Zhao, Q., Sailor, D. and Wentz, E. (2018) Impact of tree locations and arrangements on outdoor microclimates and human thermal comfort in an urban residential environment. *Urban Forestry and Urban Greening*, 32, pp. 81-91. (doi:10.1016/j.ufug.2018.03.022).

Accepted Manuscript

Title: Impact of Tree Locations and Arrangements on Outdoor Microclimates and Human Thermal Comfort in an Urban Residential Environment

Authors: Qunshan Zhao, David J. Sailor, Elizabeth A. Wentz

PII: S1618-8667(17)30566-6
DOI: https://doi.org/10.1016/j.ufug.2018.03.022
Reference: UFUG 26112

To appear in:

Received date: 18-9-2017
Revised date: 19-2-2018
Accepted date: 29-3-2018

Please cite this article as: Zhao, Qunshan, Sailor, David J., Wentz, Elizabeth A., Impact of Tree Locations and Arrangements on Outdoor Microclimates and Human Thermal Comfort in an Urban Residential Environment.Urban Forestry and Urban Greening https://doi.org/10.1016/j.ufug.2018.03.022

Impact of Tree Locations and Arrangements on Outdoor Microclimates and Human Thermal Comfort in an Urban Residential Environment

Qunshan Zhao[a1], David J. Sailor[b], Elizabeth A. Wentz[a]

[a]Spatial Analysis Research Center
School of Geographical Sciences and Urban Planning
Arizona State University
Tempe, AZ 85287-5302, USA
Email:
Qunshan Zhao: qszhao@asu.edu
Elizabeth A. Wentz: wentz@asu.edu

[b]Urban Climate Research Center
School of Geographical Sciences and Urban Planning
Arizona State University
Tempe, AZ 85287, USA
Email:
David J. Sailor: David.Sailor@asu.edu

[1]Corresponding author: Qunshan Zhao
Email: qszhao@asu.edu
Postal address:
1089 N Willow St
Chandler, AZ, 85226
Telephone: +1(480)2806586

Highlights:

- Tree shade benefits are important for residential outdoor thermal environment.
- ENVI-met was used to evaluate the climate benefits from different tree layouts.
- Equal interval tree layouts offer the largest cooling benefits to neighborhoods.
- Findings provide guidelines to effective arrange trees for cooling.

Abstract

Trees serve as a valuable asset in the urban built environment. In an arid city like Phoenix, trees are one of the primary urban green infrastructures to ameliorate extreme heat stress. Because of the cost of water and space in the desert residential environment, designing the optimal tree arrangement to maximize overall thermal benefits for residential neighborhoods is important and necessary. In this research, we first simulated a real neighborhood with current tree arrangement in ENVI-met (a holistic three-dimensional model for the simulation of surface-plant-air interactions), and validated the reliability of ENVI-met models by comparing the simulated results with systematic temperature collection transects. Further, we evaluated and compared differences in outdoor microclimates and human thermal comfort by simulating different tree layouts (clustered, equal interval, or dispersed) in the same neighborhood. Tree benefits at individual building scale and neighborhood scale are also compared and discussed. Based on the simulation, an equal interval two trees arrangement provided the most microclimate and human thermal comfort benefits in the neighborhood due to the importance of shading in the hot arid desert environment, following by clustered tree arrangement without canopy overlap. These findings will help policy makers and urban planners offer better guidelines for planting and establishing residential trees to mitigate extreme heat in the hot arid residential environment.

Keywords: tree arrangement, tree location, human thermal comfort, outdoor thermal environment, ENVI-met.

1 Introduction

The urban heat island (UHI) effect is a well-known phenomenon caused by the change of energy balance and thermal properties of the built environment (Oke, 1982). The UHI effects increase air and surface temperatures, result in higher energy demand for cooling, degrade air quality, decrease in human thermal comfort, and increase to heat-related morbidity and mortality (Bi et al., 2011; Nazaroff, 2013; Song and Wang, 2015; Wentz et al., 2016; Zhao et al., 2015). Vegetation is the most common method to alleviate the negative impacts of the UHI (Declet-Barreto et al., 2013; Huang et al., 1987; Wang et al., 2016; Zhao et al., 2014). While turf lawns and shrubbery provide surface shading, trees are more effective by blocking short-wave radiation penetration to the surface, reducing long-wave radiation exchange, and generating evapotranspiration with less water consumption comparing to turf grass (Erell et al., 2011). Without effective and adequate vegetation coverage in residential neighborhoods, urban residents experience severe human thermal discomfort and result in serious heat-related morbidity and mortality in the outdoor environment, especially to the elderly and children (Chow et al., 2012; Vanos et al., 2016)**.** Increasing tree canopy coverage in a desert city like Phoenix needs more examination because the high cost of water limits the number of trees to be planted in each of the residential household (Zhao, 2017; Zhao et al., 2017, 2018). Thus, the goal of this research is to quantify the appropriate arrangement of trees in residential neighborhoods and to optimize performance from the limited number of trees to reduce the UHI effect and improve human comfort.

Existing research to explore how location and arrangement of trees influence the built environment uses methods including remote sensing and numerical simulation. Remote sensing research shows that vegetation coverage reduces the urban surface temperature at the city and regional scales (Myint et al., 2013). However, the specific effects of tree locations and arrangements have not been explored widely because of the reduced availability of high resolution thermal satellite images (Zhao and Wentz, 2016). Recently, using high resolution thermal remotely sensed images (60 m/pixel), Myint et al. (2015) and Fan et al. (2015) showed that a clustered arrangement of trees improved cooling effects compared to dispersed tree arrangement. However, the use of remote sensing introduces two limitations. First, remote sensing techniques can only derive the top canopy surface temperature. Existing research rarely assess and compare canopy surface temperature and air temperature under the tree canopy by field measurement. Second, air temperature, wind speed, mean radiant temperature (MRT), and relative humidity need to be incorporated into the calculation of human thermal comfort under different tree locations and arrangements. Knowing the thermal perception and degree of physiological stress of an urban neighborhood is more meaningful for urban residents than just recognizing extreme heat areas from the urban surface temperature. Thus, we still do not understand thoroughly how tree locations and arrangements influence the built environment by the existing remote sensing research. As an alternative to remotely sensed data and methods, numerical simulation methods such as the 3D computational fluid dynamics (CFD) modeling, has the capabilities to simulate the urban environment of airflow, pollution dispersal, pedestrian thermal comfort, and vegetation effects (Erell et al., 2011). Numerical simulation overcomes the limitations of remote sensing because it gives the availability to simulate outdoor microclimate conditions (air temperature, surface temperature, humidity, etc.) and human thermal comfort. Most importantly, numerical models make it possible to create and test a wide variety of tree locations and arrangements scenarios that are not practical to test in situ.

Numerical models consistently show that increased vegetation or tree coverage provide a cooling effect and improve the human thermal comfort, but what varies is the extent of cooling for a given amount of vegetation. Those variations occur due to the climatic environment at different geographic locations, the volume or the type of vegetation, and building layout or wind corridor design (Hsieh et al., 2016; Yang et al., 2017). Although trees were widely confirmed to be effective in mitigating heat and improving human thermal perception in dense urban streets (Kong et al., 2017; Morakinyo et al., 2017; Tan et al., 2015, 2017), research has seldom explored how residential tree locations, spacing, and arrangements influence the outdoor microclimates and human thermal comfort. Most of the existing literature simulates outdoor microclimates and human thermal comfort by randomly locating trees to a certain percent of the coverage or is simply based on the real-world landscaping design (Chen and Ng, 2013; Hsieh et al., 2016; Jan et al., 2013; Middel et al., 2015). The obvious next step is to account for factors such as tree densities, locations, and arrangements in the numerical models to evaluate the cooling effects from trees and human thermal comfort. Further, none of the published research explores how to design tree locations and arrangements effectively to benefit both individual parcels and the surrounding residential neighborhood concurrently. Residents may want to maximize shade coverage of their south-facing facade by planting trees in the center of south front yard, but it is still unknown whether planting a tree between two houses can provide more substantial benefits to both the buildings and the neighborhood.

