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Urban forestry and cool roofs: Assessment of heat mitigation strategies in Phoenix residential neighborhoods

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ABSTRACT

The City of Phoenix (Arizona, USA) developed a Tree and Shade Master Plan and a Cool Roofs initiative to ameliorate extreme heat during the summer months in their arid city. This study investigates the impact of the City's heat mitigation strategies on daytime microclimate for a pre-monsoon summer day under current climate conditions and two climate change scenarios. We assessed the cooling effect of trees and cool roofs in a Phoenix residential neighborhood using the microclimate model ENVI-met. First, using xeric landscaping as a base, we created eight tree planting scenarios (from 0% canopy cover to 30% canopy cover) for the neighborhood to characterize the relationship between canopy cover and daytime cooling benefit of trees. In a second set of simulations, we ran ENVI-met for nine combined tree planting and landscaping scenarios (mesic, oasis, and xeric) with regular roofs and cool roofs under current climate conditions and two climate change projections. For each of the 54 scenarios, we compared average neighborhood mid-afternoon air temperatures and assessed the benefits of each heat mitigation measure under current and projected climate conditions. Findings suggest that the relationship between percent canopy cover and air temperature reduction is linear, with 0.14 °C cooling per percent increase in tree cover for the neighborhood under investigation. An increase in tree canopy cover from the current 10% to a targeted 25% resulted in an average daytime cooling benefit of up to 2.0 °C in residential neighborhoods at the local scale. Cool roofs reduced neighborhood air temperatures by 0.3 °C when implemented on residential homes. The results from this city-specific mitigation project will inform messaging campaigns aimed at engaging the city decision makers, industry, and the public in the green building and urban forestry initiatives.

Introduction

Rapid urbanization and the associated land cover changes from natural or agricultural lands to built environments have transformed cities into urban heat islands (UHI), with increased air and surface temperatures in the urban area as compared to its rural surroundings (Howard, 1833; Oke, 1982; Arnfield, 2003). Especially in hot desert climates, the expanding UHI effect is of great concern, because it increases outdoor water use (Guhathakurta and Gober, 2007, 2010) and the energy demand of cooling (Akbari et al., 2001; Akbari, 2002; Golden, 2004; Grimmond, 2007), lowers air quality (Stone, 2005; Sarrat et al., 2006), decreases thermal comfort (Hartz et al., 2006; Shashua-Bar et al., 2011), and increases illnesses and mortality related to heat stress (Harlan et al., 2006; Golden et al., 2006; Jenerette et al., 2011). In the face of global climate change, the compounding effects of UHIs and more frequent and extended heat waves further threaten the resilience of desert cities to cope with increasing temperatures.

In 2008, the US Environmental Protection Agency (EPA) published a compendium of UHI mitigation strategies, promoting urban forestry and albedo modification of hard surfaces, i.e., roofs and pavement, as key strategies to reduce urban warming (EPA, 2008). Trees can moderate climate through combined effects of (a) surface shading, which reduces surface and air temperatures by intercepting incoming solar radiation; (b) evapotranspiration; and (c) alteration of wind patterns (Oke et al., 1989; Akbari et al., 2001). High albedo surfaces, e.g., cool (high reflectance) roofs, absorb less heat during the day and reflect most of the incoming solar radiation back into the atmosphere (Taha, 1997). In recent years, several research studies that focused on UHI mitigation strategies in cities with hot summers assessed the thermal benefits of

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urban forests (Emmanuel et al., 2007; Golden et al., 2007; Shashua-Bar et al., 2009, 2010; Bowler et al., 2010; Chow and Brazel, 2012), cool roofs (Georgescu et al., 2013), or a combined strategy (Sailor, 1995; Akbari et al., 2001; Rosenzweig et al., 2009; Ng et al., 2012; Shahidan et al., 2012). At the same time, many state and local governments across the US have taken steps to mitigate the UHI through various activities, e.g., incentive programs, tree and landscape ordinances, zoning codes, plans and design guidelines, and urban forestry initiatives (EPA, 2008). In the arid southwest, policies and programs to mitigate heat and reduce energy use for summer cooling include *Million Trees LA* (McPherson et al., 2011), *TreeUtah* (http://www.treeutah.org/statewide.htm), and the *Phoenix Tree and Shade Master Plan* (City of Phoenix, 2010), among others. Although research findings on UHI mitigation strategies have informed ongoing activities, the local effectiveness of most city-specific, targeted UHI mitigation strategies has not been fully assessed, especially with regard to quantifying temperature reductions at the neighborhood scale.

This study was conducted in collaboration with the City of Phoenix to quantify the thermal impact of two heat mitigation activities currently undertaken by the City, i.e., the urban forestry and cool roof initiatives. The stakeholder questions guiding our research are: (a) In a typical residential neighborhood in Phoenix, what is the relationship between percent tree cover and mid-afternoon air temperature during pre-monsoon summer? (b) What are the cooling benefits achieved by increasing tree canopy from 10% (current) to 25% (2030 goal) and/or implementing cool roofs, under existing conditions and projected warming? Our study used a microscale model to simulate an ensemble of tree canopy cover, cool roof, and climate scenarios for a representative residential neighborhood in Phoenix. We assessed the thermal benefits of each scenario for mid-afternoon on a pre-monsoon summer day – when the warmest temperatures occur – and at the local and micro-scale, the scales at which most UHI mitigation strategies are implemented and the greatest relief is felt.

