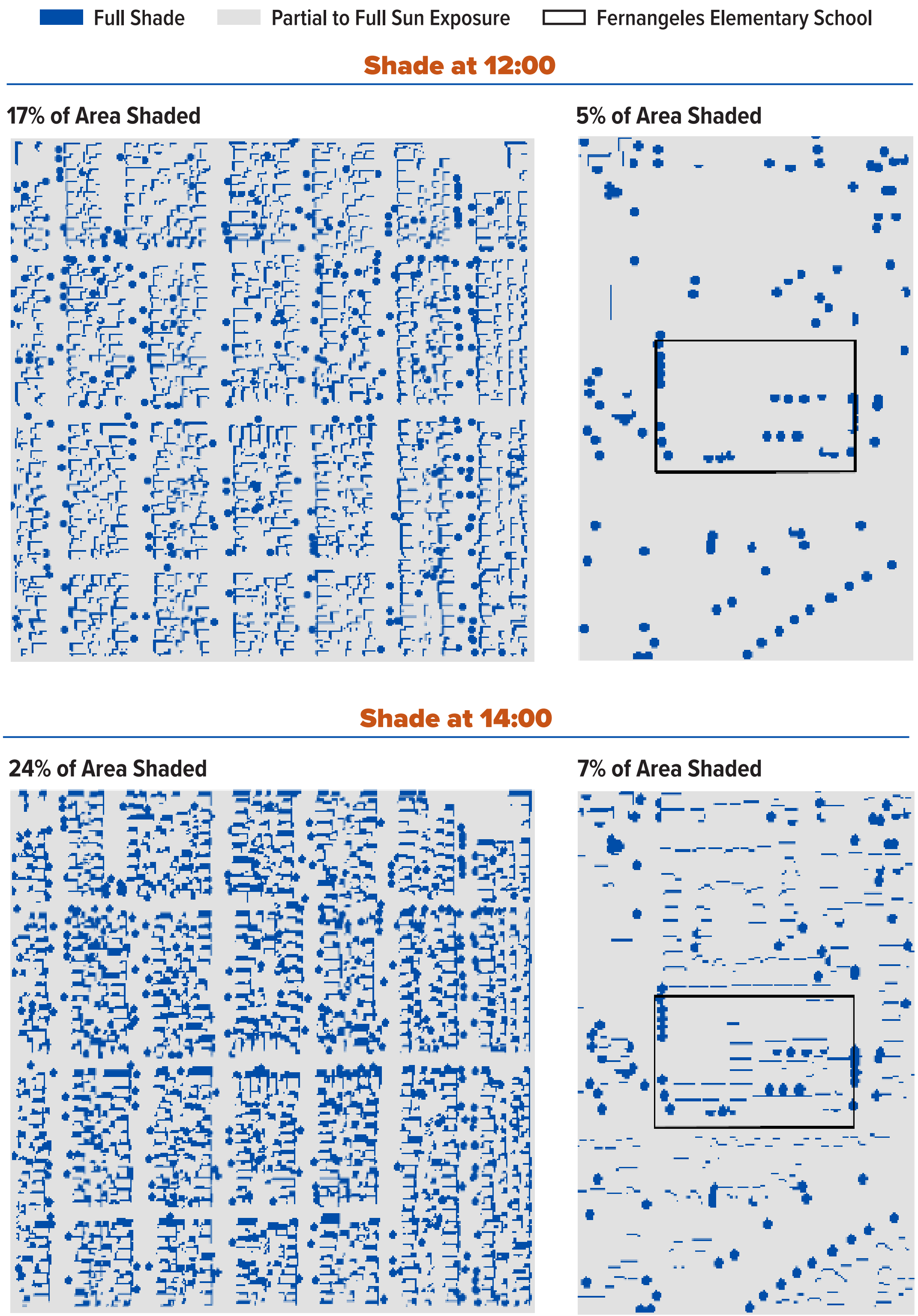

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FIGURE 12 (continued): **Shade analysis in residential neighborhood and Fernangeles Elementary School and surrounding neighborhood**

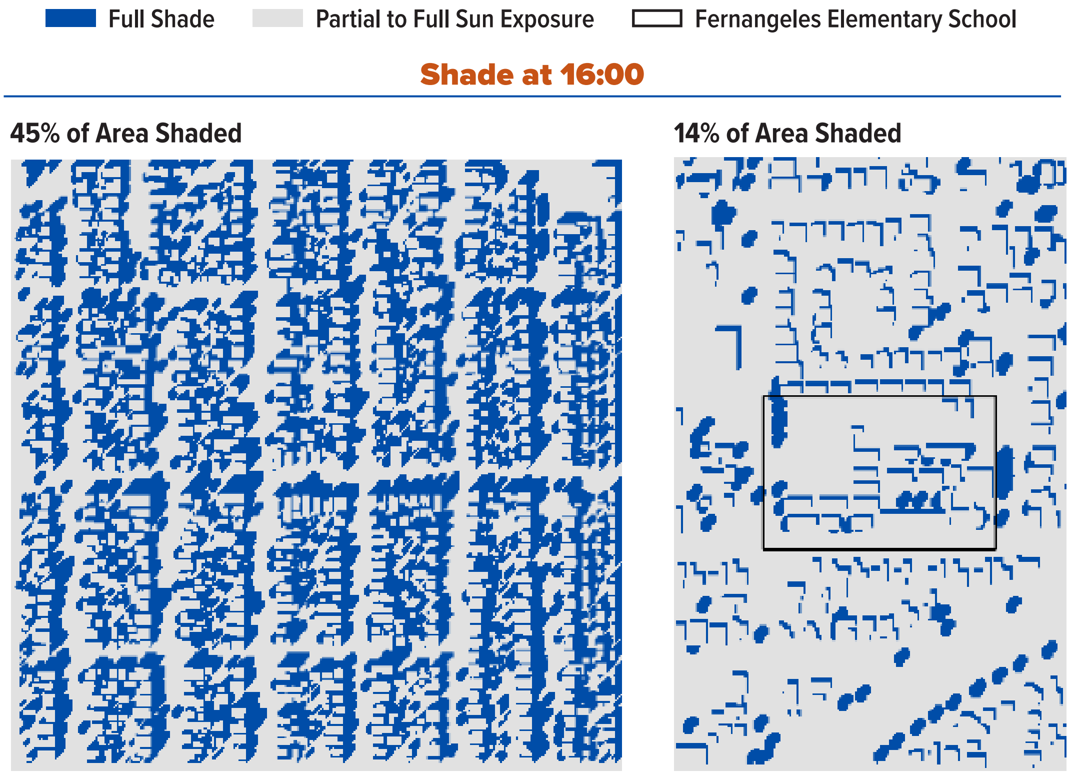
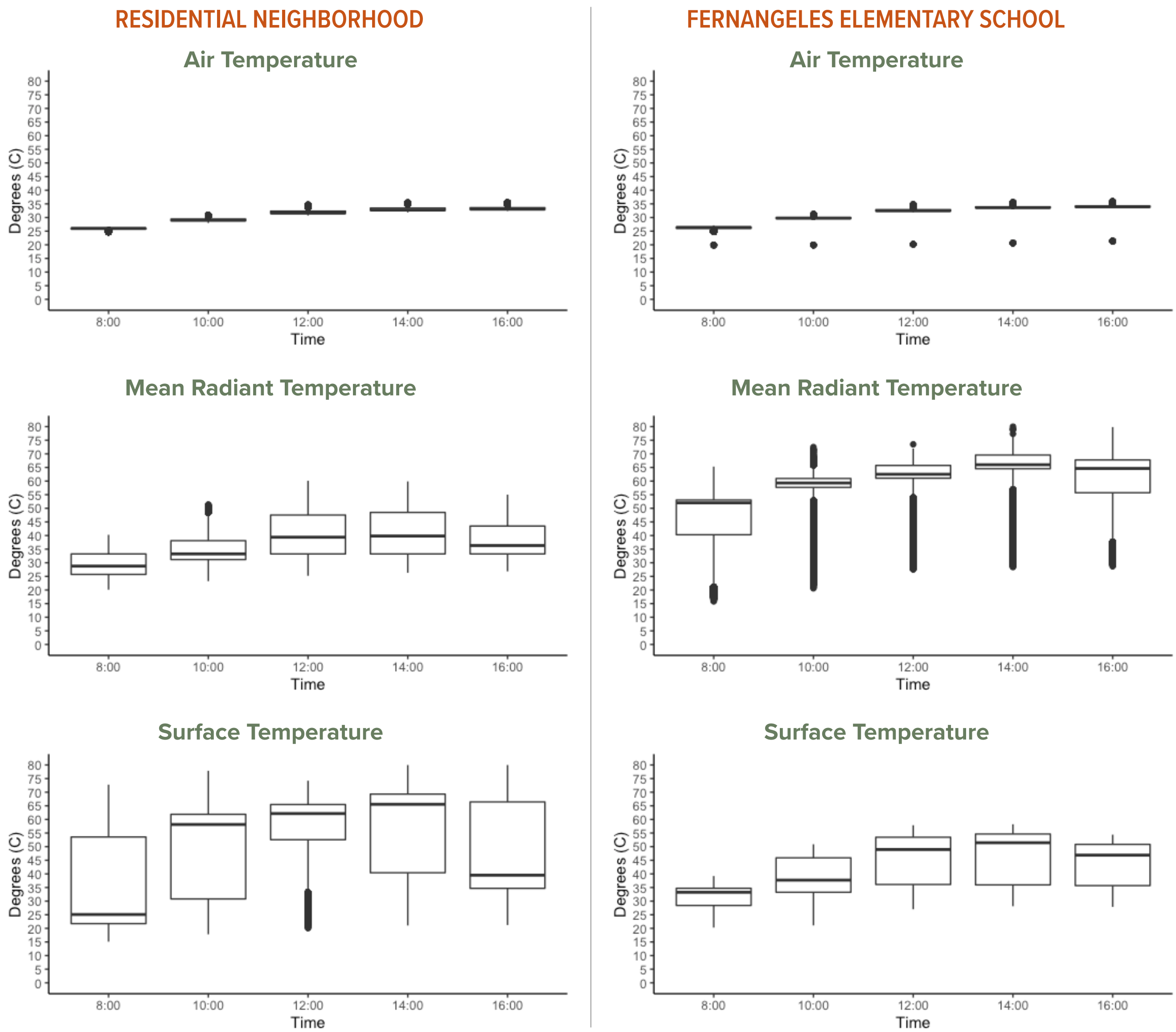