The goal of this research is to explore how tree locations and arrangements influence the outdoor microclimates and human thermal comfort. We use numerical simulation to address this question, and to determine how best to design tree locations and arrangements to benefit both individual parcels and residential neighborhood. The model reliability is first validated by mobile vehicle field measurements. Then, we designed and simulated different tree arrangements (clustered, dispersed, or equal intervals) in both building and neighborhood scales. This research will improve the theoretical and empirical understanding of the influence of tree locations and arrangements on outdoor microclimates and human thermal comfort in the desert residential neighborhood.

2 Study Area and Climatic Conditions

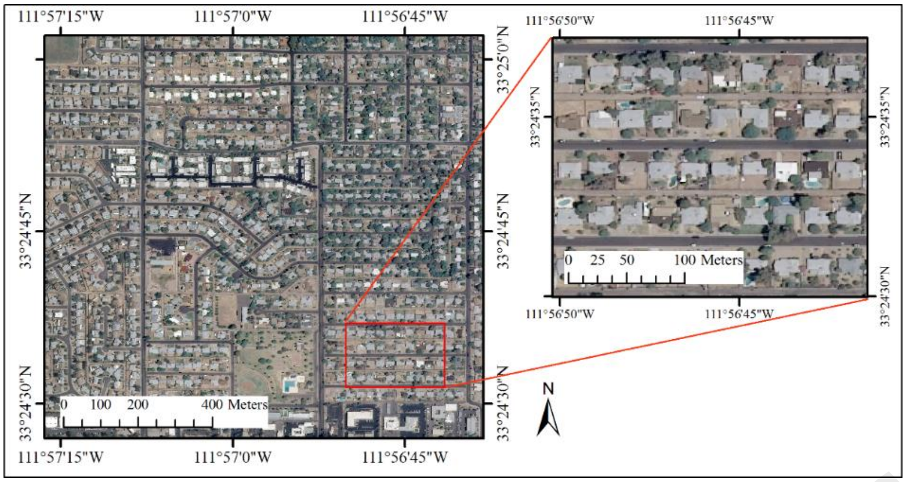


Figure 1 Study area in the city of Tempe within the greater Phoenix metropolitan area, Arizona, USA.

The study area is a residential neighborhood in the City of Tempe, AZ USA (Figure 1). The majority of this residential neighborhood consists of single-family houses built between 1950 and 1960. Most structures are single story buildings around 134 m^2 according to Maricopa County Assessor's records ("Maricopa County Assessor's Office," n.d.). The mean parcel size is around 700 m^2 with moderate size front and back yards and narrow side yards. Nearly all the parcels have neighboring houses on the west/east side of the building except those buildings that are at the end of the building rows. This compact urban layout makes it impossible to plant large shade trees at the west and east side of the building structures, and most of the residents plant their shade trees in their front yard (south) or back yard (north). Some residents maintain lawns in their yards as well.

The City of Tempe, located in the Sonora Desert, has a semi-arid climate. The mean annual rainfall is 237 mm and most of the rain occurs in the winter from December through March (112 mm) and during monsoon season at July and August (62 mm). June is the driest month with less than 1 mm mean annual precipitation. Maximum air temperature ranges from 39.3° C to 40.4° C during the summer months (June to August), and from 20.1° C to 22.6° C during the winter months (December to February). Minimum air temperature peaks at 24.0° C in July and can reach as low as 3° C in December (WRCC, 2015).

3 Methodology

The research methodology is presented in Figure 2. As a starting point, this study simulated the baseline neighborhood configuration, representing current conditions. A fieldwork measurement and validation campaign was conducted to ensure the base case model stability and accuracy. Outdoor microclimate conditions and human thermal comfort were simulated and compared under different tree densities, locations and arrangements. The final model results provided planning recommendations and understanding to better design sustainable urban residential environments.

In the base model simulation, we included lawns to accurately represent the outdoor thermal environment. For simplicity in comparing results across simulations, the test scenarios did not change or remove existing lawns. This also helped to ensure the model accuracy and enable isolation of the variable of interest (tree configuration).

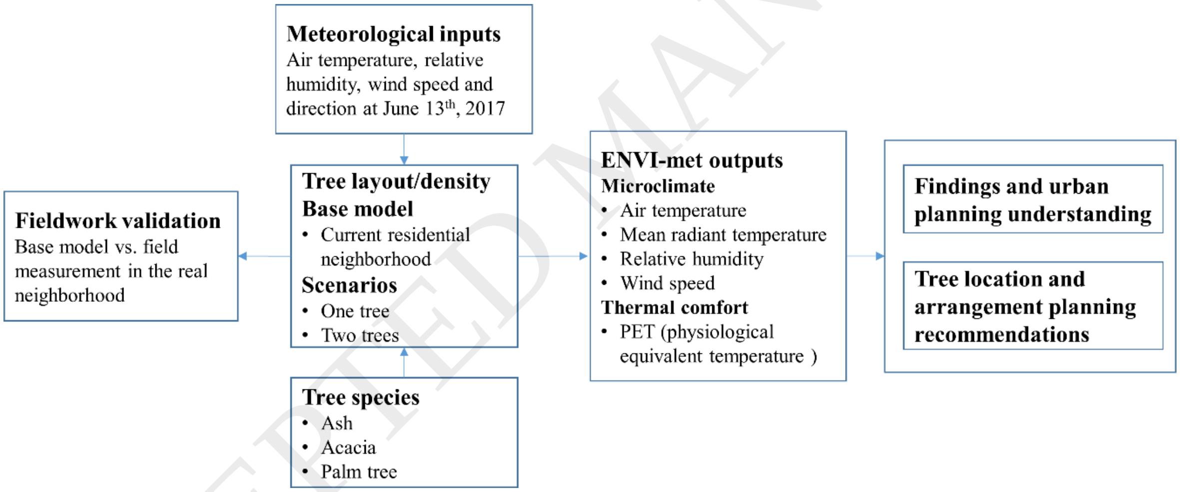


Figure 2 Methodology framework

3.1 Fieldwork Design and Measurement

To validate the accuracy of the numerical simulation results, we measured air temperature along transects in the target residential neighborhood (Figure 1). The field measurements occurred on a clear summer day with low wind speed (~ 2 m/s) and no cloud cover. We drove along transects in a vehicle equipped with GPS data loggers (QStartz Travel Recorder XT) and external shielded air temperature thermocouples (Omega thermocouples at 1.5 m height, Figure 3). The details of systematic temperature collection transects and the ENVI-met simulation area are shown in Figure

4. Data were collected in the early morning (7:00) and late afternoon (16:00) on 13 June 2017. We completed each systematic temperature collection transect from T1 to T8 (Figure 4) in 5 minutes with a driving speed of 3 m/s and a driving distance of 1620 m around the target neighborhood. The short period of the traverse helps to assure stationarity of the local microclimates for easier comparison with model output at specific corresponding simulation times. The target neighborhood was measured twice in each transect (T3 and T7 in Figure 4) and two measurement traverses (T3 and T7) were conducted immediately following each other. Transects were only conducted in the early morning and late afternoon because we focused on the daytime tree benefits of the outdoor microclimates and human thermal comfort in this research, and because these are the times of day with relatively slow variation in the ambient air temperature (i.e., near times of local temperature extrema). The fieldwork measurement results were compared with the simulation results from ENVI-met by the univariate difference measures to evaluate the model accuracy.

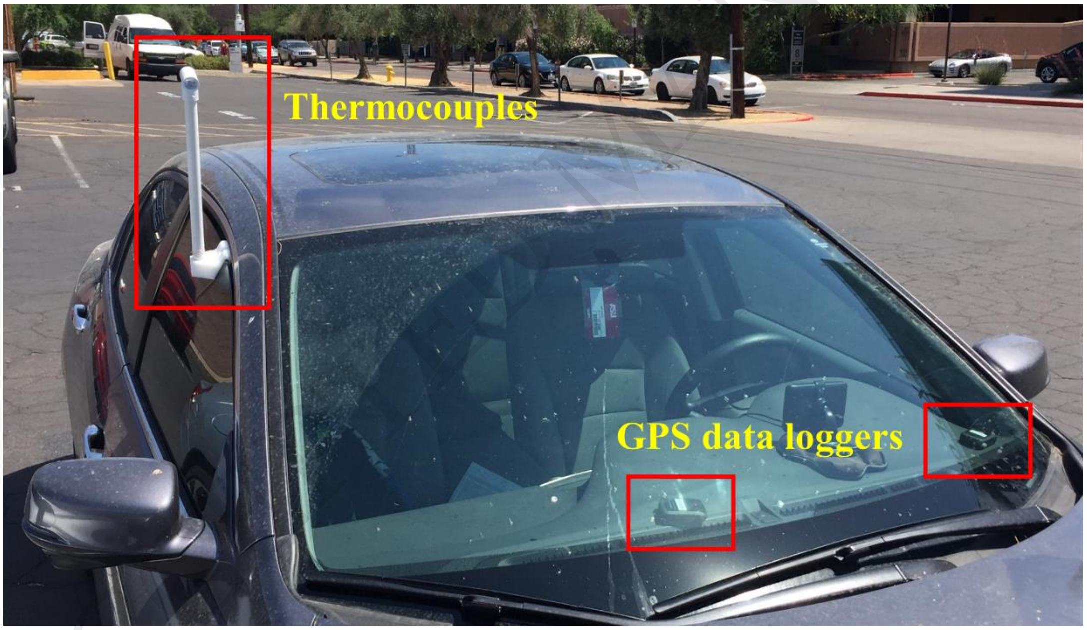


Figure 3 Vehicle-based air temperature thermocouples and GPS data logger placement for traverse measurements.