The City of Phoenix

The City of Phoenix (Fig. 1a) is the heart of the Phoenix Metropolitan Area and situated at 33°29′ N, 112°4′ W in Maricopa County, AZ. Located in the arid southwest of the US and the northeastern part of the Sonoran Desert, Phoenix experiences hot summers with mean maximum temperatures of 40 °C and above from June to August and mild winters with average daily temperatures around 15 °C. Precipitation is low and averages 208 mm annually with only 1–2 mm in May and June (Western Regional Climate Center, 2014). Incorporated in 1881 as a small agricultural community of about 2500 people, Phoenix has grown rapidly since then, despite the hot, dry climate, and has experienced extensive anthropogenic land cover changes, predominantly from farmlands and agricultural fields to residential developments prior to 1975 and from both agricultural and desert since 1975 (Knowles-Yánez et al., 1999, Chow et al., 2012). The population of the City of Phoenix has grown from 105,000 in 1950 to 1.5 million in 2012 and is currently the 6th largest city in the US (US Census Bureau, 2014). The Maricopa Association of Governments (2013) projects that Phoenix will be home to over 2 million residents by 2040.

Rapid and extensive urbanization has led to an intense UHI in Phoenix that has increased nighttime temperatures steadily, approximately 0.5 °C per decade since 1910 (Brazel et al., 2000). A time-trend analysis of air temperatures at Phoenix Sky Harbor International Airport showed nighttime temperature differences between rural and urban areas of up to 6 °C in the summer (Brazel et al., 2000). Winter mobile transect observations in Phoenix found an average UHI intensity of 8 °C (Sun et al., 2009), and a study in the spring observed a range of UHI intensity of 9.4 °C to 12.9 °C (Hawkins et al., 2004). The Phoenix UHI has been well documented and has been the focus of many research studies at various spatial and temporal scales (Stabler et al., 2005; Brazel et al., 2007; Georgescu et al., 2012; Grossman-Clarke et al., 2010; Chow and Brazel, 2012; Middel et al., 2014). This is due to several extrinsic factors, including the clear and calm weather conditions in Phoenix, projected future droughts, and ongoing urban expansion, as well as location-specific factors, such as partnerships between academic institutions and private and public sector agencies, a well-established extensive network of urban weather stations, and strong media-coverage (Chow et al., 2012). In recent years, the City of Phoenix has collaborated increasingly with researchers from Arizona State University to adopt and implement policies that incorporate UHI research findings and advance the City's sustainability goals. Examples for these collaborative efforts are the *Downtown Phoenix Urban Form Project* (City of Phoenix, 2008), which informed zoning ordinances to mitigate the UHI through optimized arrangement and design of urban features; a study to investigate the outdoor water use efficiency of urban greening scenarios (Gober et al., 2010); the *Phoenix Tree and Shade Master Plan* (City of Phoenix, 2010) to mitigate heat through an urban forest; and the 2013 Phoenix cool roofs initiative, as part of the *Green Construction Code* (City of Phoenix, 2006). This collaborative study focuses on the two most recent heat mitigation efforts of the City of Phoenix to address urban warming, i.e., the cool roofs and urban forestry initiatives.

The *Green Construction Code* (City of Phoenix, 2006) was adopted by the Phoenix City Council in 2005 and included purchasing guidelines for Energy Star Reflective Roof Certified Products to encourage cool roofs on publicly owned buildings. In addition, the City adopted a requirement for the use of high reflective cool roofs on all new city-owned buildings. In October 2012, Mayor Greg Stanton started the Phoenix Cool Roofs initiative to coat 70,000 square feet of the City's existing rooftops with reflective paint. As of January 2014, approximately 52,000 square feet of public rooftops have been coated (Fig. 1c), but the private and residential sectors have not yet been included in this effort.

The *Tree and Shade Management Task Force*, a cross-departmental committee led by the City of Phoenix Parks and Recreation Department, developed a master plan that serves as roadmap to incrementally achieve the goal of having a tree canopy cover of 25% for the entire city by 2030 (City of Phoenix, 2010). The plan outlines three goals: (1) educate the public on the benefits of trees, as there is limited understanding of the importance of the urban forest; (2) increase canopy cover to 25% and protect existing trees, because more trees are currently being lost than planted; and (3) improve planting, maintenance, and irrigation practices, e.g., use drought-resistant, low-water use trees. Stabler et al. (2005) estimated the Phoenix Metropolitan Area tree cover to be 13%, but the tree canopy cover within the City of Phoenix is currently estimated to be only 8 to 10%. Historic neighborhoods near the urban core have the highest percentage of mature tree canopy (Fig. 1b), because lush vegetation was traditionally used here for cooling before air-conditioning became widely available (Gober, 2006). In general, the Phoenix has a diverse tree palette, ranging from native species, such as palo verde, ironwood, and mesquite trees, to non-native species that were introduced from similar climates, e.g., eucalyptus, ash, elm, olive, palm, and citrus trees. A tree inventory recently completed by the City of Phoenix lists a total of 92,845 trees on publicly owned land, i.e., parks, right-of-ways, and around municipal buildings (City of Phoenix, 2014); however, the city-maintained urban forest covers less than 1% of the total land area in the City of Phoenix. In order to reach the 2030 tree canopy goal of 25%, the public needs to be engaged in the City's urban forestry initiative and increase canopy cover