FIGURE 13: **Simulated diurnal trends by climate variable in a residential neighborhood and Fernangeles Elementary School**



DESIGN AND POLICY IMPLICATIONS

BOTH OUR OBSERVED and our simulated temperature readings emphasize the importance of shade as a means of reducing temperature. Whether the shade comes from a building, a designed shade structure, or a tree, its effect is to substantially lower MRT. This finding is consistent with recent studies emphasizing the importance of investing in shade to mitigate the effects of extreme heat (Middel et al. 2021, Turner et al. 2022). Shade also plays a role in lowering LST, though its effect is less noticeable than in the case of MRT and is more dependent on surface composition: Shade reduces the temperature of asphalt more substantially than it reduces the temperature of grass.

While the effect of shade can act as a guiding principle in considering development practices, it can also inform design of site infrastructure. This study highlighted that rubber surfaces, which are often installed in play areas to soften the impacts of children's falls, result in hotter LST and MRT than any other ground cover, including asphalt. To avoid burns and overheating, shade over rubber playgrounds should be prioritized.

Both transects were less than 30% shaded by area, potentially making them "shade deserts," or areas where pedestrians and other people outdoors are at increased risk of extreme heat effects because they do not have enough access to shade during dangerously hot conditions. In considering improved shade infrastructure across the neighborhood, clusters of buildings and increased street trees could prove effective in increasing shaded areas and creating "shade corridors" for pedestrians and access to relief from the sun (Hsieh et al. 2016, Zhao et al. 2018, Park et al. 2020).

Shade infrastructure may be difficult to implement in some locations. For instance, the play yard in the Fernangeles Elementary School transect was as hot as streets or parking lots, and even partially sun-exposed asphalt was measurably warmer than fully shaded asphalt. However, modest reductions in both LST and MRT could be achieved through conversion of dark asphalt to other ground cover. Grass was uniformly cooler than asphalt, and throughout the afternoon the LST of sun-exposed grass was cooler than that of asphalt shaded solely by a building canopy. Though these effects are modest and should not be compared to the impact of shade, they could make a difference for children at play in specific locations. Additionally, providing ample shade adjacent to play areas like basketball courts could provide critical relief from the sun.

Cool pavement, which is being piloted throughout the San Fernando Valley, is another strategy worth considering in cases where shade is not viable (Garcetti 2021). Cool pavements are high-albedo coatings over asphalt that reflect heat, rather than absorbing it and re-radiating it. While cool pavements might produce lower LST at peak heat hours, they often result in higher MRT because the effect of sunlight is increased as the heat re-radiates from the pavement (Middel et al. 2021). The radiant heat "penalty" could, in theory, be offset by air temperature reductions if applied to a sufficiently large area (Ko et al. 2022), but the total area needed to achieve these theoretical offsets is not yet known. Before cool pavement is deployed, more study is needed to understand its potential costs and benefits. Assessing the potential impact of cool pavement application to site-level design is the subject of the next phase of this project.

NEXT STEPS

As part of a California Strategic Growth Council Climate Change Research Grant, UCLA's Luskin Center for Innovation is modeling microclimatic conditions and their effects on MRT, AT and LST in Pacoima and other Transformative Climate Communities program sites. These simulations will enable us to understand how various interventions like increased tree canopy and installation of high-albedo surfaces interact with site-level characteristics to produce or mitigate heat.

In collaboration with Pacoima Beautiful, we will also meet with local stakeholders to discuss their reactions to current efforts toward heat mitigation and to evaluate potential future scenarios. In particular, we will get feedback on increasing tree cover; cool pavement pilot programs; and hybrid approaches around mixed green and gray shade, cool pavement and other land surface transformations.

APPENDIX A: MODEL PERFORMANCE

WE CONSTRUCTED base models of the transect route sites in the microclimate modeling software ENVI-met, version 5.0.3, which is a non-hydrostatic computational fluid dynamics model that simulates surface-plant-air microscale interactions (Simon et al. 2020, Bruse & Fleer 1998; Middel et al. 2014). To build the models, we imported a land cover layer derived from 60-cm resolution NAIP imagery, as well as a building layer and a tree layer derived from LiDAR, into ENVI-met Suite's program Spaces, where we digitized the model based on these raster data (National Agriculture Imagery Program, 2022; Los Angeles GeoHub, 2022). Surface covers, tree species and buildings were assigned thermal property profiles from ENVI-met's database system. The meteorological data for the model were obtained from the Whiteman weather station for July 28, 2021, the day we collected field data and the soil data were set to xeric values gathered by Middel et al. (2014).

