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Assessing xeriscaping as a sustainable heat island mitigation approach for a desert city

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ABSTRACT

Metropolitan Phoenix has been amongst the most rapidly urbanizing cities in the USA, and is also subject to an urban heat island (UHI) of significant intensity and extent. There is a need to mitigate its detrimental effects through sustainable methods, such as through the application of low-water demand, xerophytic trees with broad canopies within residential yards (i.e. xeriscaping). Urban xeriscaping has the potential to reduce urban water use, urban temperatures and outdoor thermal discomfort, but evaluating its effectiveness has not been widely researched. In this study, we used a micro-scale urban climate model (ENVI-met) to generate xeriscaping scenarios in two residential areas with different existing surface vegetation cover (mesic vs. xeric). We subsequently examined the resulting impacts of xeriscaping on near-surface temperatures and outdoor thermal comfort over different spatial scales and temporal periods. Compared to existing conditions, xerophytic shade trees have strong UHI mitigation potential in existing xeric residential areas in Phoenix, with greater cooling occurring at (i.) microscales (~2.5 °C) vs. local-scales (~1.1 °C), and during (ii.) nocturnal (0500 h) vs. daytime periods (1700 h) under high xeriscaping scenarios. Conversely, increased xeriscaping resulted in net warming and increased thermal discomfort over mesic residential neighborhoods over all spatial scales and temporal periods. These varying results over different residential land cover in Phoenix therefore must be considered by stakeholders when considering xeriscaping as a UHI mitigation method.

1. Introduction

1.1. Urbanization in Phoenix and the heat island

The urbanization process results in a corresponding increase of urban temperatures compared to its rural surroundings. This phenomenon is termed the "Urban Heat Island" (UHI), and is frequently observed in cities for all climate types [44,48]. Several factors attributed to surface land-use/land cover (LULC) change from urbanization have been hypothesized to explain UHI causation. These include: (i.) increased absorption of short-wave radiation, (ii.) increased storage of sensible heat, (iii.) anthropogenic heat production, (iv.) reduced long-wave radiation loss, (v.) lower evapotranspiration rates, and (vi.) lower sensible heat loss due to reduced turbulence in urban canyons [39]. Other factors, such as synoptic weather conditions (wind-speed, cloud amount and height), topography, urban morphology, and city size, potentially modify maximum magnitudes of UHI intensity [3].

The Southwest region of the USA, which includes the states of Nevada, California and Arizona, has experienced the largest rates of urbanization in the country over the past forty years. One example of this rapid urban growth is the large metropolitan area consisting of Phoenix, Arizona, and its associated satellite cities. Metropolitan Phoenix has been among the country's fastest growing urban areas, with population increasing from 1.04 to 4.36 million residents from 1970 to 2009 [54]. This change is also reflected in significant LULC alterations. For instance, ~2553 km^2 of agricultural and desert land underwent conversion to urban surfaces from 1973 to 2003 [50], with the majority of development manifest as low-rise suburban residential areas [18]. Unsurprisingly, the magnitude of metropolitan Phoenix's UHI intensity, and the size of its spatial extent, has also increased in conjunction with its urbanization [7]. Summer UHI intensities can attain magnitudes of ~5 °C between Phoenix and its desert surroundings [6] (Fig. 1), with largest differences in urban-rural air temperatures often observed at night [51].

Although some benefits can arise from increased urban warmth, such as reduced residential heating during winter, the Phoenix UHI generally has detrimental biophysical impacts (e.g. thermal discomfort) towards humans and other flora and fauna [4].

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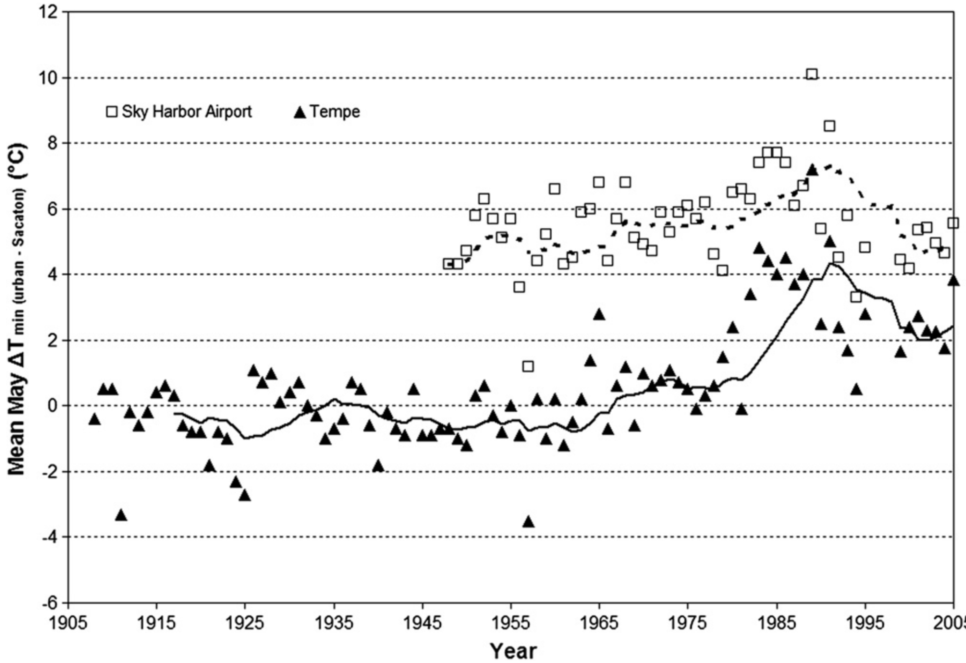

Fig. 1. Mean UHI intensity measured by the difference between mean May minimum temperatures measured at (1) Sky Harbor airport (from 1948 to 2005) and (2) Tempe meteorological station (from 1908 to 2005) with Sacaton, a meteorological station sited ~25 km away from metropolitan Phoenix. These are updated temperature time-series data based on Fig. 4d from [6]. Smoothed lines represent 10-year moving average for each station. Note rapid growth of UHI intensity post-1970.

Increased peak and total urban demand of energy [20], and residential water consumption [5], have also been observed. With mean July maximum temperatures regularly exceeding 40 °C, metropolitan Phoenix residents are subject to high daytime physical exposure to heat. A strong nocturnal UHI likely exacerbates this exposure and potentially increases residential vulnerability to heat extremes, especially with limited socio-economic capacity to adapt to such changes [11,26,53]. Further, increasing vulnerability to extreme temperatures in Phoenix can be compounded by projected climate change impacts in the Southwest U.S., which likely include higher mean temperatures and less precipitation [13].

1.2. Urban forestry as an UHI mitigation technique in Phoenix

Although there is research into modifying urban geometry [17,41] and increasing urban surface albedo and emissivity [21,45], a large body of UHI mitigation studies in arid and semi-arid cities focus on applying urban forestry at various spatial scales (e.g. through urban parks, residential yards or rooftop gardens). This method increases the urban extent of green-spaces and permeable surfaces through turf grass and/or shade trees. Urban forestry thus alters the urban surface energy balance through increasing latent heat fluxes through evapotranspiration, and reducing net urban heat storage with permeable soils [52]. Further, vegetation canopy shading also directly reduces net energy absorbed at the surface. There is much empirical evidence of green-spaces significantly reducing surface and air temperatures adjacent to urban surfaces at various spatial and temporal scales [27,42,46,47,49]. Cooling effectiveness of urban forests are influenced by several factors, such as size and ratio of green-spaces to urban area [57], and by increased urban wind-speeds and advective flux [12]. Urban forests also have other potential physical and social benefits, such as improving air quality, decreasing biodiversity loss, and providing recreational areas for residents [33]. Conversely, the effectiveness of urban forestry may be diminished by large amounts of water required for irrigation [24], which is of scarce supply in arid cities.