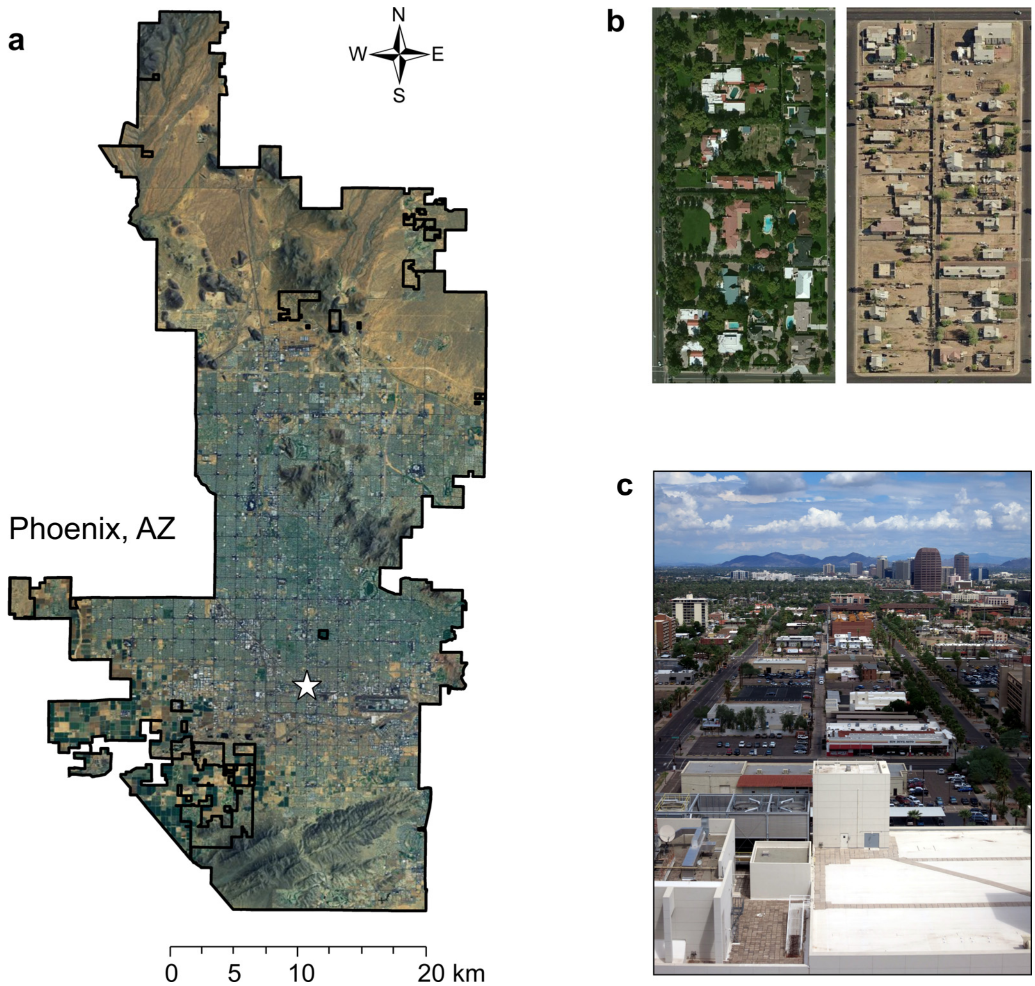

Fig. 1. (a) Aerial view of the City of Phoenix, including downtown; (b) Phoenix neighborhood with high tree canopy cover and low tree canopy cover; and (c) cool roofs and street trees in Phoenix downtown.

on private land. Assessing the impact of an increased tree canopy cover on neighborhood climate is the first step towards educating the public on the thermal benefits of trees and creating incentives for the residential sector to engage in the initiative.

In 2012, the Center for Integrated Solutions to Climate Challenges (CISCC) at Arizona State University partnered with the Climate Assessment for the Southwest (CLIMAS) program at the University of Arizona and the Decision Center for a Desert City (DCDC) at Arizona State University in a joint research project to examine what information or services were needed to help local communities with their climate adaptation planning and implementation. To establish case studies, cities in Arizona were solicited to submit proposals for assistance in their climate adaptation programs. The City of Phoenix requested assistance in assessing the benefits of their Cool Roof initiative and Tree and Shade Plan under current and future climate change conditions. The intent of this assessment was initially characterized as a way to provide documentation of benefits to justify expenditure of City funds to promote and manage these programs.

Methods

To assess the impact of the City of Phoenix urban forestry and cool roofs initiatives on near ground air temperatures, we simulated an ensemble of residential neighborhood scenarios using ENVI-met V3.1 Beta (Bruse, 2014). ENVI-met is a three dimensional atmospheric model that has been successfully used by many scholars to simulate microclimate in Phoenix after supplementing the model's plant database with native species (Chow and Brazel, 2012; Declet-Barreto et al., 2013; Hedquist and Brazel, 2014; Middel et al., 2014). For our simulations, we used the model configuration parameters from a recent study on the impact of urban form and landscaping types on mid-afternoon microclimate in Phoenix (Middel et al., 2014). The employed model parameters were evaluated for June 23, 2011, a typical pre-monsoon summer day, using observed atmospheric initial conditions from weather stations in the Central Arizona-Phoenix Long-Term Ecological Research (CAP LTER) North Desert Village (NDV) experiment (Martin et al., 2007). The model evaluation yielded a Root Mean Square Error (RMSE) of 1.41 °C (mesic), 1.81 °C (oasis), and 2.00 °C (xeric) for 2 m air temperatures; the Mean Bias Error (MBE) was −0.02 °C (mesic), 0.43 °C (oasis), and 1.20 °C (xeric); and the Mean Absolute Error (MAE) was 1.18 °C (mesic), 1.58 °C (oasis), and 1.74 °C (xeric). As model domain, we chose a Phoenix residential neighborhood scenario from Middel et al. (2014), representative of a typical single-family home subdivision. The neighborhood is classified as *Open Lowrise Local Climate Zone* after Stewart and Oke (2012), and features uniformly arranged detached 2-story buildings. The ENVI-met area input file for the neighborhood has a horizontal and vertical grid resolution of 1 m and a total of 215 × 195 × 30 grid cells plus 5 nesting grids.