To validate the accuracy of the models, we placed receptors in each of the models corresponding to locations where we collected field data. This allowed us to compare the simulated climate readings to actual field data using a model performance statistic based on methods by Willmott (1981). Each model was validated using this method, allowing us to make inferences about climate conditions beyond the locations where we collected field data (Table A1; Table A2). Data from each of the models were analyzed using the NetCDF file format. NetCDF provides data on each of the variables of interest at each hour across all pixels, allowing us to analyze diurnal trends across the whole area, versus the field data, where we can only analyze the locations where we took readings.

TABLE A1: ENVI-met model performance

AREA MODELED	PERFORMANCE METRICS	AIR TEMPERATURE (C)	MEAN RADIANT TEMPERATURE (C)
Residential Neighborhood	MBE	-0.50	-1.22
	RMSE	1.19	9.84
	MAE	1.03	5.45
	d	0.96	0.64
Fernangeles Elementary School	MBE	0.47	-4.22
	RMSE	1.11	9.65
	MAE	0.87	5.63
	d	0.96	0.38

TABLE A2: Univariate linear regression results between simulated climate variables and simulated incoming solar radiation and simulated surface cover. All models had p-values <0.000.

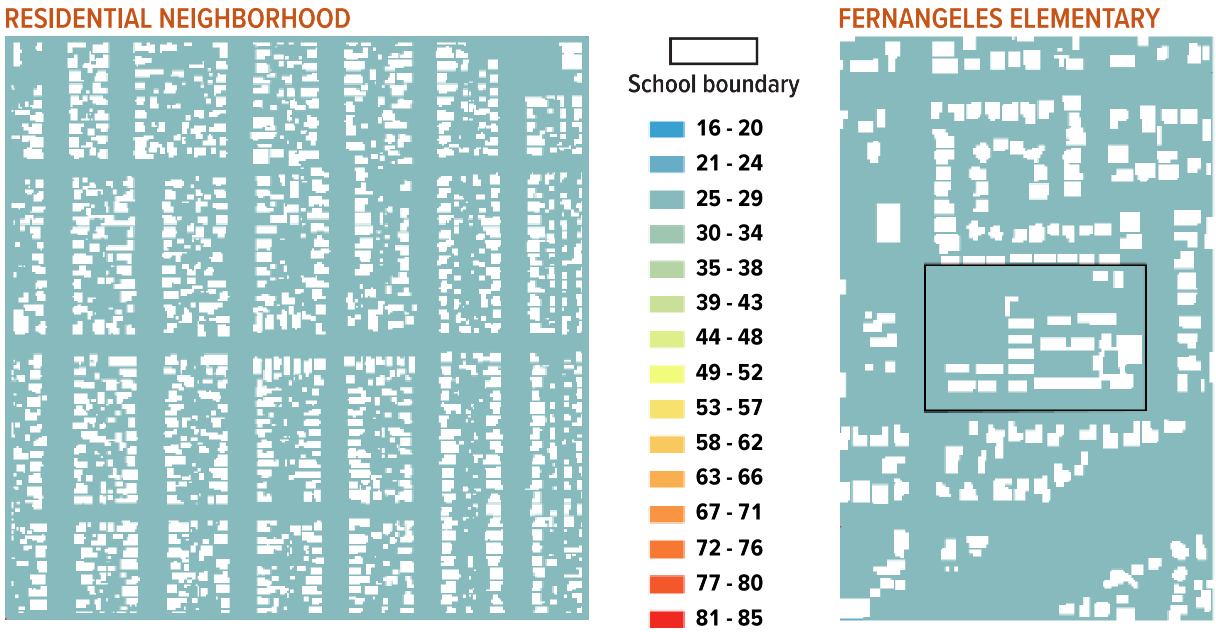
SURFACE COVER			INCOMING SOLAR RADIATION		
Temperature Variable	Standard Error	R2	Temperature Variable	Standard Error	R2
AT	0.002	>0.000	AT	8.582e-06	0.025
MRT	0.012	>0.000	MRT	1.956e-05	0.858
ST	5.609e-03	0.088	ST	1.478e-05	0.481

APPENDIX B: DIURNAL TRENDS BY SITE

The following figures show simulated AT and LST for both sites across a diurnal cycle (for MRT, see Figure 9). Trends are further broken down for AT, MRT and LST by surface composition.

FIGURE B1: Air temperature simulation results for Fernangeles Elementary School and a residential neighborhood in Pacoima