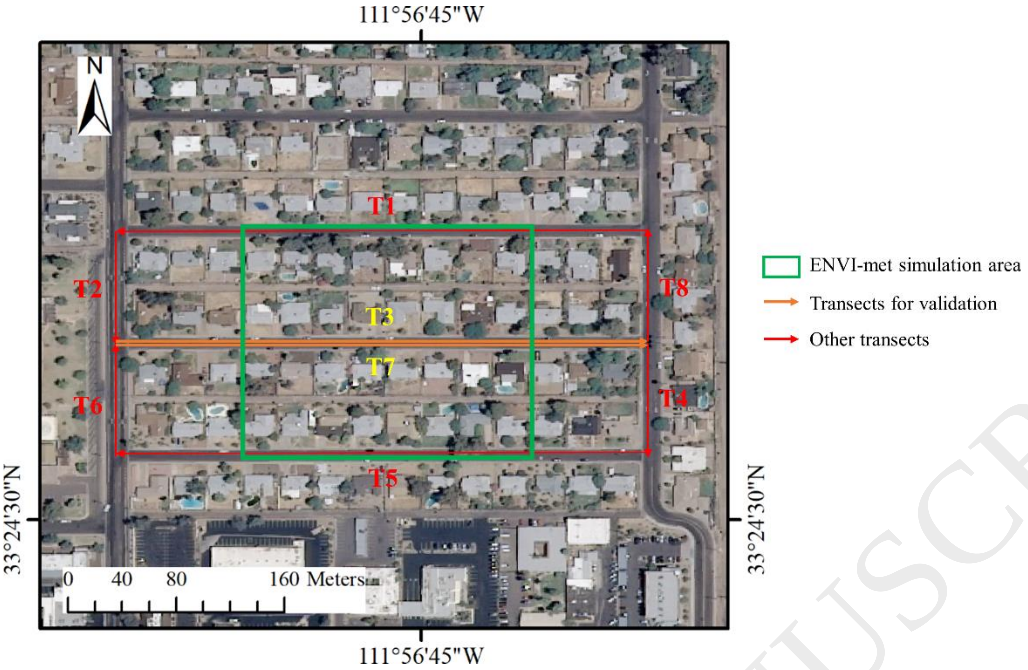


Figure 4 Details of systematic temperature collection transects.

3.2 Microclimate Numerical Simulation

The base model was first tested in the ENVI-met simulation platform to verify the numerical models can represent accurate outdoor microclimates with current building, vegetation, and soil/surface conditions (Figure 5). ENVI-met is a three-dimensional atmospheric model designed to simulate the urban surface-plant-air interactions, and has been utilized for simulating air flows between and around buildings, vegetation impacts of the local microclimates, heat exchange processes at the building walls or ground surface, and bioclimatology and pollutant dispersion (Bruse and Fleer, 1998). The ENVI-met area input and configuration parameters for validation simulation are shown in Table 1. The entire ENVI-met study area domain was 200 × 200 × 20 m with vertical and horizontal grid resolution at 1 m. To ensure the simulation stability, we added 7 nesting grids (7 m) outside of the horizontal study area domain and created a 10 m empty buffer area around the residential neighborhood within the study domain. Each housing unit was approximately 18 m × 12 m length by width. The meteorological conditions were obtained from the nearby weather station at Phoenix Sky Harbor International Airport on 13 June 2017. Since the neighborhood we wanted to understand has a mixture of trees, shrubs, and grass coverage, a xeric initial soil temperature setting was used based on Middel et al. (2014), as showed in Table 1. We manually digitized the building boundary information based on Google map, with a consistent 4 m height to represent the common single-family house in the study area. We assigned the emissivity and albedo of urban surfaces according to Erell et al. (2011), Oke (1992), and Santamouris et al. (2013) (Table 2). For the model boundaries, we used forced lateral boundary conditions for the temperature and relative humidity, using data from the Phoenix Sky Harbor International Airport weather station at 13 June 2017. Because this neighborhood was part of a large homogeneous residential neighborhood, we used cyclic lateral boundary conditions to represent the turbulent exchange coefficient by copying the inflow profile into the model domain.

Figure 5 Base model with existing tree locations and arrangements

Table 1 Summary of area input and configuration parameters for validated simulation

Parameter	Definition	Input value
Meteorological conditions	Initial air temperature (° C)	24
	Relative Humidity in 2 m (%)	13
	Inflow direction (0°: North; 90°: East; 180°: South; 270°: West.)	225°
	Wind speed in 10 m (m/s)	2
	Initial soil temperature (° C)	33.4 (upper layer, 0-20 cm) 34.4 (middle layer, 20-50 cm) 35.4 (deep layer, >50 cm)
	Cloud cover	0.00

	Roughness length at reference point (m)	0.01
Buildings'/roads' information	Street orientation	E-W
	Street width (m)	8
	Roads/Pavements/Soils/Water information	Table 2
Lateral boundary conditions (LBC)	LBC for temperature and humidity	Forced
	LBC for turbulence	Cyclic

Table 2 Summary of surface information

Type	**Albedo**	**Emissivity**	**Roughness Length**
Soil	0.20	0.95	0.015
Asphalt Road	0.15	0.95	0.010
Concrete Pavement Light	0.35	0.90	0.010
Concrete Pavement Gray	0.20	0.90	0.010
Gravel	0.15	0.90	0.010
Water	0.05	0.95	0.010

Three different types of trees were used in the base model with different leaf type, crown width and tree height: *Fraxinus velutina* (Desert ash), *Acacia salicina* (Weeping acacia), and *Washingtonia filifera* (Desert palm) (Table 3). Desert ash represents deciduous shade trees with large canopy coverage. Weeping acacia has similar height to desert ash, but it has relatively small canopy coverage (needle leaves) and fits better in a narrow vertical space. Desert palm is the typical tall palm tree with little shade coverage from the canopy. These three types of trees were the most common tree species in this specific neighborhood, and we utilized them to represent all other similar tree species in our study area. We chose the 5 cm height dense grass to simulate the urban lawns in the study area.

Table 3 Summary of tree information

Tree name	**Scientific name**	**Leaf type**	**Crown width**	**Tree height**
Desert Ash	*Fraxinus velutina*	Deciduous	5	6
Weeping acacia	*Acacia salicina*	Needles	9	6
Desert palm	*Washingtonia filifera*	Palms	9	10

Note: Tree information is obtained from the virtual library of Phoenix Landscape plants (Martin, n.d.).