We assessed the two city-specific passive cooling strategies for the mid-afternoon of June 23, 2011 in two steps. First, we focused on the urban forest initiative to investigate the relationship between percent tree canopy cover and temperature reduction at

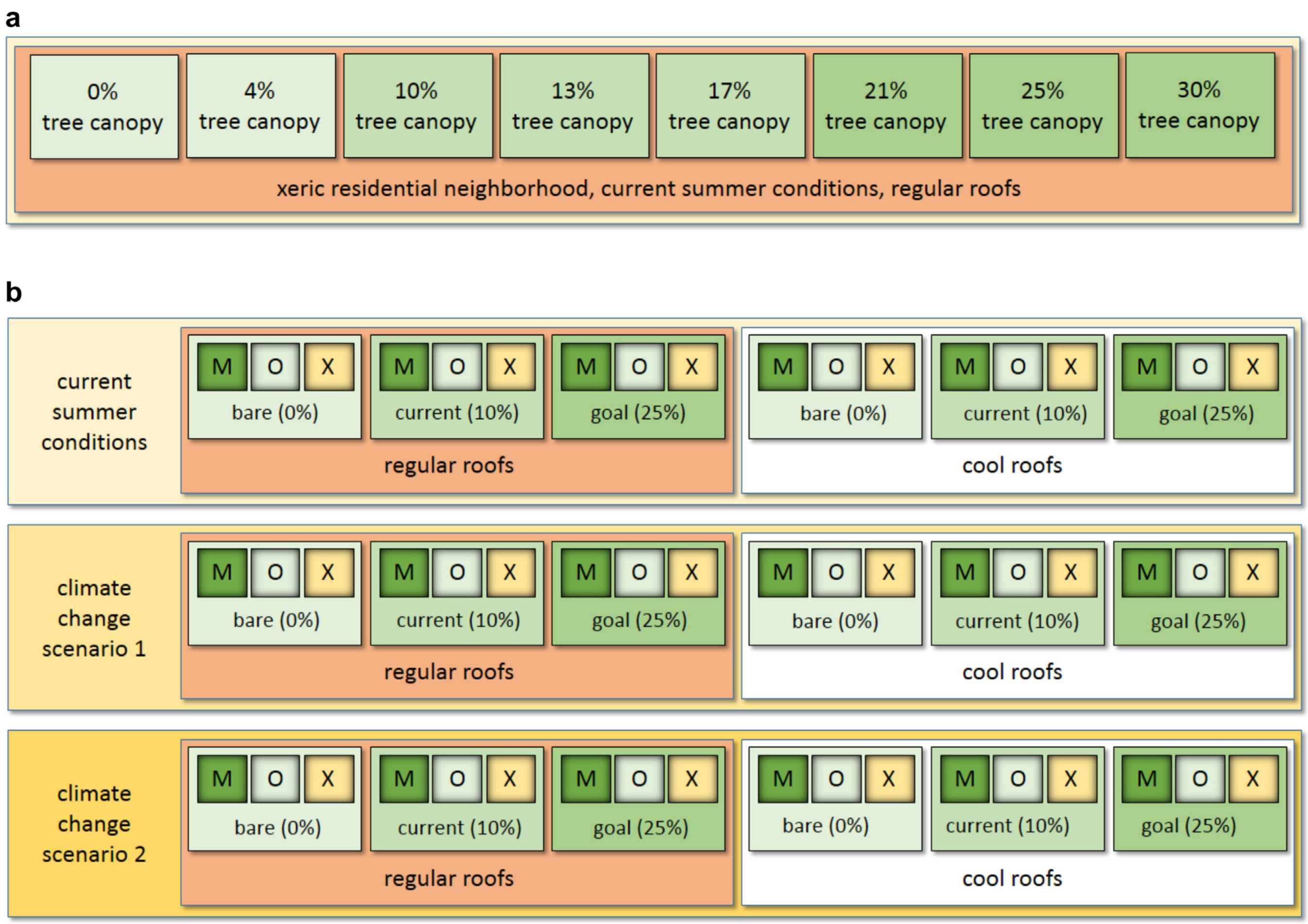

Fig. 2. (a) Tree cover scenarios from 0% to 30% for xeric residential neighborhood under initial conditions; and (b) ensemble of scenarios with varying tree cover, landscaping, roof type, and climate.

the neighborhood scale. We designed eight scenarios with varying tree canopy cover, ranging from 0% to 30% (Figs. 2a and 3), using a mix of native and non-native trees (Table 1) evenly distributed across the available space. To eliminate compounding effects of grass and other vegetation, we chose inorganic mulch as ground cover, reflective of xeric landscaping. By keeping the arrangement of buildings and streets constant, we eliminated the effects of urban form on the simulated microclimate and therefore isolated the impact of trees.