Urban forestry is prevalent in older residential suburbs of Phoenix, where residential landscaping of yards with ample turf grass and large non-native shade trees (i.e. mesic landscapes) were used to reduce ambient temperatures before the widespread use of air conditioning [18].

Given its climate, however, the widespread use of these water-intensive landscapes would be contrary to the city's long-term sustainability, especially under recent and projected future drought conditions. Hence, there has been recent focus towards using sustainable UHI mitigation methods. The aim is to create microclimates that moderate the properties of the background synoptic-scale climate, as well as to reduce the general profligacy of urban resource use [36,37]. One method is the practical use of low-water demand plants (i.e. xerophytic flora adapted to arid climates) in residential yards to both mitigate UHI and reduce urban water use. The importance of this "xeriscaping" method has been recognized by several cities within metropolitan Phoenix; for instance, the suburban cities of Tempe, Mesa and Glendale have successful programs offering financial incentives for homeowners to xeriscape. It could be argued that xeriscaping is the most pragmatic option of UHI mitigation when compared to others in metropolitan Phoenix; for example, there are practical difficulties of maintaining effectiveness of high-albedo surfaces over large spatial scales where dust storms and urban air pollution may reduce albedo over time [43], and it may not be financially feasible for large-scale (re) construction of existing high-density residential areas with new "cool" materials with high thermal inertia.

Previous research on urban forestry in Phoenix examined several of its physical aspects. One study observed micro-scale temperature variations within a small residential study area with respect to changes in surface vegetation [30]. Lower surface and near-surface temperatures were observed over mesic surfaces with ample irrigation compared to non-mesic surfaces, highlighting the influence of evapotranspirative cooling. Another study modeled the impact of increased vegetation on temperature and thermal comfort in downtown Phoenix, but not in residential suburbs [16].

No discernable improvements in thermal comfort was found using regularly-spaced shade trees when compared to other UHI mitigation methods, such as increases in surface albedo or more dense urban canyon configurations.

The LUMPS model [22] was used to study the effect of three urban forestry scenarios for 10 census tracts in Phoenix with differing neighborhood types (i.e. industrial, mesic and xeric residential areas) [19]. Each selected census tract varied from 1 to 2.6 km^2 in size. Increases in irrigated landscaping were strongly correlated to decreased UHI intensities, but this relationship was non-linear, with greatest (least) reductions in xeric (mesic) neighborhoods. One scenario replaced 10% of combined grass surfaces and trees in modeled neighborhoods with unmanaged soils to simulate urban water conservation conditions. Rates of urban cooling significantly decreased by 0.16–0.39 °C h^{-1}, and all modeled study areas (especially in xeric neighborhoods) experienced increased UHI intensities. Lastly, another LUMPS study simulated xeriscaping scenarios for 52 city of Phoenix census tracts, through removal of all grass surfaces and by increasing unmanaged soil by 20–45% [35]. Decreases in mean cooling rate and increased UHI intensity within census tracts were also documented in these scenarios. Both these studies, however, did not examine temperature impacts at spatial scales smaller than a census tract.

1.3. Study objectives

There has not been examination of xeriscaping to mitigate UHI within residential areas, especially on its explicit influence over both different spatial scales (i.e. micro- vs. local), and different residential surface types (i.e. xeric vs. mesic surfaces). We investigated the impacts of xeriscaping on air temperatures and thermal comfort within two distinct metropolitan Phoenix residential areas. We applied a micro-scale urban climate model (ENVI-met 3.1) that was first assessed for accuracy with observed hourly temperature data at meteorological stations located within each study site. Several key model parameters for surface vegetation cover and quantity were subsequently modified for each residential area under different mitigation scenarios. Simulations were also conducted during an extreme heat event (EHE) in Phoenix to coincide with high levels of physical exposure and biophysical discomfort to residents, so as to analyze the potential xeriscaping impacts during periods of very high heat exposure. We intend to answer the following questions: (i.) Are there notable differences in near-surface temperature and thermal comfort through increasing levels of xeriscaping over different residential areas during an extreme heat event in Phoenix? (ii.) How do the impacts of xeriscaping on air temperatures vary over different spatial scales and temporal periods?

2. Methods

2.1. Study areas

We selected two suburban residential neighborhoods in metropolitan Phoenix with differing surface land cover characteristics; Tempe (TMP) and West Phoenix (WPHX) (Table 1). Both study areas largely consist of single-story residential houses of similar construction materials and building heights (mean roof height $z = \sim 4$ m), but each differ in lot size and land cover type. Residential lot sizes in TMP are generally larger (from 1000 to 2600 m^2) vs. WPHX ($\sim$700 m^2), resulting in WPHX having more housing lots (245 vs. 129 units). Second, landscaped surfaces in TMP consist of mesic surfaces in the front and back yards of every residential lot, while landscaping in WPHX typically consisted of bare soil and/or gravel mulch, with significantly less lots having either mesic or xerophytic vegetation (Fig. 2). Another important distinction between sites is while land cover at the WPHX study area was representative of LULC within the larger-scale (i.e. up to 2.59 km^2) residential area, the TMP site was adjacent to a recreational park of substantial size ($\sim$8 ha) which had an extensive irrigated turf grass surface. This park space notably differed from the surrounding residential land-use. A small portion of the park ($\sim$150 × 40 m) was included at the SE corner of the study area.

These sites each represented distinct LULC categories that comprise the vast majority of metropolitan Phoenix land-use i.e. either as mesic or xeric residential areas [50]. Each site also lies within census tracts classified as highly vulnerable to extreme heat over a ten year period [11]. Further, both TMP and WPHX had meteorological stations (maintained by the Maricopa County Air Quality Department) located within each study area that recorded hourly observations of local near-surface climate data, such as temperature, relative humidity, wind-speed and wind direction. These data would be essential for model evaluation.

2.2. Urban climate modeling

We applied the ENVI-met climate model (Version 3.1 Beta 5) to simulate UHI mitigation scenarios for this study. ENVI-met is a computational fluid dynamics model based on several principles of fluid mechanics (e.g. mean air flow is based on Boussinesq-approximated non-hydrostatic Navier–Stokes equations), thermodynamics (e.g. advection-diffusion equation is utilized to distribute atmospheric temperature and specific humidity) and atmospheric physics (e.g. prognosis of turbulence and stability through E-epsilon equations to simulate distribution of turbulent energy) [9]. In brief, the main 3-d atmospheric model extends from the surface to about twice the height of the highest building or obstacle z_{max}

Table 1
Site characteristics and typical landscaping vegetation.

Study area (LULC category)	No. of housing lots	% lots with grass cover	% lots with at least one shade tree	Typical landscaping vegetation at both study sites (*species name*)
TMP (mesic residential)	129	100%	100%	Bermuda grass (*cynodon dactylon*)
WPHX (xeric residential)	245	26%	50%	Desert fan palm (*washingtonina filifera*)
				Mexican fan palm (*washingtonia robusta*)
				Bottle tree (*brachychiton populneus*)
				Seville sour orange (*citrus aurantium*)
				Coolibah (*eucalyptus microtheca*)
				Shamel ash (*fraxinus uhdei*)
				European olive (*olea europaea*)
				Chinese pistache (*pistacia chinensis*)
				Blue Palo Verde (*parkinsonia florida*)[a]
				Thornless Mesquite (*prosopis hybrid*)[a]

[a] Flora selected for xeriscaping scenarios in ENVI-met.