Air Temperature at 08:00



Air Temperature at 10:00

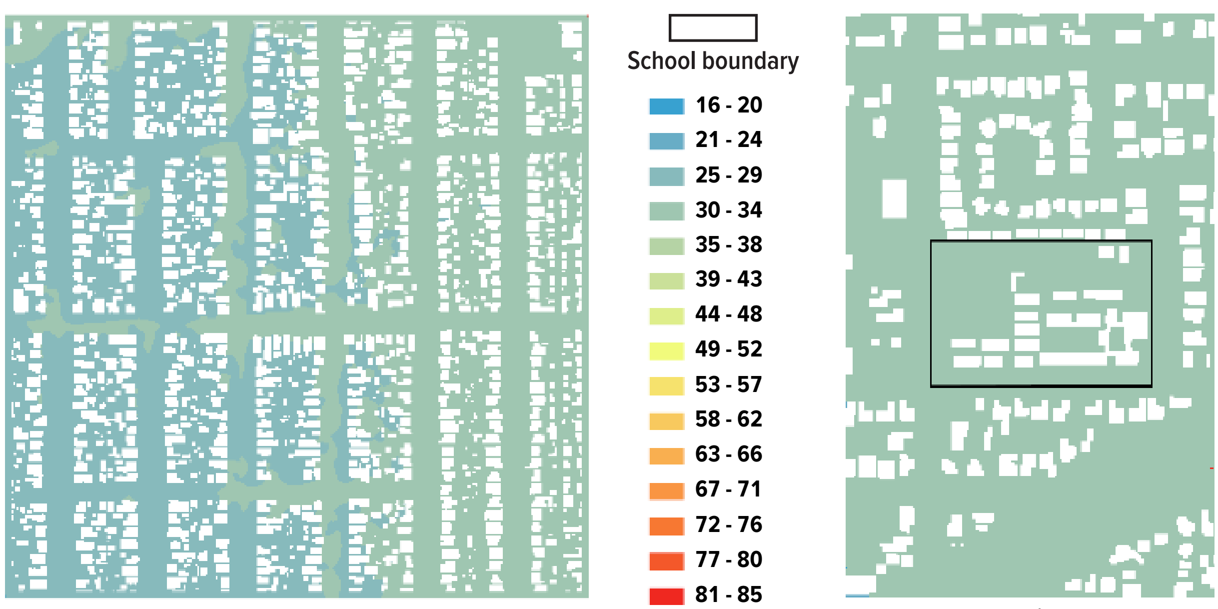


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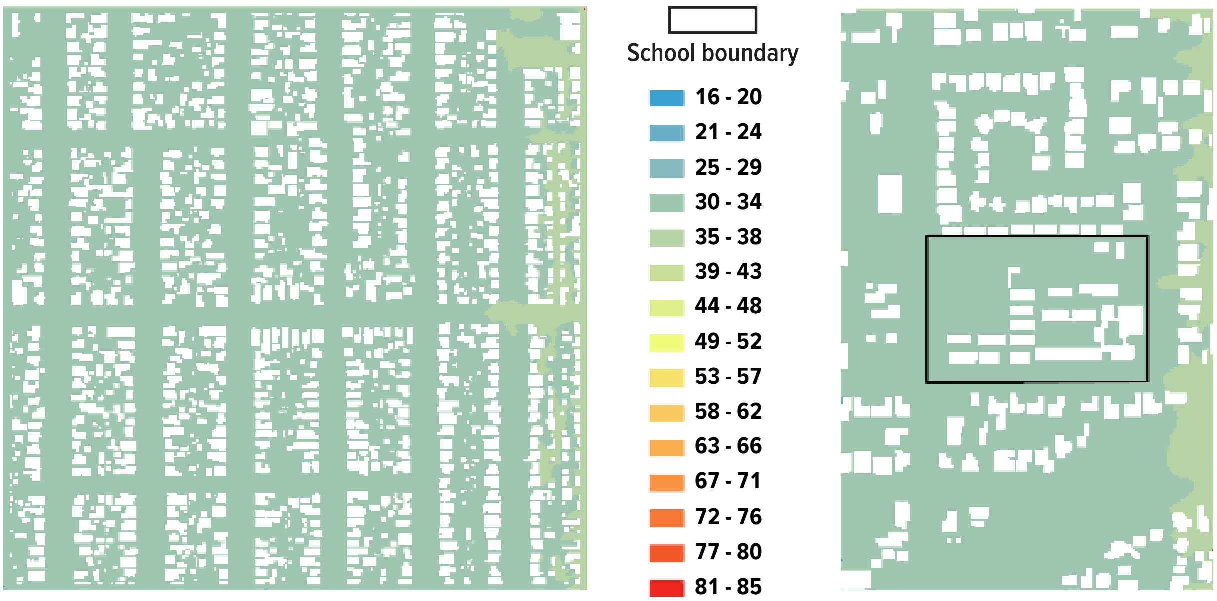
FIGURE B1 (continued): Air temperature simulation results for Fernangeles Elementary School and a residential neighborhood in Pacoima

Air Temperature at 12:00

RESIDENTIAL NEIGHBORHOOD | FERNANGELES ELEMENTARY



Air Temperature at 14:00

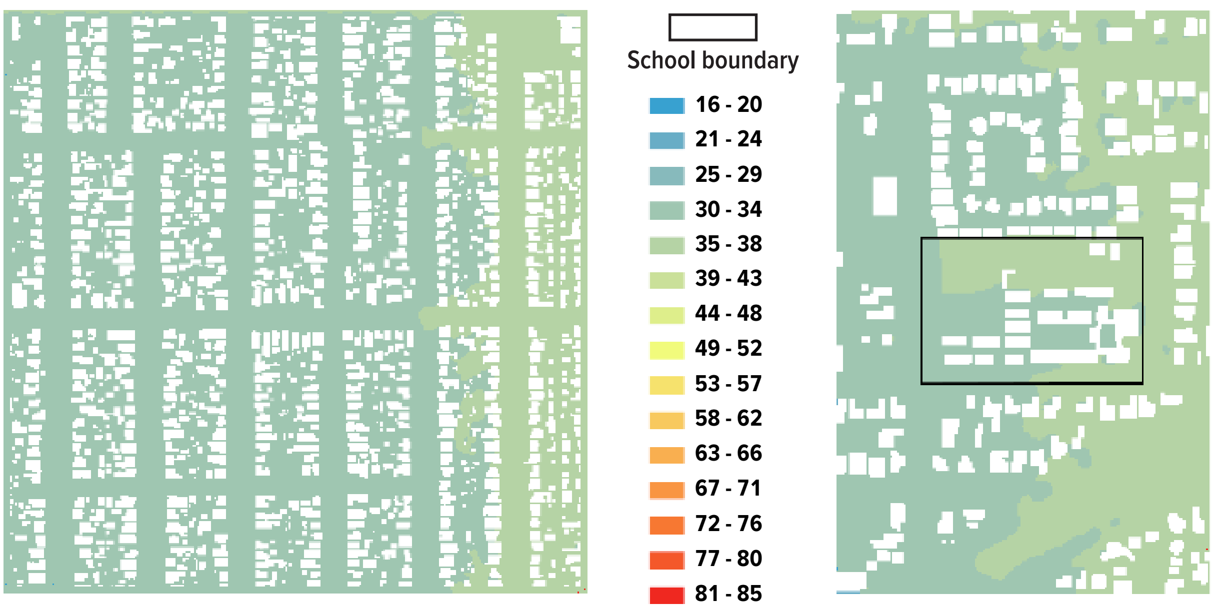


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FIGURE B1 (continued): Air temperature simulation results for Fernangeles Elementary School and a residential neighborhood in Pacoima