In the second step, we assessed the combined impact of tree canopy cover and cool roofs on mid-afternoon air temperatures for June 23, 2011 and for two climate change scenarios (Fig. 2b). We designed three landscaping scenarios for the residential subdivision that reflect the predominant yard styles in Phoenix: mesic

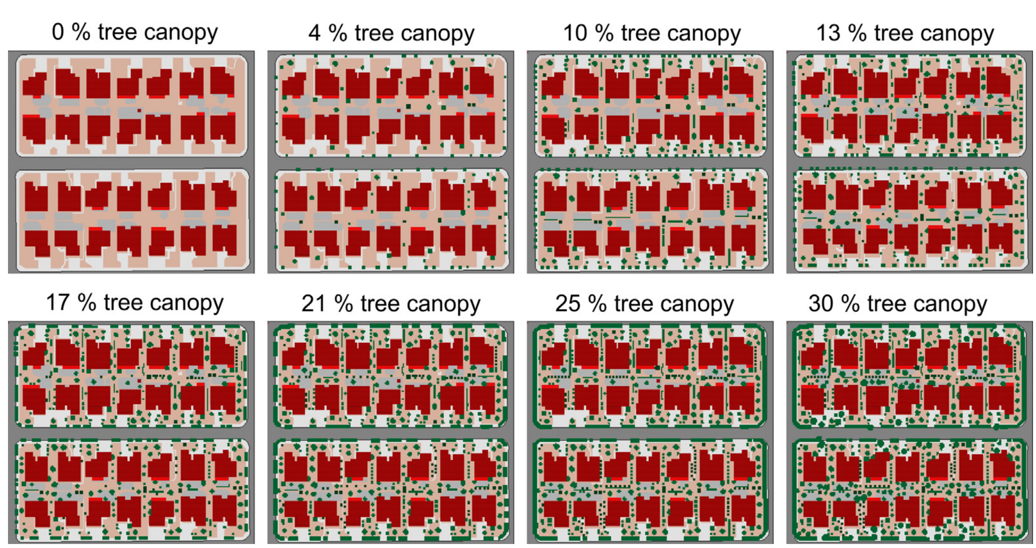

Fig. 3. Residential neighborhood in Phoenix with xeric yards and varying tree canopy cover.

Table 1
Common native and introduced tree species in Phoenix.

Tree	Species	Height (m)
Afghan Pine	*Pinus eldarica*	6
Blue palo verde	*Parkinsonia florida*	8
Bottle tree	*Brachychiton populneus*	11
Chinese elm	*Ulmus parvifolia*	9
Chinese pistache	*Pistacia chinensis*	4
European olive	*Olea europaea*	9
Ironwood	*Olneya tesota*	6
Mexican fan palm	*Washingtonia robusta*	20
Phoenix thornless mesquite	*Prosopis hybrid Phoenix*	9
Arizona ash	*Fraxinus velutina*	12
Shoestring acacia	*Acacia stenophylla*	12
Southern live oak	*Quercus virginiana*	9

(sprinkler-irrigated grass and lush vegetation), xeric (decomposing granite mulch, low-water use vegetation), and oasis (a mix between mesic and xeric). Then, we virtually planted trees to create a 10% canopy cover and 25% canopy cover in the neighborhood, using common tree species in Phoenix (Table 1). To simulate high reflective cool roofs, we set the roof albedo value in the ENVI-met configuration file to *0.88*, an Environmental Protection Agency (EPA) standard for Energy Star roof coating after a 3-year wear and tear period (Georgescu et al., 2013). We based our projected climate scenarios runs on results from the statistically downscaled CMIP3 climate model outputs for the Southwestern US, as outlined in the *Assessment of Climate Change in the Southwest United States* report (Cayan et al., 2013). Minimum and maximum average annual warming projections were, respectively, 1.1 °C and 3.3 °C, both for the low (B1) emission scenario from 2070 to 2099 and the high (A2) emission scenario from 2041 to 2070. In total, we ran 54 ENVI-met model simulations, i.e., for each of the 9 combined tree canopy cover and landscaping scenario with regular roofs and cool roofs under current conditions and for 1.1/3.3 °C warming, using the parameters listed in Table 2.

Results

Relationship between tree canopy cover and air temperature

For the each of the eight xeric neighborhood scenarios with varying tree canopy cover, we extracted 2 m air temperature values at 3:00 pm from the ENVI-met simulations of June 23, 2011.

Table 2
ENVI-met building and climate parameters, evaluated for June 23, 2011, for base conditions, and roof/climate scenarios.

Building data		Regular roofs		Cool roofs
Inside temperature (°C)			23.00	
Heat transmission walls ($Wm^{-2}K$)			1.60	
Heat transmission roofs ($Wm^{-2}K$)			6.00	
Albedo walls			0.55	
Albedo roofs		0.20		0.88
Meteorological data	**Base case**	**Climate scenario 1**		**Climate scenario 2**
Wind speed, 10 m above ground (ms^{-1})		1.50		
Wind direction (0:N, 90:E) (°)		280		
Roughness length at reference point (m)		0.01		
Initial temperature atmosphere (K)	299.00	300.10		302.30
Specific humidity in 2500 m [water/air] ($g\,kg^{-1}$)		2.39		
Relative humidity in 2 m (%)		23.00		
Cloud cover (*x*/8)		0.00		