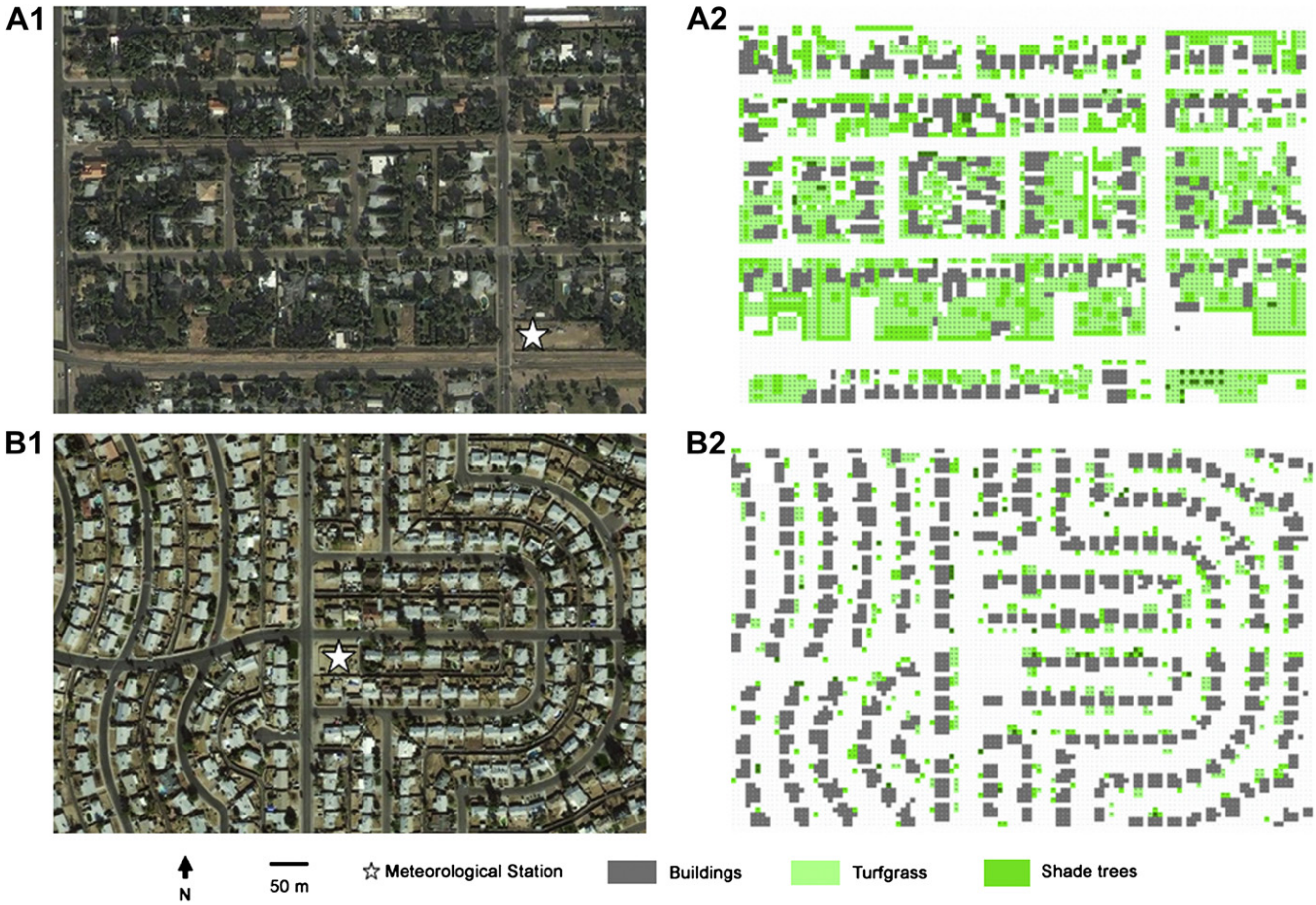

Fig. 2. Tempe (A) and West Phoenix (B) study areas. A1 and B1 depict aerial satellite view of study areas, while A2 and B2 are the area input files of the ENVI-met model environment for Tempe and West Phoenix sites respectively. Note the presence of a recreational park in the SE corner of A1 and A2.

($2z_{max}$), and the lateral model boundaries are surrounded by a user-specified nesting area of soils devoid of vegetation or buildings. Above $2z_{max}$, the near-surface 3-d model is coupled with a 1-d atmospheric model that extends up to the model's upper boundary of 2500 m. A 1-d soil model extending to 2 m below the surface is also coupled with the main atmospheric model. Vegetation is modeled as a 1-d vertical column, with its height and shape dependent on a normalized leaf (and root) area density profile. ENVI-met is able to model interactions between atmosphere, soil, vegetation and the urban environment over a 3-d grid domain system, and can calculate [8]:

- short-wave and long-wave radiation fluxes with respect to shading, reflection and re-radiation from building systems and vegetation;
- evapotranspiration and sensible heat flux from vegetation into the urban atmosphere, including full simulation of all plant physical parameters (e.g. photosynthesis rate);
- surface and wall temperatures for each grid point and wall;
- vertical water- and heat exchanges inside the soil system;
- bio-meteorological parameters (e.g. mean radiant temperature);
- dispersion of inert gases and particles, including sedimentation of particles at leaf-scale and surfaces.

ENVI-met typically models soil-air-vegetation-building interactions at horizontal spatial resolutions of between 0.5 and 10 m. Simulations are generally run for 24–48 h, with time steps between 1 and 10 s. A user-specified area input file defining the three-dimensional geometry of the study area is required for every ENVI-met simulation. This includes geo-coded building dimensions (e.g. width and height), soil (e.g. type and texture), surface (e.g. concrete or asphalt) and vegetation types (Fig. 2). In this study, we applied a local vegetation parameterization scheme based on leaf area densities of typical flora observed in residential landscapes within metropolitan Phoenix [12]. The size of each individual model grid cell was selected to match the neighborhood spatial scale (5 × 5 × 2 m), and the total model environment size was 128 × 78 × 30 cells for both TMP and WPHX. The model environment was also nested within five nesting grids with the predominant soil type of each neighborhood for improved numerical stability during model runs. ENVI-met simulations also require a configuration file containing local soil, meteorological and building input data for model initialization at each study area (Table 2). These include (i.) 2 m above surface level (a.s.l.) temperature and relative humidity, (ii.) 10 m a.s.l. wind speed and direction, (iii.) specific humidity at 2500 m a.s.l,, (iv.) soil temperature and relative humidity, and (v.) building interior temperatures, mean heat transmission (i.e. thermal conductivity divided by mean wall or roof width), and mean albedo values for roofs and walls. These data were obtained from (1) meteorological stations sited within each study area, (2) the NCEP/NCAR reanalysis project at the NOAA/ESRL Physical Sciences Division [38], (3) existing datasets listing typical thermophysical properties of typical building materials [39], and (4) field reconnaissance within both study areas.

Table 2
Selected input parameters for ENVI-met base simulations at TMP and WPHX study areas.