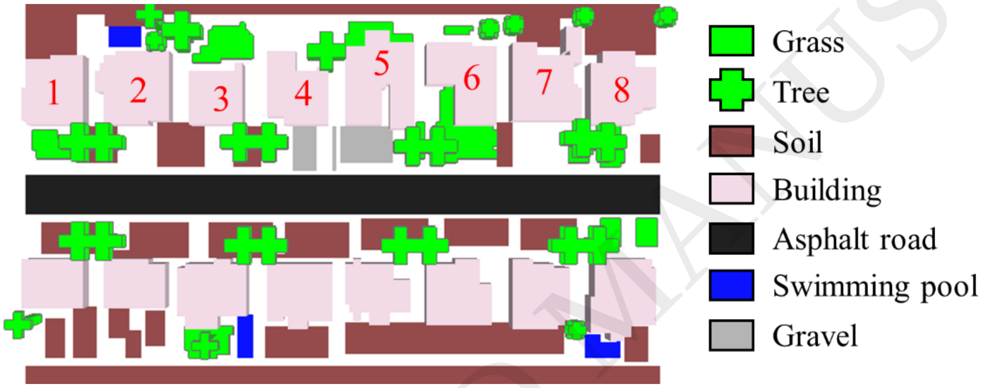
To assess the impacts of different tree locations and arrangements on the outdoor microclimates and human thermal comfort, we created 9 test scenarios in the residential neighborhood (Table 4). Since this research focused on understanding the impacts of tree locations and arrangements to the outdoor microclimates and human thermal comforts, we used the same tree species (mature weeping acacia) in all of the simulation scenarios. Due to the tree size and space limitation in the residential building front yard, we did not simulate scenarios with more than two trees for each single-family household in the designed scenarios.

Table 4 Numerical simulation scenarios

Scenario	**Tree density**	**Individual tree layout**	**Neighborhood tree layout**
1	0	N/A	N/A
2	1	Center of south front yard	Equal interval
3	1	West of south front yard	Equal interval
4	1	East of south front yard	Equal interval
5	1	West/East of south front yard	Clustered
6	2	Clustered (no canopy overlap)	Clustered
7	2	Clustered (with canopy overlap)	Clustered
8	2	Equal interval	Equal interval
9	2	Dispersed	Clustered

We removed all the existing trees in the central street of the model to create a “no-tree” scenario (Figure 6a), and created one tree and two trees scenarios with different tree arrangements (examples at Figure 6b and 6c). Results associated with the different tree arrangement for individual buildings and neighborhood were compared and evaluated. For each scenario, air temperature, MRT, wind speed, and relative humidity were simulated for 24 hours at 13 June 2017.

(a) No front yard tree (scenario 1).



(b) One front yard tree (scenario 5).

(c) Two front yard trees (scenario 9).

Figure 6 Simulated tree locations and arrangement scenarios (selected scenarios)

3.3 Human Thermal Comfort Calculation

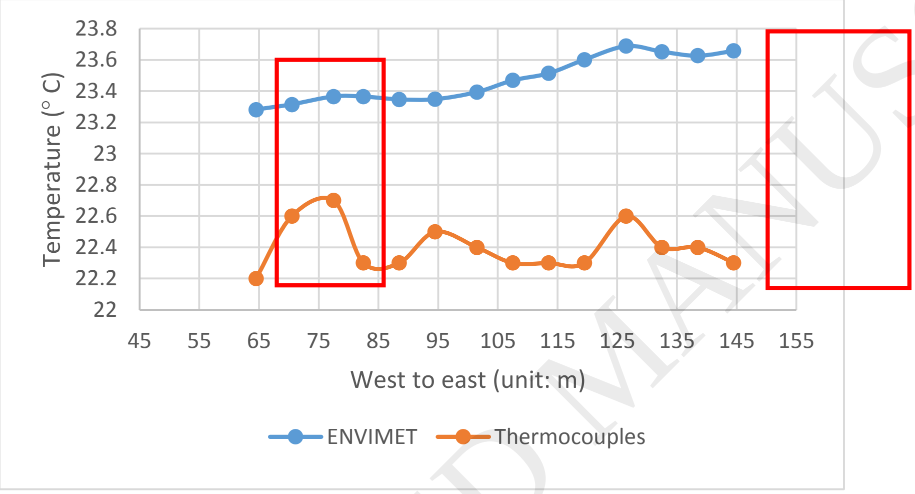
To evaluate the outdoor human thermal comfort, we used physiological equivalent temperature (PET) as the indicator to show the thermal sensation under different simulated scenarios (Mayer and Höppe, 1987). PET values were estimated by ENVI-met BioMet package to evaluate the effects of residential trees in improving outdoor pedestrians and residents comfort (Höppe, 1999). For the human parameter setting in BioMet, we used a 35-year-old male with 75 kg weight and 1.75 m height, with a static clothing insulation index (clo) of 0.2 (T-shirt and walking shorts) and metabolic rate at 93 W/m^2 (standing or light activity) based on ISO 9920 (2007) and ISO 8996 (2004).

4 Results

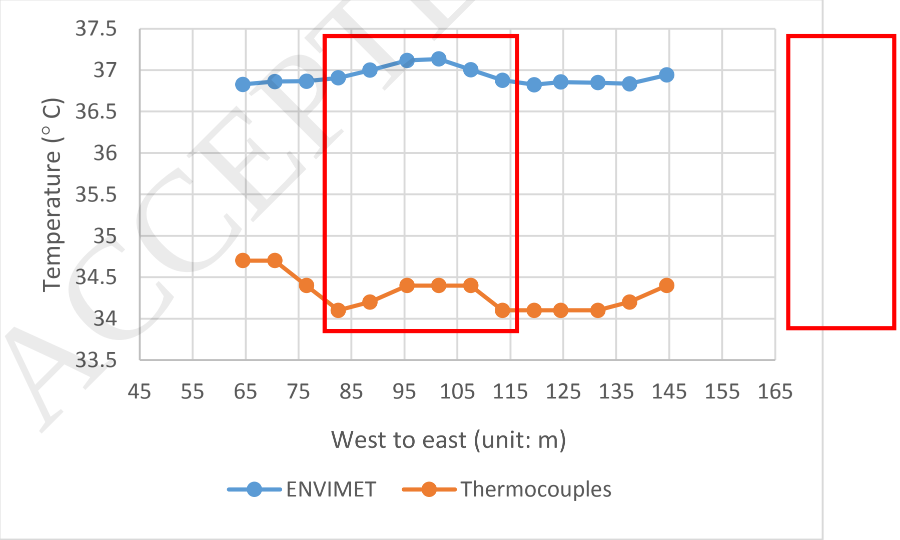
4.1 Fieldwork Validation

In support of a partial validation of model performance, we extracted 1.5 m air temperature from ENVI-met simulation results at 7:00 and 16:00 13 June 2017. Based on the location and time information from GPS, we identified the simulated air temperature on the validated transects. To avoid the boundary issues and the temperature instability at the inflow area, we used transect records within 20 m of the boundary. Since we conducted replicate traverses for each transect, we compared the mean observed temperature values with the simulated temperature at each location. In the existing research with ENVI-met, the root mean squared error (RMSE) and mean absolute error (MAE) of air temperature are reported to be typically around 1-2 ^{o}C (Middel et al., 2014, 2015). In our validation, the RMSE is 1.1 ^{o}C in the morning and 2.1 ^{o}C in the afternoon, and the MAE is 1.1 ^{o}C in the morning and 2.0 ^{o}C in the afternoon. Further, we calculated the systematic RMSE ($RMSE_S$) and unsystematic RMSE ($RMSE_U$). As shown in Table 5, the error in the simulated temperature is predominantly systematic. Since we are more interested in the temperature difference between different tree location and arrangement scenarios, the systematic errors should cancel after calculating the temperature difference. Thus, we believe the ENVI-met simulations provide reliable microclimate output for this comparison effort.

In the validation results, ENVI-met simulated temperature was consistently higher than the validated temperature transects. Several issues may influence the simulated temperature and field temperature measurements. First, we did not model shrubbery in the ENVI-met study domain, which would provide extra cooling for the study area. Further, GPS location errors and thermocouples accuracy may also influence the air temperature transect results. Lastly, ENVI-met requires a single wind direction that it maintains for the entire simulation period; we used the prevailing wind direction on 13 June, which was from the southwest. Clearly, this introduces additional uncertainty into the model results. Despite these limitations, ENVI-met does appear to capture the spatial location of local maxima in air temperature across the neighborhood in both morning and afternoon transects (shown in the red rectangular in Figure 7). This provides additional assurance of the model effectiveness for further simulation. We observe an unusual spike (0.2 ^{o}C temperature increase) in the thermocouple record at 95m in the Figure 7(a). The reason of this spike is unknown, but it may happen because of the measurement flutuation of thermocouple.



(a) Morning validation results.



(b) Afternoon validation results.

Figure 7 Fieldwork temperature validation comparison.