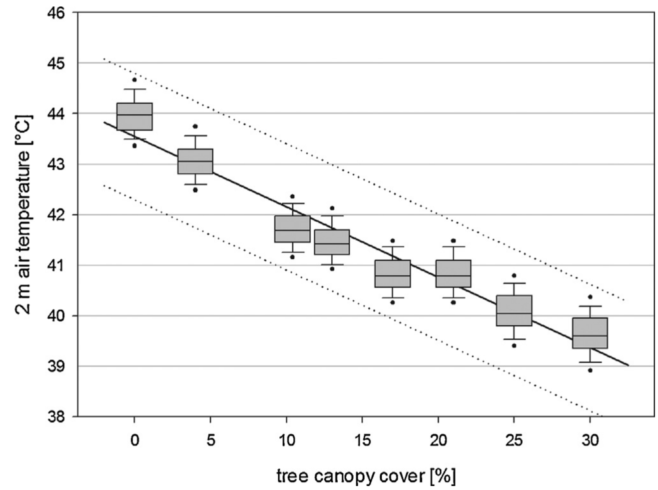

Fig. 4. Relationship between percent tree canopy cover and near ground air temperatures at the neighborhood scale as modeled by ENVI-met for June 23, 2011, at 3:00 pm. The upper and lower bounds of the box plots indicate the 25th and 75th percentile of the 2 m air temperature values in the model domain, the whiskers represent the 10th and 90th percentiles, and the dots stand for the 5th and 95th percentile.

We chose 3:00 pm, because mid-afternoon is the hottest time of day, and, thus, shade trees are the most beneficial in terms of human comfort. To significantly reduce the edge effect that occurs at the western border of the model domain due to the inflow profile, we excluded 65 boundary grids at the western border of the model domain from the temperature averages. Box plots summarize the neighborhood temperatures for the eight tree planting scenarios (Fig. 4). Modeling results exhibit a linear relationship between percent tree canopy cover and near ground air temperature, with $R^2 = 0.88$ and 0.14 °C air temperature reduction per percent increase in canopy cover. These findings are in line with results from other studies investigating tree canopy cover impacts on air temperatures. Hamada and Ohta (2010) found a significant negative correlation between summer afternoon air temperature and percent tree cover within a 200 m radius from an observation site in Japan. Myint et al. (2013) investigated the relationship between surface temperatures and land cover types in Phoenix and found a linear relationship between tree cover and daytime temperatures for July 2005. Simpson (1998) reported a mid-day air temperature reduction of 0.04 °C to 0.20 °C for every one percent increase in canopy cover.

The relationship between canopy cover and cooling becomes less clear when examined in combination with varying neighborhood designs. Grass and other vegetative cover have an impact on air temperature, mainly through evapotranspiration. Modifications of land surface cover changes the heat storage capacity of the urban environment and urban form further affects microclimate through a change in wind patterns and shading. Finally, the arrangement of trees (dispersed vs. clustered) and tree species may have an impact on the cooling benefit. These compounding effects need further investigation through a more comprehensive, observational study.

Cooling benefit of trees and cool roofs at the neighborhood scale

We ran an ensemble of 54 neighborhood scenarios with ENVI-met, combining three landscaping options (mesic, oasis, and xeric), three tree planting scenarios (no trees, current canopy cover, 2030 canopy goal), two roof scenarios (regular roofs, high reflective cool roofs) and three climate scenarios (June 23, 2011; +1.1 °C; +3.3 °C). For each of the 54 scenarios, we extracted average neighborhood mid-afternoon air temperatures to assess the cooling benefits of each heat mitigation measure under current and projected climate conditions. Again, 65 grids at the western border of the model domain were excluded from the calculation to eliminate edge-effects.

The simulation results for 2 m air temperature at 3 pm in the residential neighborhood are illustrated in Fig. 5. Results are arranged in a matrix and grouped by climate scenario (rows) and roof type (columns). A 9 by 9 sub-matrix displays neighborhoods by percent tree canopy cover (rows) and landscaping style (columns). As expected, the scenario with the lowest air temperatures is the residential neighborhood with mesic landscaping that has a combination of 25% tree canopy cover and cool roofs under current climate conditions (row 3, column 4) with an average neighborhood temperature of 37.4 °C. In contrast, the hottest scenario is the xeric neighborhood with no tree cover and regular roofs under the high emission climate change scenario (row 7, column 3). Near ground air temperatures for this scenario average 46.7 °C. Across all columns of the matrix, an increase in tree canopy cover from 0% to 10% decreases average neighborhood temperatures by 2.0 °C. Increasing tree canopy cover further to 25% leads to an additional temperature reduction of 2.4 °C – a total cooling benefit of 4.4 °C, as compared to the bare neighborhood. Switching landscaping from xeric to oasis, i.e., adding grass patches to residential backyards, reduces neighborhood temperatures by 0.2 °C to 0.3 °C on average. Replacing all inorganic mulch by turf has a local cooling effect of 1.7 °C to 1.9 °C. These results are consistent with observational studies in hot and dry climates. In Athens, Greece, Shashua-Bar et al. (2010) evaluated passive cooling scenarios in urban streets having tree canopy cover. They found a cooling benefit of 2.2 °C at 15:00 h for a tree coverage of 35% and an additional 1.2 °C cooling effect for a 70% tree cover scenario. Microclimate observations during a controlled experiment in the arid Negev Highlands, Israel, yielded a daytime temperature reduction of up to 2.5 °C for a bare courtyard that was planted with trees and grass (Shashua-Bar et al., 2009). Srivanit and Hokao (2013) investigated the local cooling effects of trees using on-site measurements and ENVI-met simulations for a hot dry summer day in Japan. An increase of tree canopy by 20% reduced air temperatures by 2.3 °C. In Phoenix, Golden et al. (2007) investigated the cooling potential of trees located on parking lots and found that the tree canopy reduced 2 m air temperatures by 3.5 °C at noon. Chow and Brazel (2012) suggested xerophytic shade trees as sustainable UHI mitigation measure for Phoenix and estimated a daytime cooling benefit of 1.1 °C at the local scale, with cooling benefits of 2.5 °C at the microscale. These findings emphasize the importance of strategic tree location in heat mitigation.