Category	User input during simulations	
Meteorological inputs	TMP	WPHX
Wind speed and direction 10m a.s.l.	1 m s^{-1}/90°	1.5 m s^{-1}/230°
Mean roughness length of study area	0.35 m	0.3 m
Specific humidity at 2500 m a.s.l.	3 g kg^{-1}	3 g kg^{-1}
Relative humidity at 2 m a.s.l.	24%	20%
Initial atmospheric temperature[a]	301 K	305 K
Soil inputs		
Initial soil temperature at upper layer (0–20 cm)	304 K	306 K
Initial soil temperature at middle layer (20–50 cm)	305 K	307 K
Initial soil temperature at lower layer (below 50 cm)	306 K	308 K
Relative humidity upper layer	35%	20%
Relative humidity middle layer	40%	25%
Relative humidity lower layer	45%	30%
Building inputs		
Building interior temperature	298 K	298 K
Mean heat transmission[b] of walls	1.94 W m^{-2} K^{-1}	1.94 W m^{-2} K^{-1}
Mean heat transmission of roofs	6 W m^{-2} K^{-1}	6 W m^{-2} K^{-1}
Mean wall albedo	0.4	0.4
Mean roof albedo	0.5	0.5

[a] This is the mean air mass temperature assumed to be more or less independent from surface layer processes for the duration of the simulation (M. Bruse, pers. comm.). Site parameters were estimated as an average value of T_{2m} data over 24 h.
[b] Estimated thermal conductivity of building material (W m^{-1} K^{-1}) divided by mean wall thickness (m).

All model simulations were run for 24 h, with updated surface data every 60 s, starting from sunrise (0500 h) during July 4–5 2007. This period was selected as it occurred during the middle of an EHE from July 3–6 2007 as defined by criteria set by Meehl and Tebaldi [34]. Highest observed maximum and minimum temperatures at the National Weather Service's Sky Harbor Airport meteorological station were 46.7 and 33.9 °C respectively during this EHE [23]. From the simulations, we obtained the spatial distribution of potential temperatures throughout the model environment, which were subsequently converted to absolute near surface (2 m a.s.l.) temperatures (T_{2m}) through Poisson's equation. We used T_{2m} data in our analysis as direct comparisons with meteorological station data at each study area could be made for model evaluation. We specifically focused on temperature data taken at 5 p.m. and 5 a.m. local time (LT), which corresponded to approximate summer maximum and minimum temperatures in Phoenix. Apart from T_{2m}, we also examined magnitudes of mean radiant temperatures (MRT) calculated by ENVI-met at 2 m a.s.l. to quantify outdoor thermal comfort [1]. We used MRT as it is the most important meteorological input parameter when deriving the human energy balance, especially during summer conditions, and it also has the greatest influence on other thermophysiological indices like Predicted Mean Vote (PMV) and Physiological Equivalent Temperature (PET) [32]. Further, there are ample MRT data obtained from other cities that would enable a useful comparison of this study's results [28].

However, several limitations of ENVI-met must be discussed at this point. First, the simplified 1-d atmospheric inflow model (up to the model's upper boundary of 2500 m a.s.l.) restricts the ability to dynamically simulate regional/meso-scale thermal and turbulence exchanges that potentially influence micro-scale climates. This may be problematic if regional weather conditions vary greatly over the model simulation period, but very stable and strong anticyclonic conditions were present during the EHE period documented in our study. Second, building facades throughout the model environment are parameterized with a single mean heat transmission value, which oversimplifies the heterogeneity of the urban environment. Third, the lack of horizontal soil transfer within the model potentially affects accurate calculations of soil heat storage [17]. Despite these limitations, ENVI-met has been widely applied in urban climatology, building design and planning research at micro-scales [1,16,17], which demonstrates the model's capability.

2.3. UHI mitigation scenarios

We selected three xeriscaping scenarios for each site (Table 3); low (where 10% of selected residential housing lots at each site undergo conversion to xeric vegetation), medium (25%) and high (50%). We first calculated the number of lots that would undergo landscaping conversion in each case. For the low and medium scenarios, we randomly selected housing lots throughout each study area for the conversion process. Given the incentive options from cities in metropolitan Phoenix, we argue that a random selection pattern is more likely to occur in reality as opposed to a systematic selection process, such as designated xeriscaping "zones" within the study area. For the high xeriscaping scenario, however, every alternate house in both study areas was selected for conversion akin to a "chessboard" pattern. Given the prior literature, we expected that our xeriscaping scenarios would result in contrasting impacts in our study areas; higher and lower mean temperatures at TMP and WPHX respectively.

Model outputs from each scenario were compared with base simulations with existing land and vegetation parameters. We focused on simulated conversion of mesic landscape treatments at both TMP and WPHX to flora adapted to desert conditions. We followed xeriscaping guidelines suggested by the City of Mesa [14], which offered financial rebates for homeowners to convert previous mesic surface cover in both front and back yards to at least 50% xeric cover. In our simulations, selected residential lots had half of its previous yard surface left as bare soil/ground, and the other half replaced with mature xeric shade trees. The trees selected were the Blue Palo Verde (*parkinsonia florida*) and Thornless Mesquite (*prosopis hybrid*) (Fig. 3). These vegetation species have been parameterized for ENVI-met simulations based on observed leaf area density (LAD) measurements of mature trees in Chow et al. [12], and these data were applied in our simulations. While alternative xerophytic plants could have been selected, species like Creosote Bush (*larrea tridentata*) and Fishhook Barrel Cactus (*ferocactus wislizenii*) have limited direct shade potential to

Table 3
Xeriscaping conversion scenarios and alterations to model parameters.

Scenario	Selection method of houses undergoing conversion	Alterations to model parameters	Number of lots undergoing xeriscaping	
			TMP	WPHX
Low (10%)	Random assignment throughout model environment	Front and back yard surfaces of individual residential lots replaced with 50% bare soil and 50% mature Blue Palo Verde (7.5 m) and Thornless Mesquite (9 m) trees	13	25
Medium (25%)			32	61
High (50%)	Alternate assignment (i.e. chessboard pattern)		65	123

Fig. 3. Examples of typical mature (a) Thornless Mesquite (*prosopis hybrid*) and (b) Blue Palo Verde (*parkinsonia florida*) tree species used for landscaping in a Southwestern US desert city. (Source: City of Tucson (a), and Arizona State University (b)).

significantly alter microclimates. Both selected tree species have broad canopies when mature, and typically require significantly less total irrigation than mesic shade trees. For instance, a 21 m^2 residential yard with covered with Bermuda grass typically requires an estimated $\sim$19 000 l y^{-1} of water for proper maintenance in Phoenix's climate [55], whereas a properly xericscaped yard with mature Palo Verde or Thornless Mesquite trees require little or zero supplemental watering. This substantial water savings from xeric shade trees would thus be beneficial for improving the sustainability of an arid city, and their utility has been recognized by the City of Phoenix's Tree and Shade Master Plan [15].

3. Results

3.1. Model evaluation

Hourly T_{2m} data from both meteorological stations in TMP and WPHX were compared with mean modeled T_{2m} throughout the model environment (Fig. 4). WPHX observed higher temperatures throughout most of the 24 h period, peaking at 45.1 °C at 1700 h LT. The ameliorative impact of greater surface vegetation within TMP was apparent in lower temperatures observed throughout most of the day. This was evident during the nocturnal period, with minimum temperatures at 0500 h LT being 25.3 °C, compared to 31.1 °C at WPHX. Observed T_{2m} were compared with mean ensemble T_{2m} modeled over all model surfaces during each ENVI-met base simulation at TMP and WPHX. The model generally underestimated daytime T_{2m} and overestimated nighttime T_{2m} at both sites. This feature was also apparent in previous applications of this model in Phoenix [12,16].