Table 5 Temperature differences between the simulated and validated dataset

	RMSE (°C)	MAE (°C)	$RMSE_S$ (°C)	$RMSE_U$ (°C)
Morning (7:00)	1.1	1.1	1.1	0.2
Afternoon (16:00)	2.1	2.0	2.1	0.1

4.2 Numerical Simulation Results

4.2.1 Outdoor Microclimates Comparison

To compare how tree densities, locations, and arrangements influence the outdoor microclimates, we extracted 1.5 m air temperature at the hottest time in the summer afternoon (15:00) for all 9 scenarios. We selected 4 buildings at the center of the study domain (building 3, 4, 5, and 6, Figure 5) and calculated the mean temperature of their entire south front yard to represent the neighborhood temperature. Results are shown in Figure 8. In the one tree scenarios, locating a single tree on the west side of the house front yard provides the most air temperature cooling benefit to the neighborhood (0.11 °C air temperature cooling compared to no tree scenario). The worst case is planting trees at the east side of front yard because most of the afternoon shading is projected to the front yard of the adjacent parcel. When planting two trees in each residential parcel, an equal interval tree arrangement generates the largest mean cooling benefit for the neighborhood (0.19 °C air temperature cooling compared to no tree scenario). Clustered tree arrangement with overlap produces the least cooling benefit.

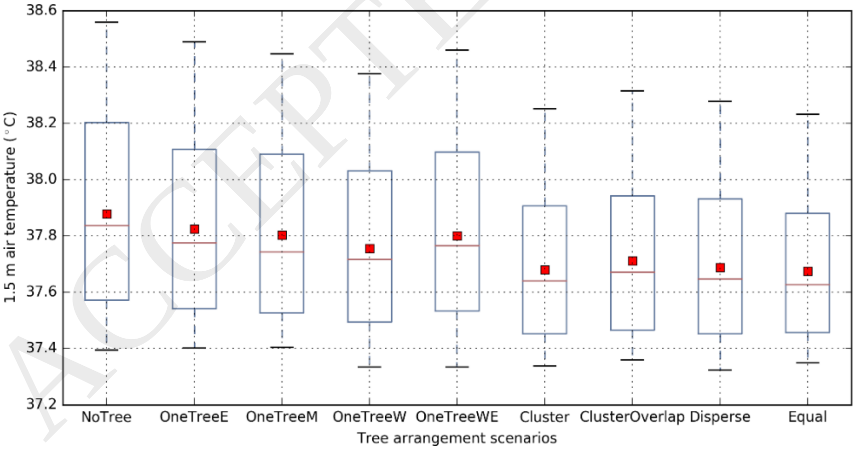


Figure 8 Boxplots of 1.5m air temperature comparison under different tree arrangement scenarios. (The upper and lower bounds of the box plots indicate the 25th and 75th percentile of the values, the whiskers represent the 5th and 90th percentiles, the red points show the mean value, and the red lines illustrate the median value)

Mean radiant temperature, which sums all short wave and long wave radiation fluxes to the human body (Thorsson et al., 2007), is one of the most important factors that influences the human thermal comfort. In Figure 9, we show how 1.5 m MRTs vary in all different scenarios at 15:00. Planting one tree in the middle of building south front yard can produce approximately 5.3 °C mean cooling benefit of MRT to the neighborhood. The best one tree arrangement (establish one tree in the middle of front yard) offers 0.6 °C more mean MRT cooling benefit than the worst one tree arrangement (plant one tree in the west/east of front yard). Adding the second tree into the neighborhood can generate another 5.3 °C mean cooling benefit (10.6 °C MRT cooling benefit compared to no tree scenario) when these trees are equally distributed. The best two trees arrangement (equal interval) provides 1.2 °C more mean MRT cooling benefit than the worst two trees arrangement (dispersed).

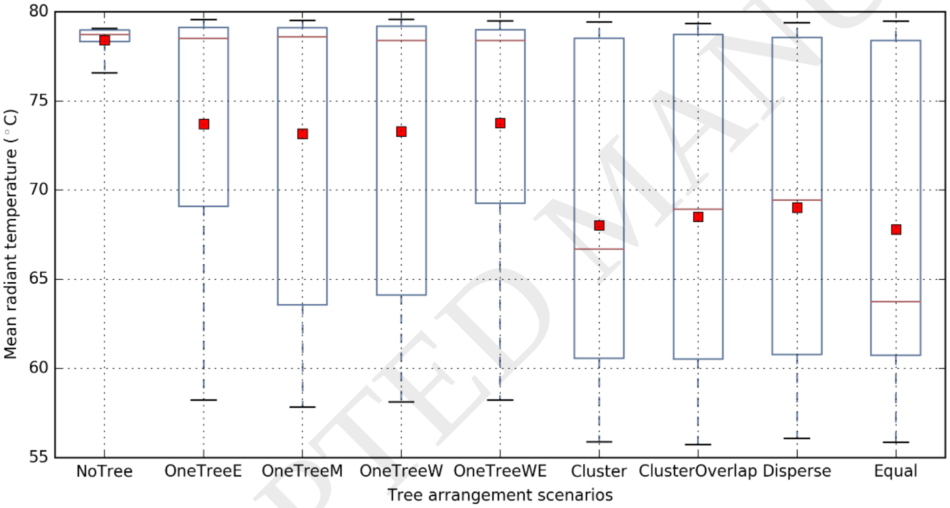


Figure 9 Boxplots of MRT comparison under different tree arrangement scenarios

Neighborhood wind speed comparison is shown in Figure 10 under different tree locations and arrangements scenarios at 15:00. Increasing tree densities in the neighborhood decreases the neighborhood wind speed. When we locate the first residential shade tree in the building south front yard, the mean wind speed decreases by 0.1 m/s. With the second residential shade tree, the mean wind speed further decrease by 0.05 m/s. When locating one tree in the middle of the front yard, trees had the least influence to the wind environment. After adding another tree to each house's front yard, the clustered tree arrangement with overlap had the highest wind speed in the neighborhood. In this tree arrangement, trees are clustered in the middle of the front yard and do not block the wind corridor between buildings. The wind speeds of clustered arrangement without overlap and equal interval arrangement are very similar to each other.

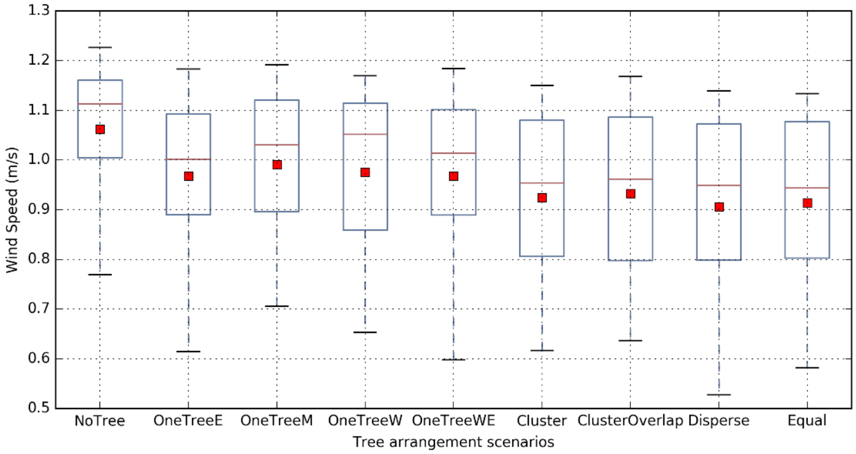


Figure 10 Boxplots of wind speed comparison under different tree arrangement scenarios

4.2.2 Human Thermal Comfort Comparison

With the simulated air temperature, relative humidity, wind speed, and MRT, we simulated the PET at 1.5 m for both the entire neighborhood and two individual parcels in the neighborhood. Figure 11 shows the PET comparison in the residential neighborhood at 15:00. To achieve the best PET at 1.5 m, equal two trees arrangement is the best option to reduce mean PET from 50.5 ^{o}C (no tree) to 49.6 ^{o}C. If the residents only plan to plant one tree in their front yard, a single tree in the middle of the front yard offers the most human thermal comfort by decreasing mean PET from 50.5 ^{o}C to 50.1 ^{o}C.