Compared to the cooling impact of trees, the impact of cool roofs on local daytime temperatures modeled by ENVI-met is relatively low. Across all climate and tree scenarios, 2 m air temperature reduction through the implementation of cool roofs only amounts to 0.3 °C for the neighborhood. Results from other studies assessing the impact of cool roofs on air temperatures range from minor cooling benefits to significant benefits, due to varying modeling assumptions and parameterizations, geography, and scenarios. Our results are consistent with the low end range of these studies.

Li et al. (2014) simulated cool roofs with the Weather Research and Forecasting (WRF) model in the Baltimore-Washington metropolitan area, using an albedo value of 0.7. They found a 2 m air temperature reduction of up to 0.6 °C at 3:00 pm. Using WRF for Bakersfield, California, Ban-Weiss et al. (2014) found an afternoon temperature decrease of 0.2 °C when replacing all existing roofs with cool roofs. At the global scale, Oleson et al. (2010) estimated an urban daily maximum decrease of 0.6 °C by implementing white roofs. At the regional scale, Georgescu et al. (2012) simulated the effects of cool roofs on the Arizona Sun Corridor's regional temperatures for various urban expansion scenarios and found that highly reflective roofs could offset urban-induced warming by about 50%, but also changed precipitation patterns in the region. This study shows that implementing cool roofs for heat mitigation comes with tradeoffs that need to be considered.

Discussion

An increase in tree canopy cover from the current 10% to the City of Phoenix goal of 25% resulted in a 2.0 °C temperature reduction at the local scale and could offset the amount of urban warming predicted by the more conservative climate change scenario. However, the City's goal of 25% tree canopy cover by 2030 can only be achieved with public support. Further research is necessary to systematically assess the impact of the arrangement and type of trees on the heat mitigation potential of the urban forest, especially in the context of various urban forms and compared to or combined with artificial shading structures. Tree layout, spacing, and location are key factors for optimal cooling, because shading is localized. Trees provide more cooling benefits at the microscale than the local scale, therefore, tree placement at strategic locations is important to increase pedestrian comfort and energy savings from buildings.

There is a wide range of research results on the impact of cool roofs on air temperatures, from 0.2 °C up to 1.5 °C, mainly because studies were conducted at small to large scales in various climates using a variety of models, parameterizations and assumptions. Our ENVI-met simulations for cool roofs are in agreement with the lower end range of these studies and show no significant daytime temperature reduction at 2 m height across all tree and climate scenarios. However, we would expect an impact on building energy performance, which could be quantified through a building energy simulation. The impact of cool roofs on pedestrian thermal comfort also needs further investigation, since albedo modification of urban materials changes the radiation balance of the urban environment. A full economic benefit analysis of cool roofs should not only assess the costs and diurnal cooling benefit of high reflective roofs, but also include an analysis of how the cooling benefit might decline over time due to dust and dirt, how the roofs might impact precipitation patterns in the region.

The impact of trees and cool roofs on nighttime temperatures, and thus on the UHI, also needs further investigation. ENVI-met 3.1 has several shortcomings that make the model unsuited for nocturnal cooling analyses and limit its use to daytime situations. First, the ENVI-met meteorological forcing parameters cannot be adjusted during the simulation, resulting in a conservative diurnal temperature curve that underestimates maximum temperatures during the day and overpredicts minimum temperatures at night. Second, in the model, walls and roofs do not store heat and consequently do not release heat at night. Therefore, ENVI-met overestimates emitted long-wave radiation during the day and underestimates it at night. Third, previous research found that the rate of nighttime cooling is lower under tree canopies due to a reduced sky-view factor (Akbari et al., 2001). This heat retention cannot be modeled with ENVI-met. Despite these limitations, ENVI-met yields reasonable results for daytime simulations if the model is calibrated well. Lastly, ENVI-met does not account for anthropogenic heat. Waste heat release from A/C systems in some Phoenix neighborhoods was found to increase 2 m air temperatures by 1 °C and more during the night using the WRF model (Salamanca et al., 2014). The mean warming effect was found to be negligible for near surface temperatures during the day at the regional scale, but heat emission reductions due to reduced energy use of buildings with cool roofs should be investigated further at the microscale using building energy models.