We evaluated the accuracy of predicted ENVI-met (*P*) with observed time-series temperatures (*O*) using both correlation (i.e. r^2) and difference measures (i.e. *RMSE*) (Fig. 5), where accuracy is defined as the degree to which magnitudes of *P* approaches magnitudes of *O*. The suite of difference measures used include the mean bias error (*MBE*), mean average error (*MAE*), root mean square error (*RMSE*) and its derived systematic ($RMSE_S$) and unsystematic

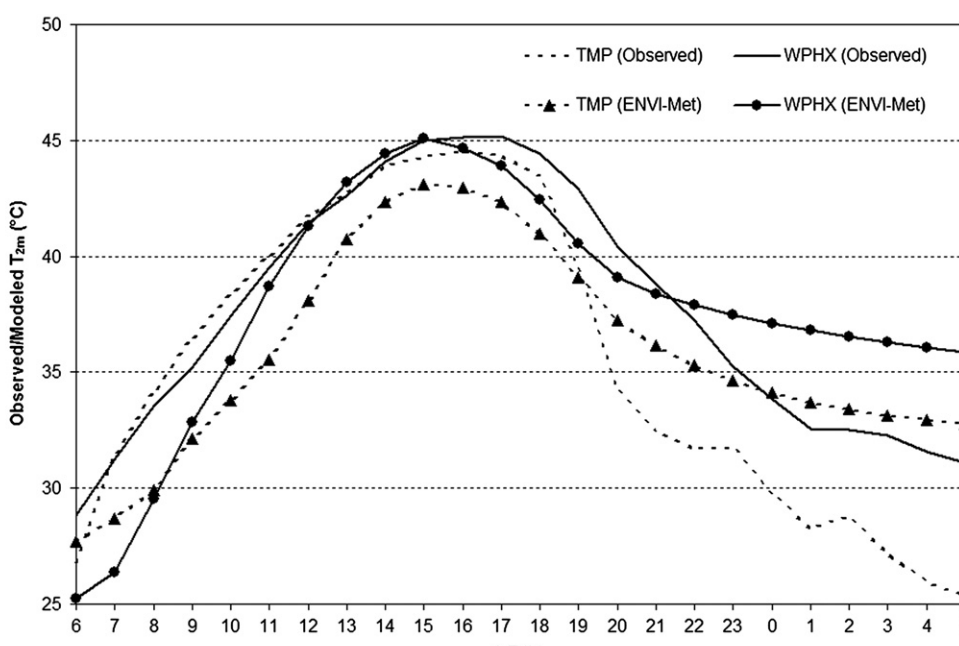

Fig. 4. Comparison between observed hourly near-surface temperatures (T_{2m}) from July 4–5 2007 taken at both TMP and WPHX meteorological stations with mean ensemble T_{2m} from ENVI-met simulations for each study study area.

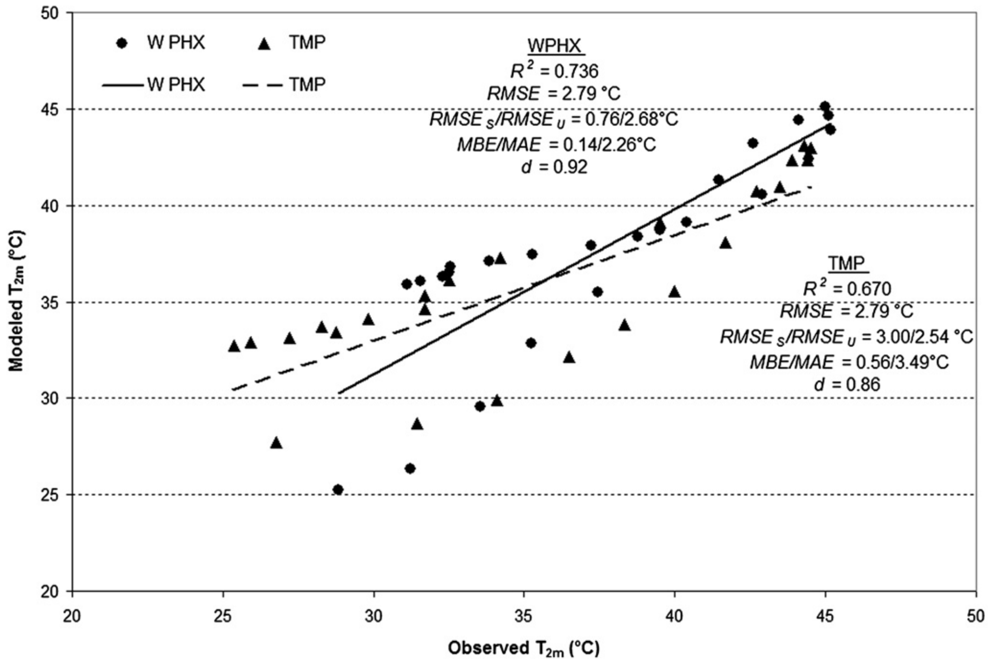

Fig. 5. Evaluation of observed vs. modeled T_{2m} time-series data from Fig. 4. R^2 = coefficient of determination; *RMSE* = root mean squared error; $RMSE_S$ = systematic *RMSE*; $RMSE_U$ = unsystematic *RMSE*; *MBE* = mean bias error; *MAE* = mean average error; *d* = index of agreement.

($RMSE_U$) components, and the index of agreement (d) [56]. These difference measures – especially d – are useful in determining how error-free modeled *P* vs. *O* are. $RMSE_S$ and $RMSE_U$ are also important in indicating possible errors in model design, with lower $RMSE_S$ magnitudes desired. Magnitudes of $RMSE_U$ that approach *RMSE* are preferred, indicating 'good' model performance [25].

Even with the underestimation (overestimation) of peak daytime (nighttime) temperatures, modeled T_{2m} data showed generally good agreement with observed meteorological station data at both sites, which was apparent with both correlation ($r^2 > 0.67$) and difference indices ($d > 0.86$).

There were also acceptably low magnitudes of *MBE*, *MAE* and *RMSE*, suggesting that base scenario designs for TMP and WPHX were largely accurate. There was, however, a notable exception with $RMSE_S > RMSE_U$ at TMP, possibly indicating inaccurate parameterization of this site. This could be explained by the influence of the large recreational park adjacent to the SE study area boundary. It has been postulated that the source area of urban temperature sensors

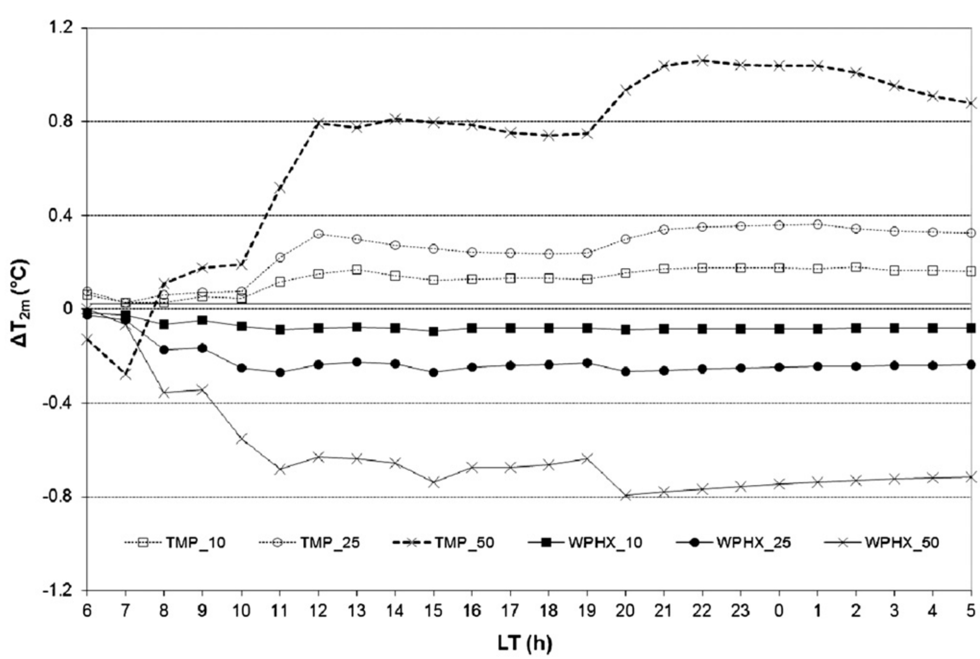

Fig. 6. Difference (ΔT) between T_{2m} time-series data from base simulations with modeled ensemble mean T_{2m} from all UHI mitigation scenarios. The suffix "10" = low xeriscaping (surface conversion of 10%); "25" = medium xeriscaping (25%); "50" = high xeriscaping (50%) for both TMP and WPHX study areas.