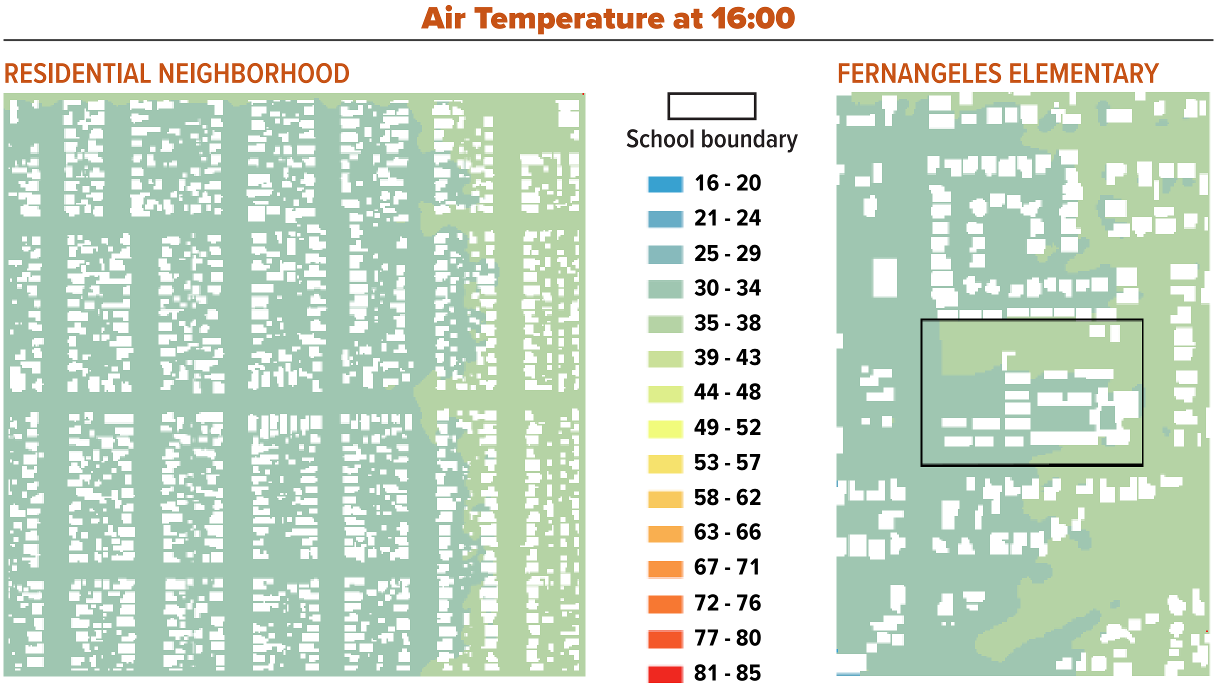
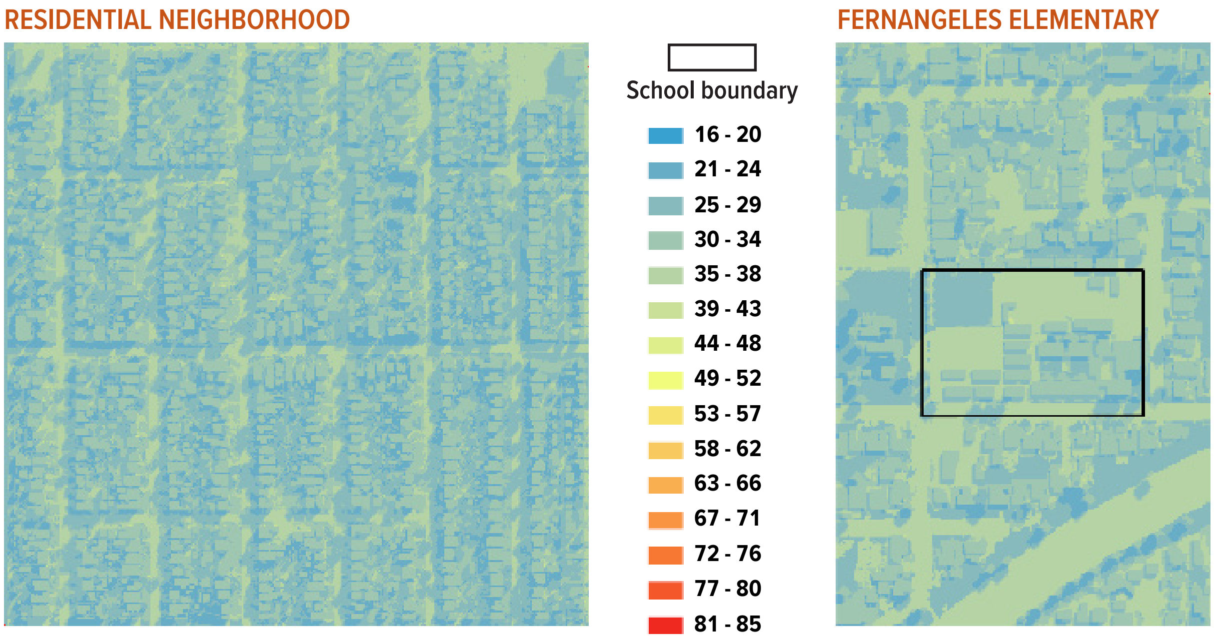


FIGURE B2: **Surface temperature simulation results for Fernangeles Elementary School and a residential neighborhood in Pacoima**

Surface Temperature at 08:00



Surface Temperature at 10:00

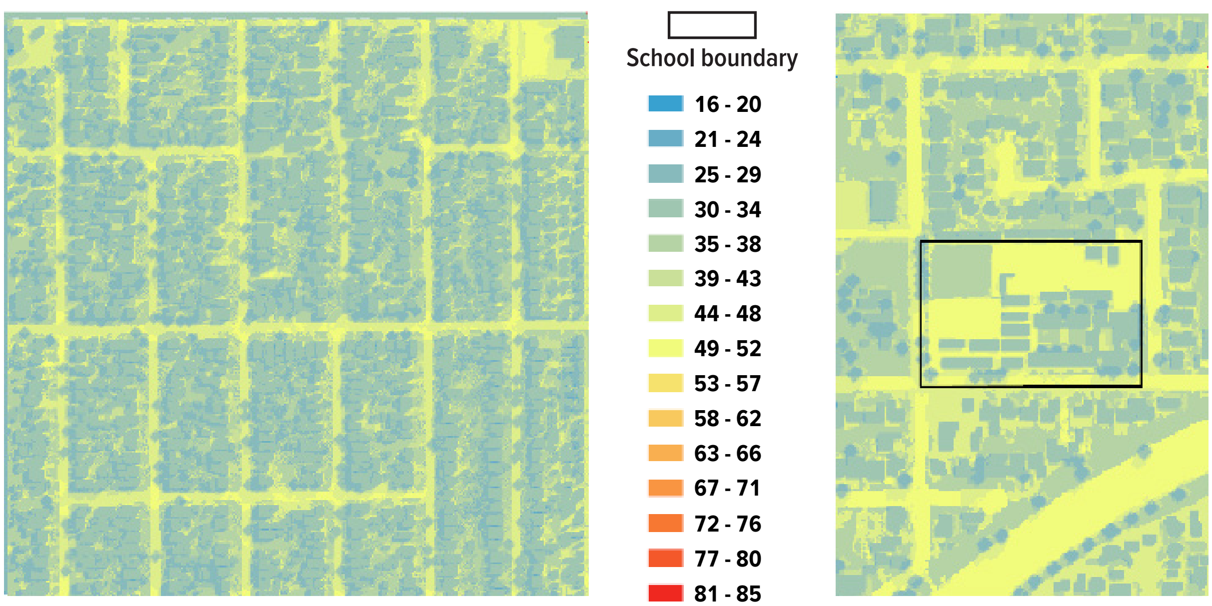


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FIGURE B2 (continued): Surface temperature simulation results for Fernangeles Elementary School and a residential neighborhood in Pacoima