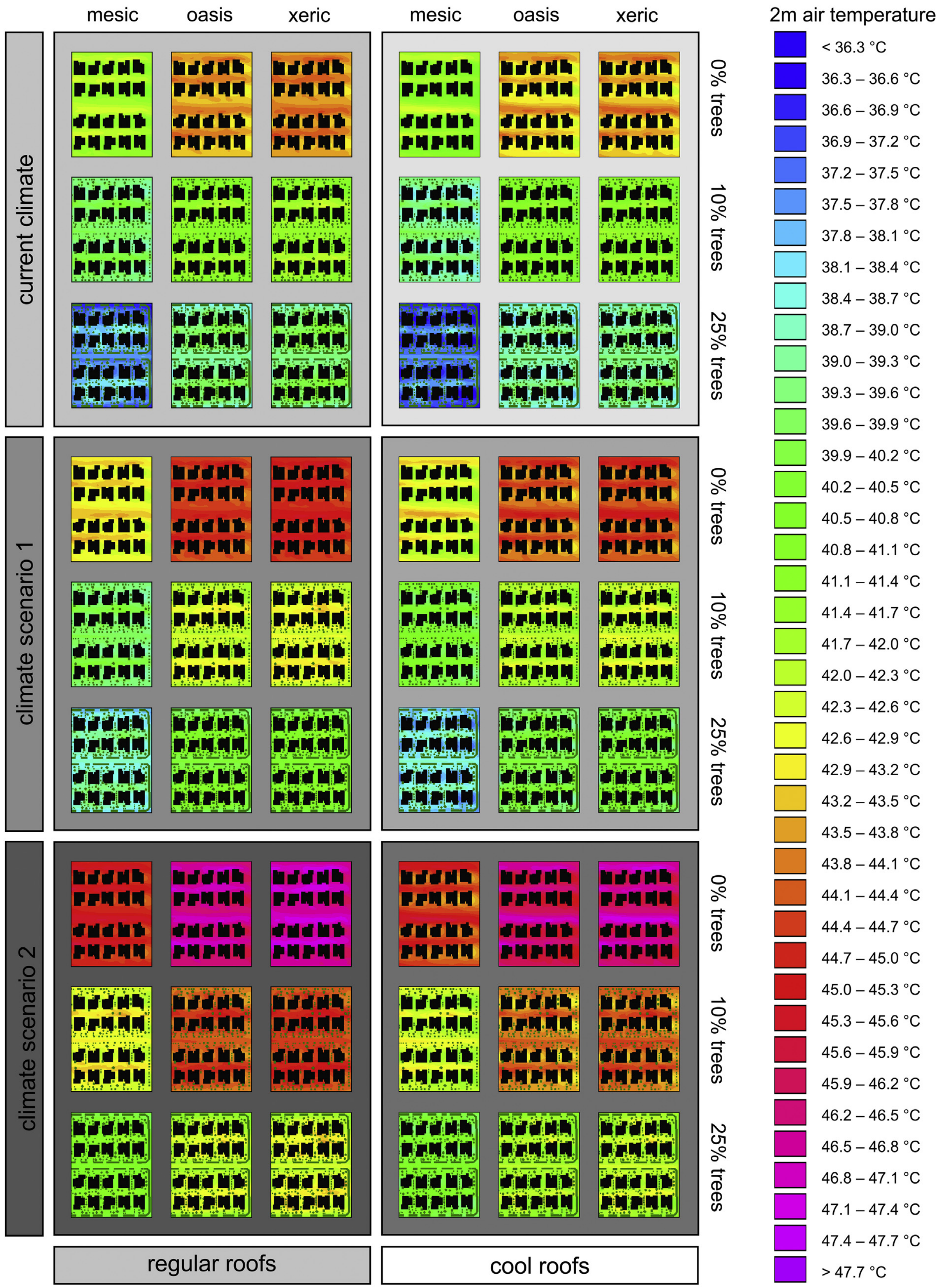

Fig. 5. ENVI-met simulations for an ensemble of 54 scenarios that combine landscaping styles and heat mitigation strategies for current and projected pre-monsoon summer climate in Phoenix; simulations for June 23, 2011, 3:00 pm.

In addition to shade benefits during the day, trees provide various ecosystem services and socio-economic benefits, e.g., air quality improvement, higher property value, reduced building energy-use, noise mitigation, reduction of storm water runoff and flooding, reduced street maintenance costs, carbon sequestration, creation of wildlife habitats, and recreational opportunities for residents (McPherson et al., 2005; Nowak and Dwyer, 2007). However, maintaining a healthy urban forest requires maintenance costs and, in desert environments, irrigation. A cost–benefit analysis and full economic assessment of the Phoenix urban forest, assessing benefits against costs, was beyond the scope of this project, but should be conducted for a comprehensive assessment of all tree benefits and management costs. Recent studies attempted to determine the environmental and socio-economic value of urban forests for the cities of Toronto, Canada (Millward and Sabir, 2011) and Los Angeles, California (McPherson et al., 2011) using the iTree software. The City of Phoenix recently completed an inventory for trees on publicly owned land (City of Phoenix, 2014), which could provide the basis for a cost–benefit analysis, but needs to be expanded to private properties first. An economic analysis of the Phoenix urban forest should also include an assessment of environmental costs that are associated with increased irrigation demands. With the prospect of more frequent and extended droughts in the southwestern US due to climate change, increasing tree canopy cover in Phoenix to 25% will put additional stress on the water supply. For sustainable heat mitigation in the desert, design strategies need to be developed that maximize the collective benefits from the urban forest in balance with water use and costs, e.g., water-sensitive urban design with low water use trees and artificial shading structures.

Conclusions

This study has several implications for heat mitigation measures and climate adaptation in Phoenix. First, our model results show that increased tree coverage in Phoenix neighborhoods reduces air temperatures, but the magnitude of this impact, even at a 25% tree canopy cover, may not be sufficient to offset increased temperatures due to climate change. However, trees can be one component of a climate adaptation strategy. Second, further research is needed to quantify the cooling, social, economic, and environmental benefits; the promotion and management costs; and water use implications of a tree program in a comprehensive economic assessment. Finally, the benefit of cool roofs for heat mitigation and climate change adaptation needs to be further investigated for the entire Phoenix region. Cool roofs have benefits that extend beyond their impact on ambient temperatures. To assess their role in UHI mitigation and climate change adaptation, a comprehensive analysis of implementation and maintenance costs, property values, building energy savings, and thermal comfort implications is needed.

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