extends to a circle of ∼500 m radius around the instrument [40]. This source area would include the dimensions of the entire park, which is not included in the model scenarios. In contrast, the source area of the WPHX sensor does not include dissimilar LULC types from its modeled environment. In our estimation, this factor likely accounted for the systematic error in the TMP model. Nonetheless, the fair r^2 and high d indicates that our model parameterization were suitable for the study's objectives.

3.2. Temperature and thermal comfort variations between xeriscaping scenarios

We plotted differences in 24 h ensemble T_{2m} between all xeriscaping scenarios with the base model parameters from both TMP and WPHX (ΔT_{2m}) (Fig. 6), which describes local-scale temperatures variations. Despite relatively minor alterations in green-space, mean impacts to T_{2m} arising from the low and medium xeriscaping scenarios were noticeably discernable at both sites. In TMP, low and medium xeriscaping scenarios displayed marginal increases in warming during the day (approximately +0.2 °C), but increases in ΔT_{2m} magnitude were slightly larger at night, especially in the medium scenario (approximately +0.35 °C). In WPHX, however, low and medium xeriscaping scenarios resulted in mean local-scale decreases in ΔT_{2m} by −0.1 and −0.3 °C respectively. In contrast, larger variations in mean ΔT_{2m} were observed for high xeriscaping scenarios at both study sites. At TMP, local-scale increases of mean ΔT_{2m} in late afternoon temperatures were about +0.8 °C, with further nocturnal increases in excess of +1 °C. Conversely, local-scale ΔT_{2m} at WPHX were consistently lower by around −0.7 °C for most of the simulation, with little slightly larger observed nocturnal cooling of ΔT_{2m} (−0.75 vs. −0.65 °C) compared to daytime magnitudes.

We subsequently compared and examined the impact of xeriscaping over micro- and local-spatial scales by plotting ΔT_{2m} maps between base with all three xeriscaping scenarios during approximate maximum (1700 h) and minimum (0500 h) temperature timings for TMP (Fig. 7) and WPHX (Fig. 8). Magnitudes of micro-scale (i.e. at the spatial scale of individual residential lots) warming in TMP are significantly larger than at local scales (i.e. the total model environment). A notable pattern of maximum warming magnitudes increasing with higher xeriscaping scenarios was evident, with larger ΔT_{2m} increases observed at 0500 h compared to 1700 h (e.g. +2.6 °C vs. +1.5 °C under the high xeriscaping scenario). Conversely, significantly lower micro-scale ΔT_{2m} were observed at WPHX. The pattern

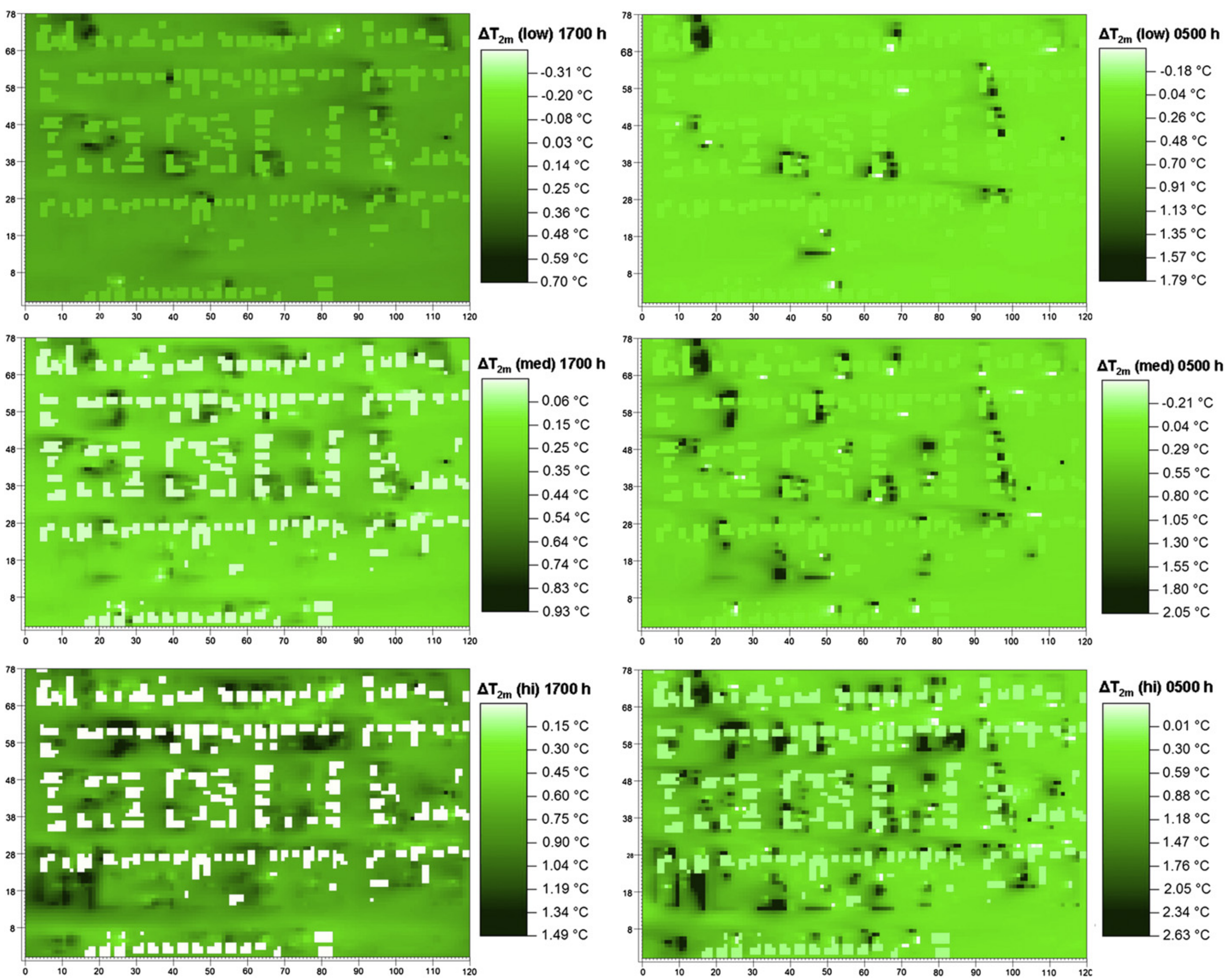

Fig. 7. Difference plots of 2m a.s.l. temperatures (ΔT_{2m}) between base simulations and modeled scenarios in TMP for low (top), medium (middle) and high (bottom) xeriscaping respectively during 1700 h (left) and 0500 h LT (right).

