Characterizing Sustainable Performance and Human Thermal Comfort in Designed Landscapes of Southwest Desert Cities

by

Kaylee Colter

A Thesis Presented in Partial Fulfillment
of the Requirements for the Degree
Master of Science

Approved April 2016 by the
Graduate Supervisory Committee:

Chris Martin, Chair
Paul Coseo
Ariane Middel

ARIZONA STATE UNIVERSITY

May 2016

ABSTRACT

During summer 2014, a study was conducted as part of the Landscape Architecture Foundation Case Study Investigation to analyze features of three sustainably designed landscapes. Each project was located in a southwest desert city: Civic Space Park in Phoenix, AZ, the Pete V. Domenici US Courthouse Sustainable Landscape Retrofit in Albuquerque, NM, and George "Doc" Cavalliere Park in Scottsdale, AZ. The principal components of each case study were performance benefits that quantified ongoing ecosystem services. Performance benefits were developed from data provided by the designers and collected by the research team. The functionality of environmental, social, and economic sustainable features was evaluated. In southwest desert cities achieving performance benefits such as microclimate cooling often come at the cost of water conservation. In each of these projects such tradeoffs were balanced by prioritizing the project goals and constraints.

During summer 2015, a study was conducted to characterize effects of tree species and shade structures on outdoor human thermal comfort under hot, arid conditions. Motivating the research was the hypothesis that tree species and shade structures will vary in their capacity to improve thermal comfort due to their respective abilities to attenuate solar radiation. Micrometeorological data was collected in full sun and under shade of six landscape tree species and park ramadas in Phoenix, AZ during pre-monsoon summer afternoons. The six landscape tree species included: Arizona ash (*Fraxinus velutina* Torr.), Mexican palo verde (*Parkinsonia aculeata* L.), Aleppo pine (*Pinus halepensis* Mill.), South American mesquite (*Prosopis spp*. L.), Texas live oak (*Quercus virginiana* for. fusiformis Mill.), and Chinese elm (*Ulmus parvifolia* Jacq.). Results showed that the tree species and ramadas were not similarly effective at improving thermal comfort, represented by physiologically equivalent temperature (PET). The difference between PET in full sun and under shade was greater under *Fraxinus* and *Quercus* than under *Parkinsonia*, *Prosopis*, and ramadas by 2.9-4.3 °C. Radiation was a significant driver of PET ($p<0.0001$, $R^2=0.69$) and with the exception of ramadas, lower radiation corresponded with lower PET. Variations observed in this study suggest selecting trees or structures that attenuate the most solar radiation is a potential strategy for optimizing PET.

ACKNOWLEDGMENTS

This research was funded in part by the Landscape Architecture Foundation Case Study Investigation. Contributions of all the Case Study project designers and clients are greatly appreciated. Gratitude is also owed to the City of Phoenix for their permission to conduct this research within city parks. Along with the insights and expertise shared regarding this research, I am thankful to Chris Martin for inspiring me to confidently pursue my own scientific questions, to Ariane Middel for mentoring me through even the smallest dilemma, and to Paul Coseo for reminding me of the value of my experience. Finally, this research could not have been possible without the support of friends, family, and my husband and unpaid intern, Cole.

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CHAPTER 1

QUANTIFYING THE SUSTAINABLE PERFORMANCE OF DESIGNED LANDCAPES: THREE CASE STUDIES FROM SOUTHWEST DESERT CITIES

Introduction

During the summer of 2014 a study was conducted as part of the Landscape Architecture Foundation (LAF) Case Study Investigation to create profiles of three sustainably designed landscape projects. Each profile was intended to provide useful information about the sustainable features of each park and was added into an online database for landscape architects and urban designers to utilize as a resource. Information pertinent to each project such as size, location, and construction costs were complied with narrative components such as lessons learned and challenges faced during construction. The sustainable features section highlighted sustainable features that provided a one-time benefit and cost comparisons highlighted the expenses of a sustainable construction method compared to a traditional method. The key features of the case studies were performance benefits. Each performance benefit highlighted an ongoing benefit provided by the project and quantified it in an easily interpreted manner. The benefits were derived through a combination of data provided by the project designers and data collected by the research team. The methodology for each performance benefit and cost comparison is included in this text. The full case study profile can be accessed online through the LAF website (http://landscapeperformance.org/).

Methodology: Civic Space Park

Introduction

Located in the heart of Phoenix, AZ near Arizona State University's (ASU) downtown campus, Civic Space is a 0.41 ha public park designed to be a 'cool island' in the city center. Construction of the park was completed in 2009 for a total budget of $13.2 million. The site is in an urban location surrounded by development on all sides. Prior to development the site was a mixture of parking lots and previous buildings, which classified the site as a greyfield with no significant landscape features. The City of Phoenix is located within the Sonoran Desert and within USDA Zone 9. The mean rainfall and potential evapotranspiration for the city is 203 mm and 2286 mm per year, respectively. Daily maximum air temperatures during the summer months can be extreme with a mean of 90 days per year over 37 °C.