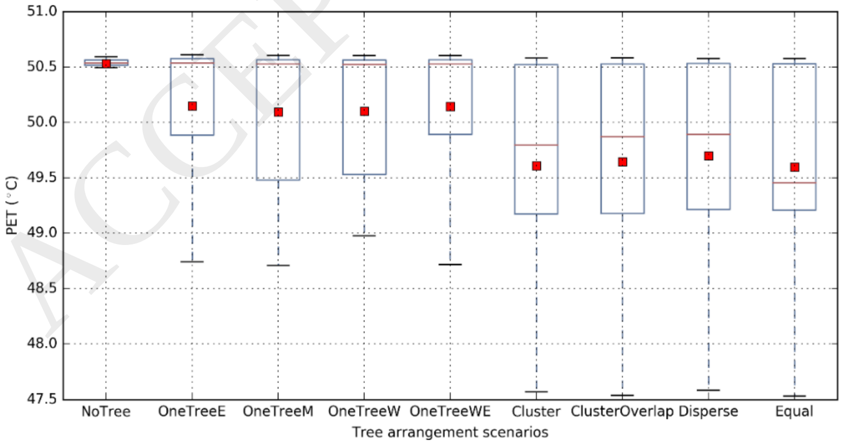
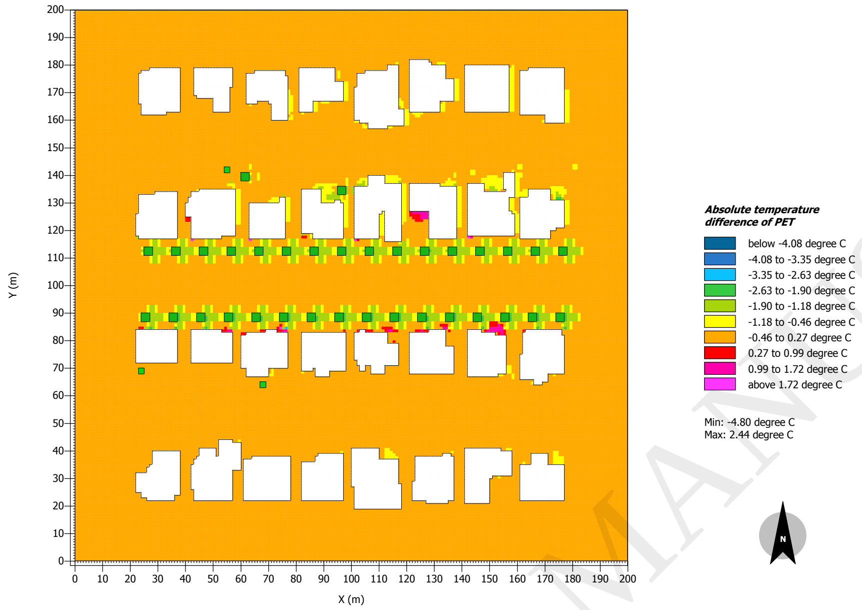
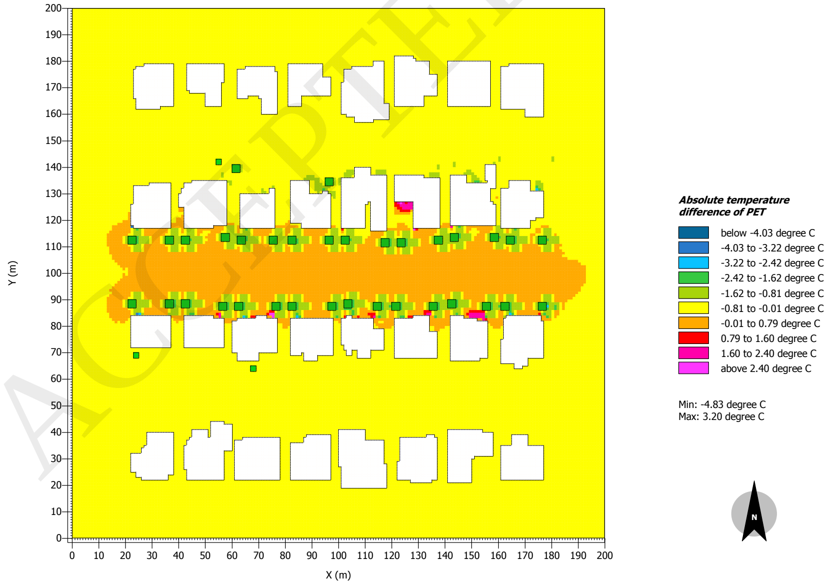


Figure 11 Boxplots of PET comparison under different tree arrangement scenarios in the neighborhood

Figure 12 shows two examples of the PET temperature difference at 15:00. Each of the single trees can induce around 1-1.5 ^{o}C cooling benefit to the human thermal comfort at the pedestrian level. With an equal interval tree arrangement (Figure 12a), PET reduction from trees were more homogeneous in the neighborhood comparing to the dispersed tree arrangement, and less cooling benefit were overlapped in the equal interval tree arrangement.



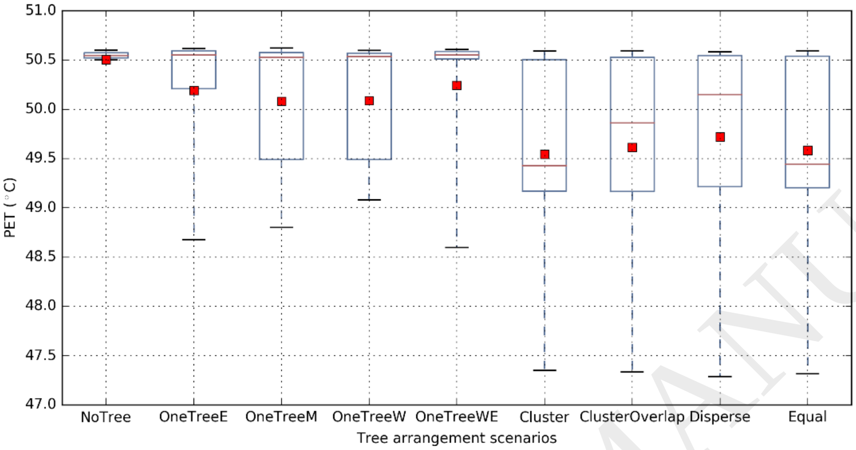
(a) Two trees equal arrangement scenario vs. no tree scenario.



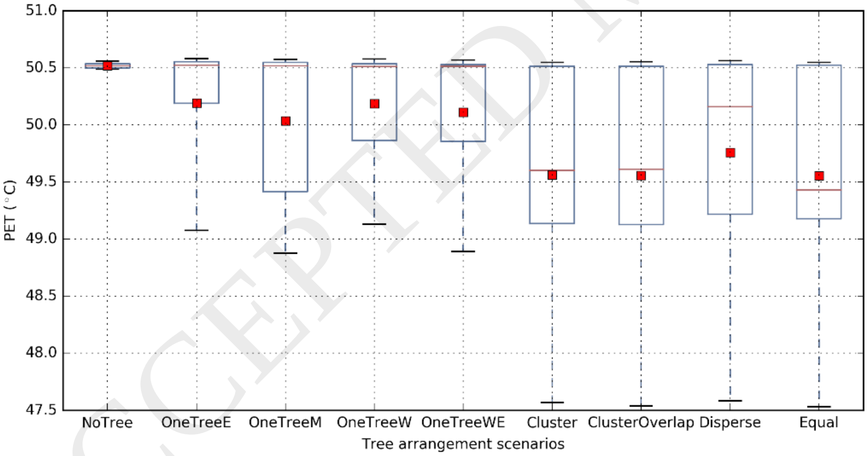
(b) Two trees dispersed arrangement scenario vs. no tree scenario.

Figure 12 PET temperature difference scenarios (green squares represent the tree locations).

Moreover, we picked two individual parcels to understand how tree locations and arrangements influence their front yard human thermal comfort at 15:00. The PET comparison is shown in Figure 13. The overall results are similar to the neighborhood scale, but we can observe a difference when locating one tree at the west/east corner of the building. Because two individual trees were located between building 5 and 6 (Figure 5) and most of the afternoon shading cast to the building 6's front yard. This specific tree arrangement results in evident cooling benefit on the building 6 as showed in Figure 13b.



(a) Individual parcel (building 5).



(b) Individual parcel (building 6).