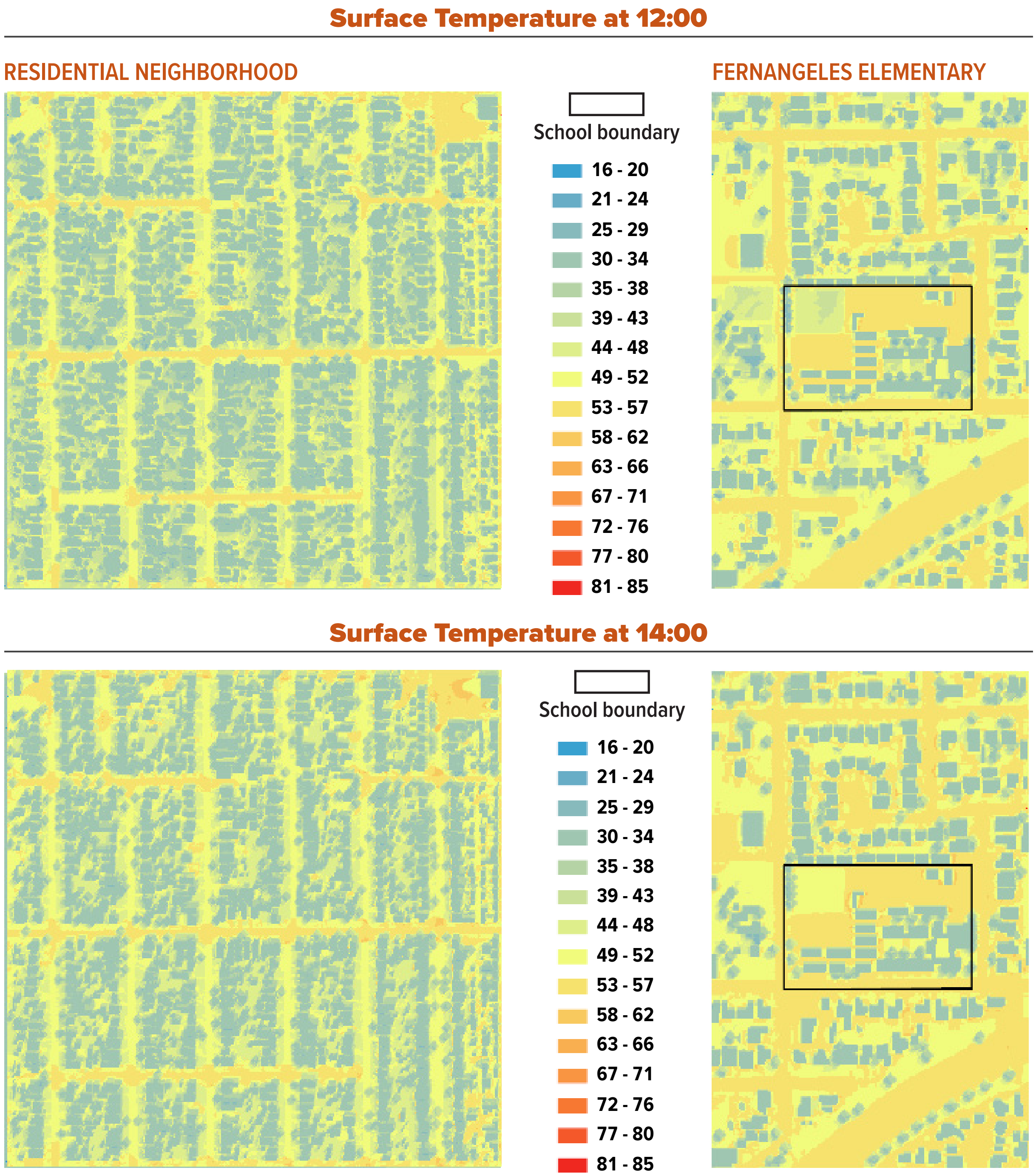

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FIGURE B2 (continued): Surface temperature simulation results for Fernangeles Elementary School and a residential neighborhood in Pacoima

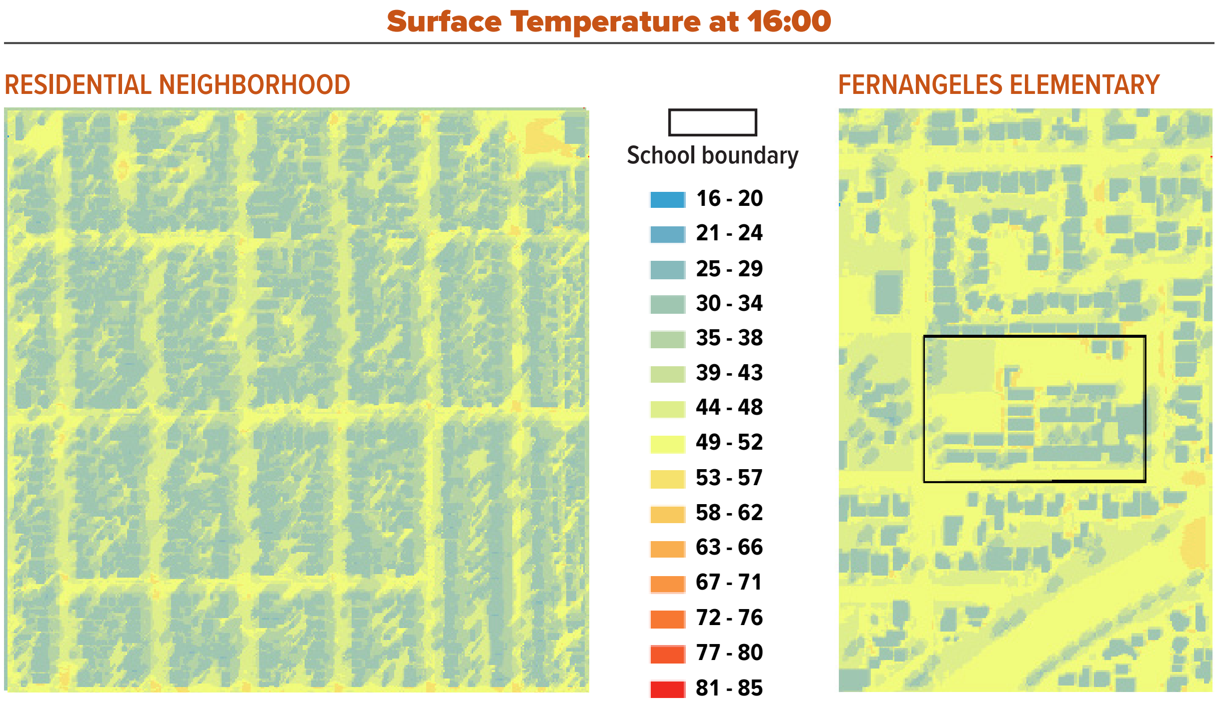


FIGURE B3: **Simulated diurnal trends by climate variable and by land cover in a residential neighborhood and Fernangeles Elementary School**