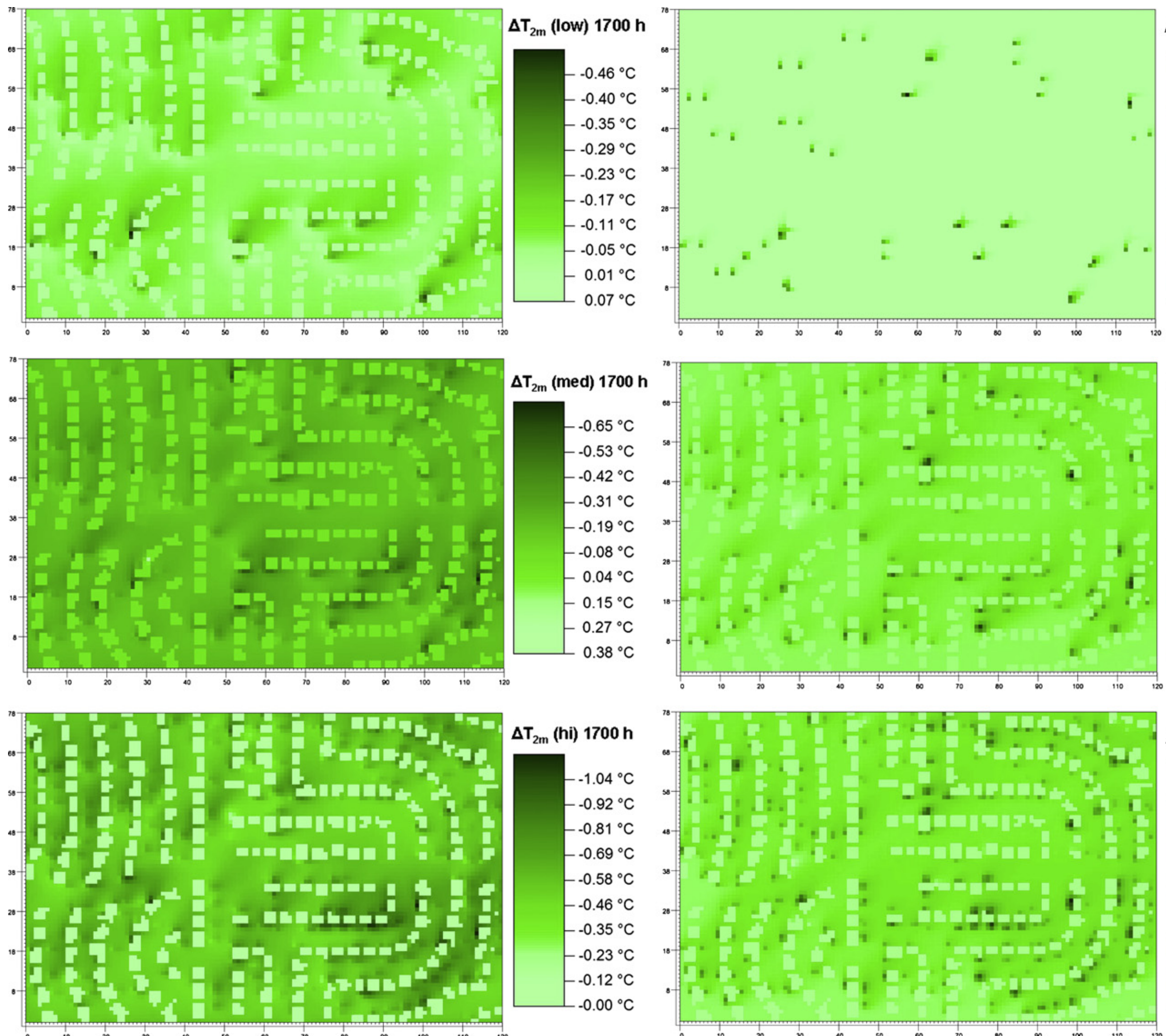

Fig. 8. Same as Fig. 7 but for WPHX.

of maximum cooling magnitudes with higher xeriscaping was also mirrored, with greater nocturnal vs. daytime cooling (e.g. −2.4 vs. −1 °C under the high xeriscaping scenario) Figs. 7 and 8 also reveal the distinctive "patchy" micro-scale pockets of warming or cooling that is limited to the individual residential lot and adjacent houses, especially in both low xeriscaping scenarios. Lastly, it is notable that ΔT_{2m} variations in TMP were least in the SE corner of the study area, which is part of the recreational park.

Advection and near-surface turbulence appears to influence the spatial variation of temperatures at both sites. During the simulations, the predominant wind direction was from the E and SW at TMP and WPHX respectively (Table 2). At TMP, advection likely resulted in the notable areal expansion of higher T_{2m} towards the west, especially at 0500 h. This pattern was also apparent in WPHX, which observed SW winds shifting cooler temperatures towards NE of the model environment. The influence of advection is also notable when examined under scenarios of increasing xeriscaping, as the pockets of cooler/warmer micro-scale patches correspondingly expand and affect more unconverted residential lots located further away (e.g. between 20 and 50 m or 3-4 lots in WPHX, and 50–75 m or 6-8 lots in TMP). Near-surface atmospheric stability could also be a factor in explaining temperature variations between 1700 and 0500 h; generally unstable (during 1700 h) and stable (during 0500 h) atmospheric conditions could affect micro- and local-scale turbulence and advection, and subsequent spatial distribution of thermal impacts.

Lastly, we examined outdoor thermal comfort using hourly 2 m a.s.l. ensemble mean radiant temperature (MRT) data that were derived from ENVI-met (Fig. 9). It is apparent that daytime MRT magnitudes reflect the extreme discomfort during the EHE in Phoenix for both residential areas, with peak average daytime (nocturnal) MRT of 83.9 (26.1) and 93.3 (30.6) °C occurring at 1600 (0500) h for TMP and WPHX respectively. Similarly high daytime and nocturnal MRT magnitudes were also reported in summer observations taken within the desert city of Beni-Isguen, Algeria [2]. Notable variations in MRT existed between study sites, however. Generally, the higher T_{2m} in WPHX, combined with less surface evapotranspiration from fewer mesic surfaces, corresponded in substantially higher daytime and nighttime MRT magnitudes – and greater thermal discomfort – when compared to TMP. Distinct increases (decreases) in MRT at TMP (WPHX) occurred with greater xeriscaping at each site, especially during maximum temperature conditions. For instance, the high xeriscaping scenario resulted in a change of mean MRT at TMP by +11.3 °C and +4.8 °C at 1600 and 0500 h respectively; conversely, the high scenario at WPHX observed −2.6 °C (1600 h)