Figure 13 Boxplots of PET comparison under different tree arrangement scenarios for two individual parcels

5 Discussion

Our simulation model demonstrated that effective tree locations and arrangements can improve outdoor microclimates and human thermal comfort. The research results first confirm that higher tree densities contribute more cooling benefits to human thermal comfort (PET) than to the outdoor air temperature alone. Further, the comparison between different tree locations and arrangement scenarios reveals the importance of arranging residential shade trees. To maximize the tree cooling benefits, the results suggest the following guidelines: avoid tree canopy overlap; provide more shading to buildings; and create effective ventilation conditions by avoiding blocking existing wind corridors between buildings. Because radiation exchange is often the principal factor influencing desert microclimate conditions (Shashua-Bar et al., 2011), MRT is the most important factor influencing human thermal comfort in the residential neighborhood.

By comparing the cooling benefits in the entire neighborhood and individual parcels, tree cooling benefits to the neighborhood and individual parcels are not contradicted. Multiple individual "cold spots" with effective tree arrangements in the neighborhood create an overall cooler neighborhood. This finding emphasizes the importance of wisely designing tree locations and arrangements in the individual house front yard. An appropriate tree arrangement will not only benefit the house owners, but also benefit the overall thermal environment in the residential neighborhood.

Although conventional wisdom recommends planting residential shade trees at the southwest corner of the building front yard for maximum shade benefits to houses, our simulation results show that this strategy does not result in the most effective neighborhood cooling. The air temperature comparison show that locate a single tree at the west corner can provide the most temperature cooling benefits, however, the cooling magnitude is relatively small (0.11 ^{o}C air temperature cooling). When locating a single tree in the middle of the front yard, we will lose 0.05 ^{o}C air temperature cooling benefits, but gain 0.14 ^{o}C cooling of MRT, which is three times that of the air temperature cooling benefit. Both the west and the central front yard arrangements are a reasonable choice to plant a single residential shade tree in the modelled climate.

It is noteworthy that the two most effective strategies for improving neighborhood thermal comfort are (1) locating a single tree in the middle of the front yard and (2) locating two trees at equal intervals, both of which reduce PET by 1-1.5 ^{o}C across the neighborhood. The cooling benefits from trees can actually decrease the human thermal comfort level from "extra hot" to "very hot" in this hot summer day (Crewe et al., 2016). Both tree arrangement scenarios correspond with findings in Zhao et al. (2017). These results support that the best tree arrangement can provide the best shading benefits to the outdoor human thermal comfort as well as the buildings. In a neighborhood without homeowner association (HOA) regulations, it is difficult to arrange residential trees in a strictly equal interval arrangement. Thus, it is important to make the urban residents understand the importance of tree shade in the hot arid desert environment and offer advice when they attempt to plant a new tree to their residential parcel. For a residential neighborhoods with HOA regulations, adding a maximum tree number regulation and emphasizing the importance of avoiding tree canopy overlap is important and necessary.

In a desert city, evapotranspiration is largely inhibited by extreme heat (Upreti et al., 2017). Thus, radiation exchange is the dominant factor to influence the overall urban thermal environment. The tree locations and arrangements recommendation in this research may not be effective in another climate zone such as the tropical monsoon climate cities. In a hot humid environment, both shading and ventilation are important factors to be considered. In other climates, excessive clustered tree arrangement may reduce the wind speed and decrease the evaporation rate of people's skin, which will have a detrimental effect on human thermal comfort (Hsieh et al., 2016). The best tree arrangement will be expected to find the balance of shading benefits as well as satisfactory wind environment in the residential neighborhood.

Several limitations exist in this research. Although the microclimates and human thermal benefits from residential trees are very important, we did not account for the ecological, aesthetic, health, and physiological benefits of trees (Roy et al., 2012; Sarajevs, 2011). Nor did we consider the role of irrigation requirements. Further, we only used one common desert shade tree in the simulation. It provided limited coverage of tree shade with its needle leaves. Other tree species with different tree height, leaf area index, canopy density, and crown size may recommend different results from this research (Armson et al., 2013). The tree growing process can also be considered in the future research to understand how trees will influence the urban built environment in a long time period (Rahman et al., 2015). Lastly, vehicle-based validation transects (especially during the night time) need to be repeated more frequently in a 24-hours period with higher accuracy GPS sensors, and it would be expedient to set up a small weather station to measure the air temperature, relative humidity, and wind speed in the experimental neighborhood. This will further improve the overall microclimate simulation and validation results.

6 Conclusions

Trees provide important benefits to outdoor microclimates and human thermal comfort in the desert environment. Considering the planting, maintenance, and irrigation costs, it is important to maximize tree benefits with limited number of trees. This research uses microclimate numerical simulation to explore how best to arrange trees to benefit both individual households and residential neighborhoods. The flexibility of numerical models makes it possible to simulate and compare the outdoor microclimates and human thermal comfort under a wide range of tree locations and arrangements. We recommend that urban residents plant shade trees without canopy overlap. If possible, trees should not block wind corridors or impede air movement. This research is one of the pioneering attempts to explore the importance of tree locations and arrangements, and investigate tree benefits for both individual parcels and residential neighborhoods. The research results will help guide the design of urban vegetation and HOA regulations for the long-term sustainability of urban desert environments.

Acknowledgements

This material is based upon work supported by the National Science Foundation under grant number DEB-1637590, Central Arizona-Phoenix Long-Term Ecological Research (CAP-LTER) and supported in part by the National Aeronautical and Space Association under award number #3-LCLUC13-2-0012. Any opinions, findings, and conclusions expressed in this material are those of the author(s) and do not necessarily reflect the views of National Science Foundation and National Aeronautical and Space Association. The first author is partly supported by the Dissertation Research Grant from American Association of Geographers. The authors would like to thank the anonymous reviewers for their valuable comments and suggestions to improve the manuscript.

Reference

Armson, D., Rahman, M.A., Ennos, A.R., 2013. A comparison of the shading effectiveness of five different street tree species in Manchester, UK. Arboric. Urban For. 39, 157–164.

Bi, P., Williams, S., Loughnan, M., Lloyd, G., Hansen, A., Kjellstrom, T., Dear, K., Saniotis, A., 2011. The Effects of Extreme Heat on Human Mortality and Morbidity in Australia: Implications for Public Health. Asia. Pac. J. Public Health 1010539510391644. https://doi.org/10.1177/1010539510391644

Bruse, M., Fleer, H., 1998. Simulating surface–plant–air interactions inside urban environments with a three dimensional numerical model. Environ. Model. Softw. 13, 373–384.

Chen, L., Ng, E., 2013. Simulation of the effect of downtown greenery on thermal comfort in subtropical climate using PET index: a case study in Hong Kong. Archit. Sci. Rev. 56, 297–305. https://doi.org/10.1080/00038628.2012.684871

Chow, W.T.L., Chuang, W.-C., Gober, P., 2012. Vulnerability to Extreme Heat in Metropolitan Phoenix: Spatial, Temporal, and Demographic Dimensions. Prof. Geogr. 64, 286–302. https://doi.org/10.1080/00330124.2011.600225

Crewe, K., Brazel, A., Middel, A., 2016. Desert New Urbanism: testing for comfort in downtown Tempe, Arizona. J. Urban Des. 1–18. https://doi.org/10.1080/13574809.2016.1187558

Declet-Barreto, J., Brazel, A.J., Martin, C.A., Chow, W.T.L., Harlan, S.L., 2013. Creating the park cool island in an inner-city neighborhood: heat mitigation strategy for Phoenix, AZ. Urban Ecosyst. 16, 617–635. https://doi.org/10.1007/s11252-012-0278-8

Erell, E., Pearlmutter, D., Williamson, T.J., 2011. Urban microclimate: designing the spaces between buildings, 1st ed. ed. Earthscan, London ; Washington, DC.

Fan, C., Myint, S.W., Zheng, B., 2015. Measuring the spatial arrangement of urban vegetation and its impacts on seasonal surface temperatures. Prog. Phys. Geogr. 39, 199–219. https://doi.org/10.1177/0309133314567583

Höppe, P., 1999. The physiological equivalent temperature–a universal index for the biometeorological assessment of the thermal environment. Int. J. Biometeorol. 43, 71–75.