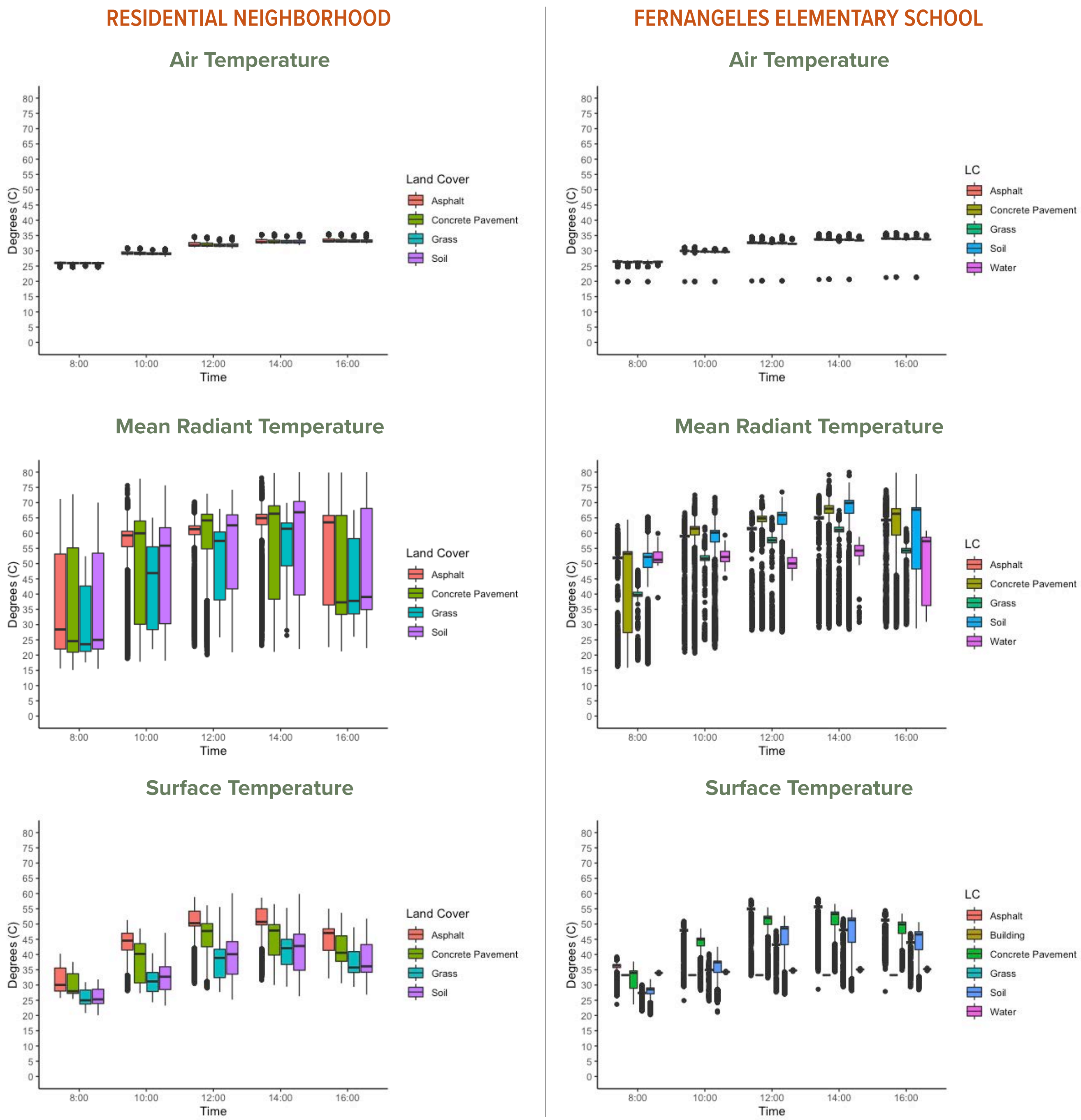


FIGURE B4: Simulated diurnal trends by climate variable and by shade versus sun exposed in a residential neighborhood and Fernangeles Elementary School

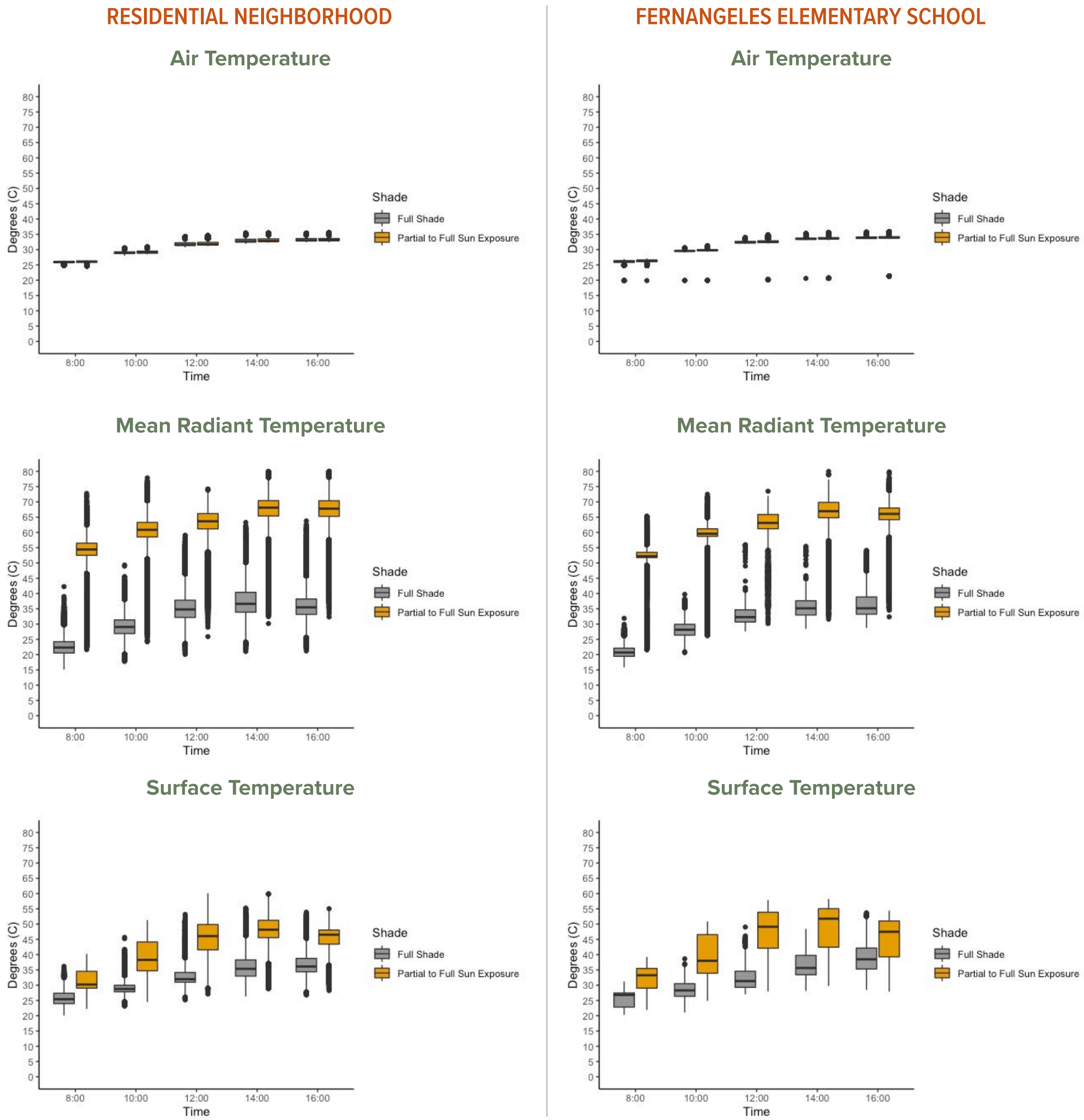


FIGURE B5: Simulated diurnal trends by climate variable, sun exposure, and land cover in a residential neighborhood and Fernangeles Elementary School