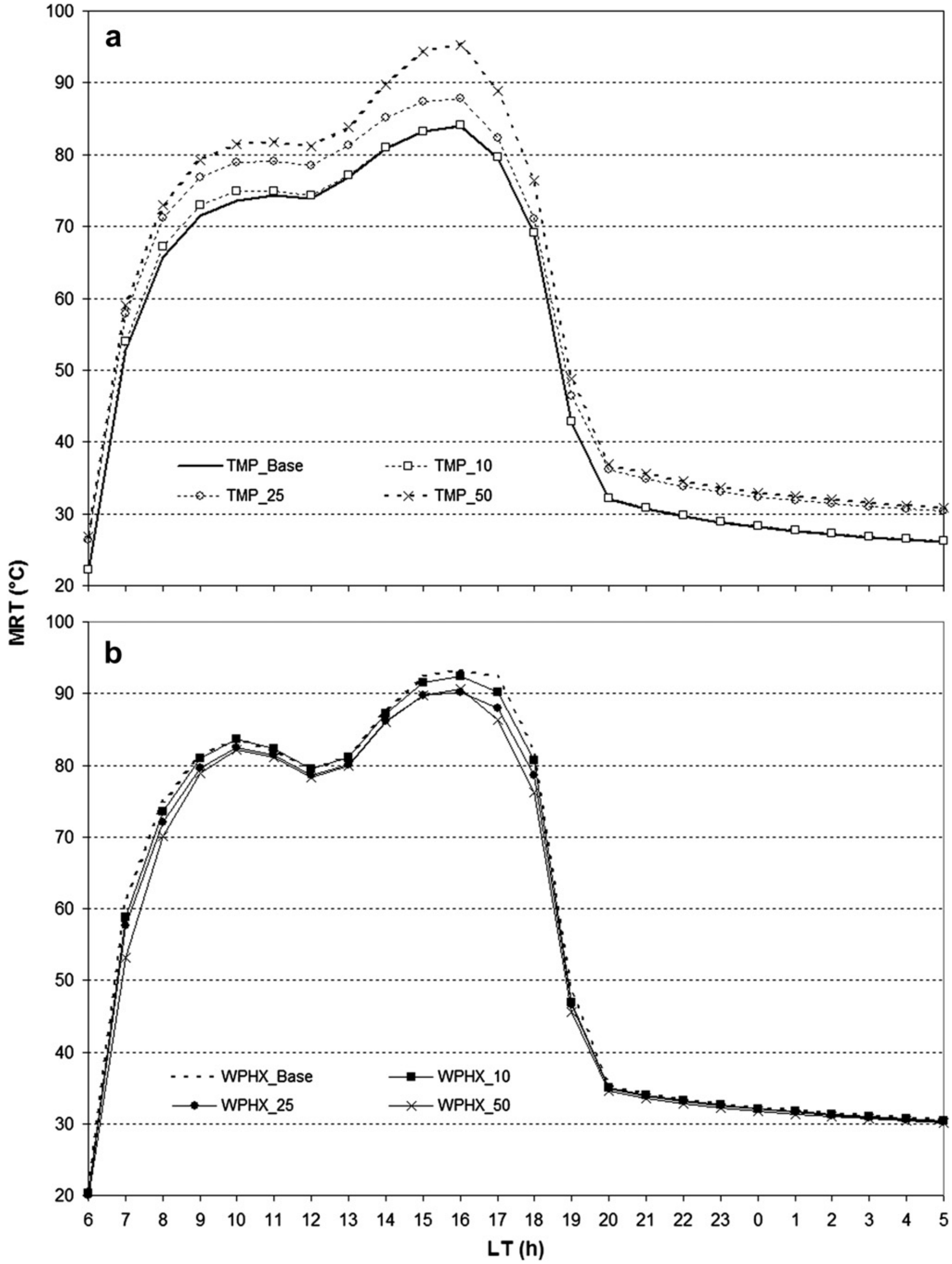

Fig. 9. Ensemble hourly 2 m a.s.l. mean radiant temperature (MRT) calculated by ENVI-met for both base and all UHI mitigation scenarios at TMP (a) and WPHX (b). Suffix descriptors for both sites follow Fig. 6.

and −0.5 °C (0500 h). These trends were similar in pattern to variations of T_{2m} for all scenarios.

4. Discussion and conclusion

To summarize, a key result from this study is the encouraging potential of xeriscaping with shade trees as a UHI mitigation method, especially within dry/xeric residential areas in Phoenix. The combined effect of both increased shading and evapotranspiration from the selected xeric trees at WPHX results in distinct daytime and nighttime cooling impacts. The effectiveness of cooling also varies between spatial scales. Magnitudes of cooling are markedly larger at microscales (i.e. the residential lot and adjacent buildings), with potential maximum nocturnal cooling ranging from 1.5 to 2.4 °C in areas immediately adjacent to the shade trees. Cooling magnitudes are substantially less at larger, local spatial scales (i.e. the entire study area), but these impacts are still discernable, especially with higher xeriscaping levels. On the other hand, xeriscaping impacts on temperatures and thermal comfort clearly differ between residential LULC categories, as the removal of water-intensive surfaces and trees consequently increased temperatures in the mesic residential area at TMP. These considerable temperature increases are most likely due to decreased evapotranspiration and shade. Likewise, changes in outdoor thermal comfort quantified by MRT in each scenario mirrored the variations in temperatures at both TMP and WPHX. Increasing levels of xeriscaping conversion (i.e. from low to high) also resulted in greater variations in the magnitude of MRT at both sites, possibly from the addition (and removal) of shade trees that block direct insolation at the surfaces of WPHX and TMP respectively.

This cooling potential of xeric shade trees is an important consideration for sustainable UHI mitigation approaches in Phoenix, especially as previous xeriscaping model simulations with LUMPS only accounted for turf grass removal but not the addition of spatially explicit trees at micro- or local spatial scales [19,35]. The application and careful management of shade trees are therefore essential in not only reducing near-surface temperatures in xeric residential neighborhoods, but also improving outdoor thermal comfort through shade for pedestrians under conditions of extreme daytime temperatures. Further, the dynamic influence of advection and near-surface turbulence was not considered in previous xeriscaping studies. Here, advection is potentially important in expanding the micro-scale cooling influence in the xeric residential neighborhood, possibly through the turbulent mixing of cooler air that integrates cool micro-scale "patches" over a larger area. This spatial expansion of cooling from advection is further magnified with higher levels of xeriscaping at WPHX, further highlighting the utility of this method in mitigating UHI especially when widely applied.

Our results suggest that proposed xeriscaping methods in Phoenix, and possibly in other arid cities, should include low-water demand shade trees, especially within existing xeric residential areas. With the majority of residential areas in metropolitan Phoenix classified as xeric surfaces in a recent categorization of urban LULC of the entire city [10], widespread xeriscaping with shade trees could potentially be effective in reducing UHI intensities at a large scale whilst reducing residential water consumption. Large-scale residential xeriscaping in other existing mesic neighborhoods similar to TMP, however, likely results in greater thermal discomfort to residents. The detriment of projected warming has to be evaluated against the potential water savings from the elimination of water-intensive residential vegetation in existing mesic neighborhoods. For instance, if we assumed that $\sim 1365\ m^2$ of Bermuda grass lawns in TMP were replaced under a high xeriscaping scenario (i.e. 65 houses with $\sim 21\ m^2$ of lawn space in TMP), the potential water savings could be ~ 1.24 million liters per year. This estimate has to be compared with total residential water use in order to evaluate if these savings are substantial. We must note, however, that detailed domestic indoor and outdoor water consumption data for each household in the study areas are not readily available to evaluate this assumption. The analysis of potential tradeoffs between microclimate cooling vs. neighborhood water use is thus beyond the scope of this study.

Overall, the study points out the need for concomitant water assessments and the incorporation of other modeling schemes to better understand the role of xeriscaping as a sustainable UHI mitigation method in arid cities like Phoenix. While this study demonstrates the importance of considering spatial scale differences with modeling urban climates and the UHI, possible future research could compare the local-scale results from ENVI-met with other local-scale urban climate models, such as LUMPS, TEB [31], or SLUCM [29], to evaluate inter-model performance. It is important for stakeholders (e.g. planners, scientists and policy makers) interested in modifying and attaining sustainable urban climates to acknowledge that no single model developed for a specific spatial and temporal resolution can provide a comprehensive tool to evaluate possible UHI mitigation scenarios or other aspects of urban climate. Analyzing projected urban climates by using a combination of urban climate models applied across different scales could be useful, if these models are properly evaluated with observed data.

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