Hsieh, C.-M., Jan, F.-C., Zhang, L., 2016. A simplified assessment of how tree allocation, wind environment, and shading affect human comfort. Urban For. Urban Green. 18, 126–137. https://doi.org/10.1016/j.ufug.2016.05.006

Huang, Y.J., Akbari, H., Taha, H., Rosenfeld, A.H., 1987. The potential of vegetation in reducing summer cooling loads in residential buildings. J. Clim. Appl. Meteorol. 26, 1103–1116.

ISO 8996, 2004. , Ergonomics of the thermal environment -- Determination of metabolic rate.

ISO 9920, 2007. , Ergonomics of the thermal environment -- Estimation of thermal insulation and water vapour resistance of a clothing ensemble.

Jan, F.-C., Hsieh, C.-M., Ishikawa, M., Sun, Y.-H., 2013. The Influence of Tree Allocation and Tree Transpiration on the Urban Microclimate: An Analysis of a Subtropical Urban Park. Environ. Urban. ASIA 4, 135–150. https://doi.org/10.1177/0975425313477751

Kong, L., Lau, K.K.-L., Yuan, C., Chen, Y., Xu, Y., Ren, C., Ng, E., 2017. Regulation of Outdoor Thermal Comfort by Trees in Hong Kong. Sustain. Cities Soc. https://doi.org/10.1016/j.scs.2017.01.018

Maricopa County Assessor’s Office [WWW Document], n.d. URL https://mcassessor.maricopa.gov/index.php (accessed 9.11.17).

Martin, C., n.d. Virtual Library of Phoenix Landscape Plants [WWW Document]. URL http://www.public.asu.edu/~camartin/Martin%20landscape%20plant%20library.htm (accessed 7.17.17).

Mayer, H., Höppe, P., 1987. Thermal comfort of man in different urban environments. Theor. Appl. Climatol. 38, 43–49.

Middel, A., Chhetri, N., Quay, R., 2015. Urban forestry and cool roofs: Assessment of heat mitigation strategies in Phoenix residential neighborhoods. Urban For. Urban Green. 14, 178–186. https://doi.org/10.1016/j.ufug.2014.09.010

Middel, A., Häb, K., Brazel, A.J., Martin, C.A., Guhathakurta, S., 2014. Impact of urban form and design on mid-afternoon microclimate in Phoenix Local Climate Zones. Landsc. Urban Plan. 122, 16–28. https://doi.org/10.1016/j.landurbplan.2013.11.004

Morakinyo, T.E., Kong, L., Lau, K.K.-L., Yuan, C., Ng, E., 2017. A study on the impact of shadow-cast and tree species on in-canyon and neighborhood’s thermal comfort. Build. Environ. https://doi.org/10.1016/j.buildenv.2017.01.005

Myint, S.W., Wentz, E.A., Brazel, A.J., Quattrochi, D.A., 2013. The impact of distinct anthropogenic and vegetation features on urban warming. Landsc. Ecol. 28, 959–978. https://doi.org/10.1007/s10980-013-9868-y

Myint, S.W., Zheng, B., Talen, E., Fan, C., Kaplan, S., Middel, A., Smith, M., Huang, H.-P., Brazel, A., 2015. Does the spatial arrangement of urban landscape matter? Examples of urban warming and cooling in Phoenix and Las Vegas. Ecosyst. Health Sustain. 1, art15. https://doi.org/10.1890/EHS14-0028.1

Nazaroff, W.W., 2013. Exploring the consequences of climate change for indoor air quality. Environ. Res. Lett. 8, 015022. https://doi.org/10.1088/1748-9326/8/1/015022

Oke, T.R., 1992. Boundary layer climates. Routledge, London; New York.

Oke, T.R., 1982. The energetic basis of the urban heat island. Q. J. R. Meteorol. Soc. 108, 1–24. https://doi.org/10.1002/qj.49710845502

Rahman, M.A., Armson, D., Ennos, A.R., 2015. A comparison of the growth and cooling effectiveness of five commonly planted urban tree species. Urban Ecosyst. 18, 371–389. https://doi.org/10.1007/s11252-014-0407-7

Roy, S., Byrne, J., Pickering, C., 2012. A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones. Urban For. Urban Green. 11, 351–363. https://doi.org/10.1016/j.ufug.2012.06.006

Santamouris, M., 2013. Energy and Climate in the Urban Built Environment. Routledge.

Sarajevs, V., 2011. Health benefits of street trees. Res. Agency For. Comm.

Shashua-Bar, L., Pearlmutter, D., Erell, E., 2011. The influence of trees and grass on outdoor thermal comfort in a hot-arid environment. Int. J. Climatol. 31, 1498–1506. https://doi.org/10.1002/joc.2177

Song, J., Wang, Z.-H., 2015. Impacts of mesic and xeric urban vegetation on outdoor thermal comfort and microclimate in Phoenix, AZ. Build. Environ. 94, Part 2, 558–568. https://doi.org/10.1016/j.buildenv.2015.10.016

Tan, Z., Lau, K.K.-L., Ng, E., 2017. Planning strategies for roadside tree planting and outdoor comfort enhancement in subtropical high-density urban areas. Build. Environ. https://doi.org/10.1016/j.buildenv.2017.05.017

Tan, Z., Lau, K.K.-L., Ng, E., 2015. Urban tree design approaches for mitigating daytime urban heat island effects in a high-density urban environment. Energy Build. https://doi.org/10.1016/j.enbuild.2015.06.031

Thorsson, S., Lindberg, F., Eliasson, I., Holmer, B., 2007. Different methods for estimating the mean radiant temperature in an outdoor urban setting. Int. J. Climatol. 27, 1983–1993. https://doi.org/10.1002/joc.1537

Upreti, R., Wang, Z.-H., Yang, J., 2017. Radiative shading effect of urban trees on cooling the regional built environment. Urban For. Urban Green. 26, 18–24. https://doi.org/10.1016/j.ufug.2017.05.008

Vanos, J.K., Middel, A., McKercher, G.R., Kuras, E.R., Ruddell, B.L., 2016. Hot playgrounds and children’s health: A multiscale analysis of surface temperatures in Arizona, USA. Landsc. Urban Plan. 146, 29–42. https://doi.org/10.1016/j.landurbplan.2015.10.007

Wang, Z.-H., Zhao, X., Yang, J., Song, J., 2016. Cooling and energy saving potentials of shade trees and urban lawns in a desert city. Appl. Energy 161, 437–444. https://doi.org/10.1016/j.apenergy.2015.10.047

Wentz, E.A., Rode, S., Li, X., Tellman, E.M., Turner, B.L., 2016. Impact of Homeowner Association (HOA) landscaping guidelines on residential water use. Water Resour. Res. n/a-n/a. https://doi.org/10.1002/2015WR018238

WRCC [WWW Document], 2015. URL https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?az8499 (accessed 7.9.17).

Yang, A.-S., Juan, Y.-H., Wen, C.-Y., Chang, C.-J., 2017. Numerical simulation of cooling effect of vegetation enhancement in a subtropical urban park. Appl. Energy 192, 178–200. https://doi.org/10.1016/j.apenergy.2017.01.079

Zhao, Q., 2017. Evaluating the Effectiveness of Tree Locations and Arrangements for Improving Urban Thermal Environment (PhD Thesis). ARIZONA STATE UNIVERSITY.

Zhao, Q., Myint, S.W., Wentz, E.A., Fan, C., 2015. Rooftop Surface Temperature Analysis in an Urban Residential Environment. Remote Sens. 7, 12135–12159. https://doi.org/10.3390/rs70912135

Zhao, Q., Wentz, E.A., 2016. A MODIS/ASTER Airborne Simulator (MASTER) Imagery for Urban Heat Island Research. Data 1. https://doi.org/10.3390/data1010007

Zhao, Q., Wentz, E.A., Murray, A.T., 2017. Tree shade coverage optimization in an urban residential environment. Build. Environ. 115, 269–280. https://doi.org/10.1016/j.buildenv.2017.01.036

Zhao, Q., Wentz, E.A., Murray, A.T., 2014. Shade Optimization in a Desert Environment, in: Extended Abstract Proceedings of the GIScience 2014. Presented at the 8th International Conference on Geographic Information Science, pp. 118–121.

Zhao, Q., Yang, J., Wang, Z.-H., Wentz, E., 2018. Assessing the Cooling Benefits of Tree Shade by an Outdoor Urban Physical Scale Model at Tempe, AZ. Urban Sci. 2, 4. https://doi.org/10.3390/urbansci2010004