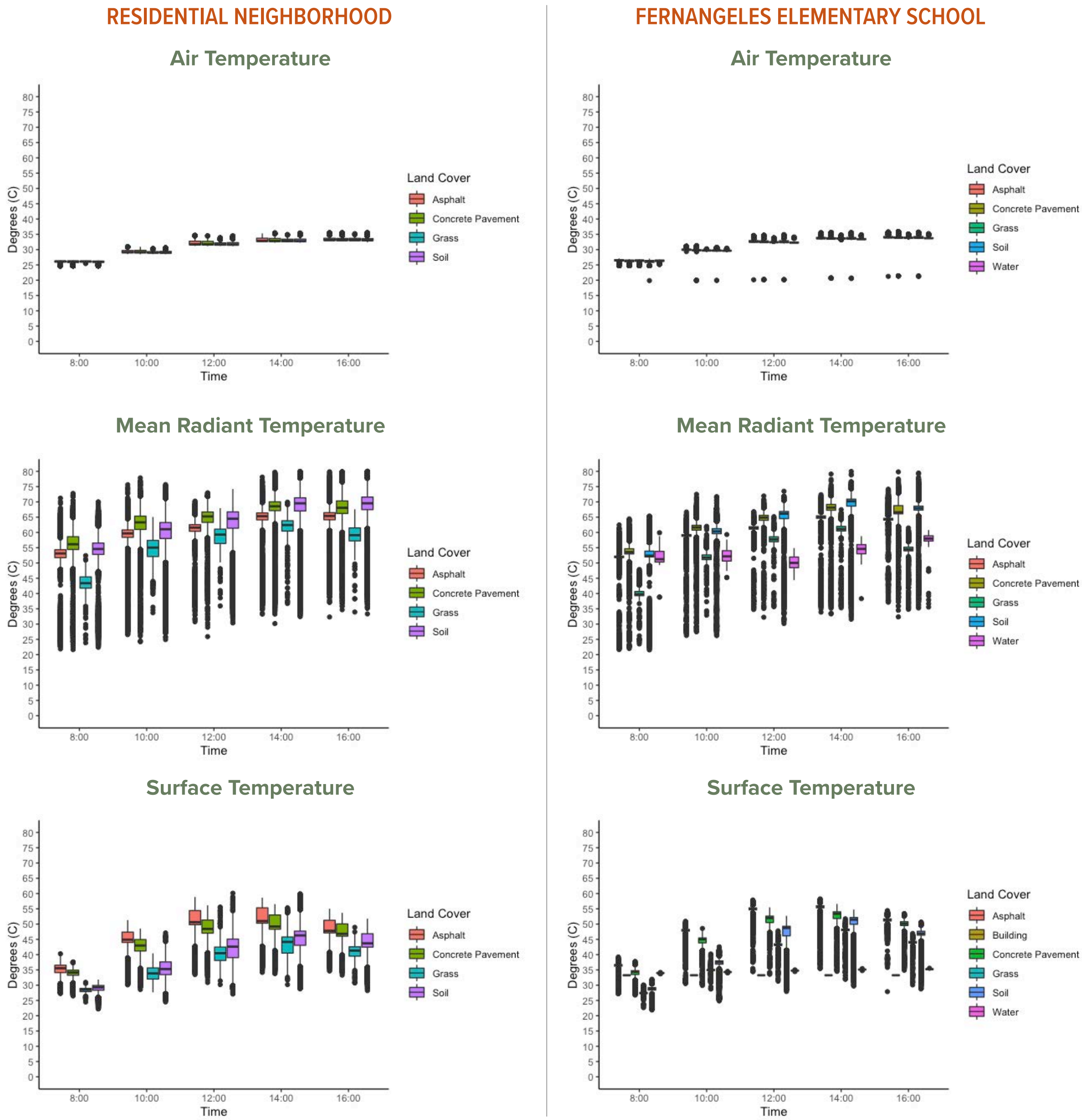
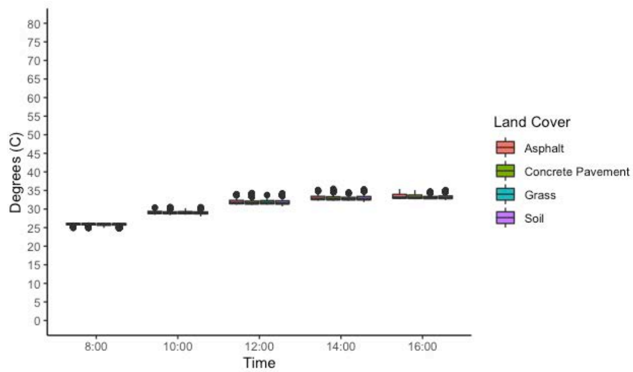


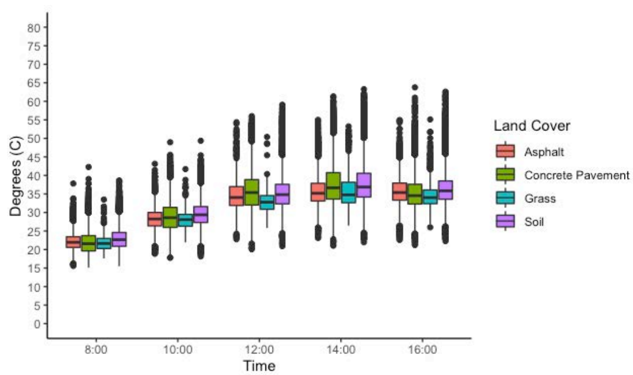
FIGURE B6: Simulated diurnal trends by climate variable, shade, and land cover in a residential neighborhood and Fernangeles Elementary School

RESIDENTIAL NEIGHBORHOOD

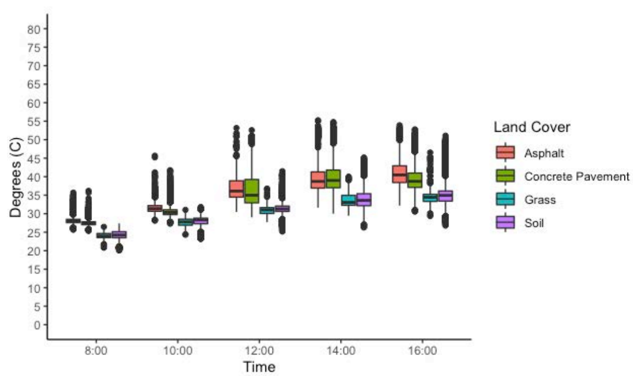
Air Temperature



Mean Radiant Temperature

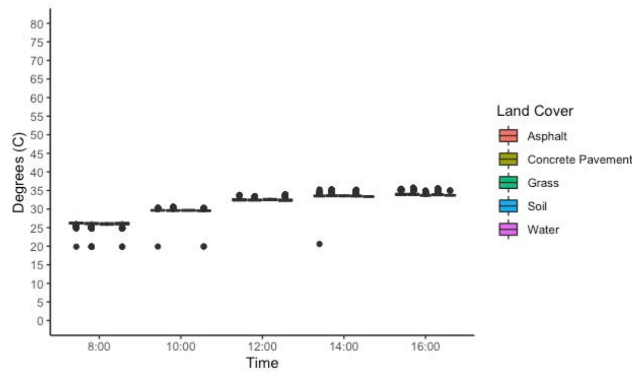


Surface Temperature

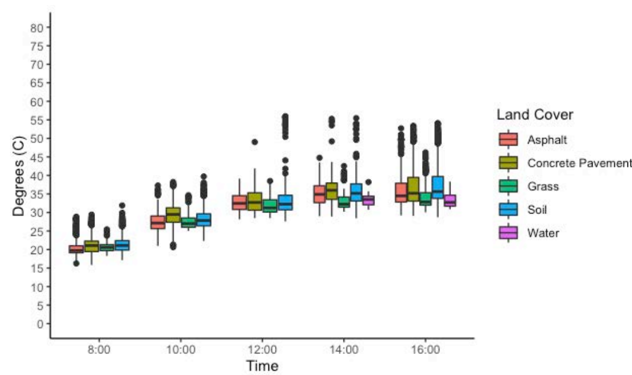


FERNANGELES ELEMENTARY SCHOOL

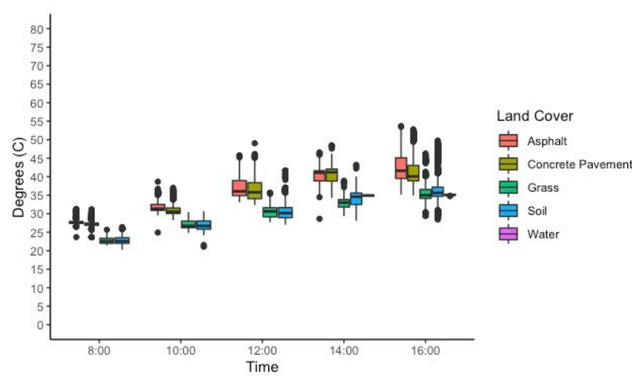
Air Temperature



Mean Radiant Temperature



Surface Temperature



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