Project Features

The design goals of the park were to provide shade, reduce summer temperatures, increase soil permeability, and provide a space for public life downtown. Using a combination of shade trees and undulating shade structures, the park was designed to provide shade for 70% of the site at full maturity. The park was also planned to include a landmark art installation by artist Janet Echelman, lawn areas, permeable paving, solar power, a covered stage, splash pad, and interactive LED light columns. Civic Space was funded as the open space component of a downtown revitalization effort that connected Arizona State University (ASU) Downtown Campus with park amenities such as the historic A.E. England Building that was restored as part of the Civic Space project. The building now houses event space, classrooms, and retail space that provide additional revenue for the City and create activity in the park. The sustainable features of this park include:

- 111 new trees selected to optimize shade and water conservation
- All trees planted in hardscape areas, 33 total, were planted in structural soil to expand the effective root zone
- Permeable concrete sidewalks provided new hardscape areas without increasing impermeable surfaces and stormwater runoff
- All stormwater runoff is collected on-site and infiltrated in 128 subsurface infiltration chambers with a total capacity of 271 m^3
- Passive cooling techniques like the water feature wall provide microclimate cooling benefits
- A 75 kW solar power array provides power to supply the park features

Performance Benefits

An underlying theme of the research was evaluating the role of an urban oasis in ameliorating temperature for human comfort and heat island mitigation. This project was not designed to meet the standards of any sustainable rating system; therefore limited data was collected during the construction phase, which concluded five years prior to this study. Meaning that performance benefits for this project primarily had to be generated from data collected during the summer research effort. After conducting preliminary site visits and interviews, it was clear that the social aspects and efforts at temperature mitigation should be the focus of research for this park. A challenge to collecting the social data was that the project timeline coincided with summer when park use by general visitors and ASU students sharply decreases. Since park use in Phoenix is so strongly influenced by temperature the research team felt that evaluating temperature profiles in the park would also provide useful insights into use of the park.

Collects and infiltrates up to 271 m^3 of water per storm event in underground chambers located on-site. Water collected in the chambers is infiltrated into a permeable subgrade, replenishing the equivalent daily water use of 179 families each time the chambers are filled.

Typical City of Phoenix development guidelines requiring on-site stormwater management were waived for Civic Space Park. Despite this waiver the design team still pursued a strategy to manage stormwater on-site, preventing the addition of stormwater run-off to the municipal stormwater system. Geotechnical surveys revealed that a highly permeable layer, due to the proximity of the Salt River, was located at a relatively shallow depth. This provided the design team with the opportunity to use an underground infiltration system to safely manage stormwater in a manner that also contributed to the recharge of groundwater resources.

Construction documents provided by the design firm indicated the installation of eight rows each with 16 StormTech SC-740 chambers (AECOM, 2009). The product cut sheet for StormTech SC-40 Chambers indicated a total storage capacity of 2.1 m^3 for each chamber installed over a 152 mm gravel foundation (StormTech, 2014). The total capacity of all chambers was calculated by multiplying the number of chambers by the capacity: 128 chambers x 2.1 m^3 =

271 m^3. To relate the impact of the infiltration volume the research team calculated an equivalent for the amount of water used by an average American household. The EPA indicates that an average American family of four utilizes 1,514 L of water each day. To see how many families worth of water could be recharged by the stormwater chambers, the total chamber capacity was converted into liters: 271 m^3 x 1000 L/m^3 = 271,000 L. This value was then divided by 1,514 L to find the equivalent number of families: 271,000 L / 1,514 L = *179 families.* If the infiltration chambers were filled to capacity the infiltration would offset the average amount of water used by 179 American families each day. However, this calculation only accounted for the amount of water needed to fill the chambers once. Chambers could be filled in different increments and by multiple storm events throughout the year, affecting the total amount of annual water infiltration.

Doubles the productivity (rate of photosynthesis) of trees planted within hardscape areas by utilizing structural soil to expand the effective root zone.

The park design utilized structured soil to increase the effective soil area for trees planted in hardscape plazas. Typically growth of trees planted in hardscape areas is severely constrained by limited rooting volumes due to the high levels of soil compaction required for the stability of paving materials. When properly installed, structured soil provides a stable base for paved materials as well as pore space for root growth, which should provide for increased tree health and growth (Bassuk, 2008). To establish if this was the case for Civic Space, the research team measured the net leaf gas exchange fluxes (net atmospheric carbon sequestration or photosynthesis) of trees planted within landscape areas and trees planted within hardscape dominant plazas using structural soil. The team also tested two control trees of the same species that were planted off-site in a more typical hardscape condition without structural soil. The results showed that the park trees planted within hardscape dominant plazas using structural soil to expand the effective root zone were performing at a rate greater than the park trees planted within landscape areas without soil compaction issues. Moreover, this rate of productivity was two times greater than the rate observed for control trees within typical urban conditions with significant paving and soil compaction (Table 1).

Fig. 1. Location of Trees Selected for Recording Net Leaf Gas Exchange and Air Temperature Data at Civic Space Park in Phoenix, AZ USA.

Fig. 2. From Left to Right Installation of Structural Soil and Growth of Trees in 2009 at Civic Space Park in Phoenix, AZ USA.

Leaf gas exchange of *Pistacia chinensis* Bunge (Chinese pistache), *Fraxinus velutina Torr.* (Arizona ash) and *Pyrus kawakamii* Hayata (Chinese evergreen pear) were analyzed using a LI-6200 infrared gas analyzer operating in closed system mode. With the exception of the Chinese evergreen pear, trees that were sampled were the same as those that were used to record shaded air temperatures (Fig. 1). Trees selected were similar in size, age, leaf surface area, and health. The most recently physiologically mature sun-adapted leaves were chosen for measurements. Two to seven leaves per tree were sampled. Data were recorded from 1000-1200 hr on June 5, 2014. This time frame was selected because it was the earliest time of day that all of the trees were equally exposed to sunlight, which reduced potential bias due to the availability of sunlight. All environmental and physiological data were analyzed using JMP statistical software (JMP 8.02, SAS Institute, Cary, NC).

In Civic Space Park, structural soil made an improvement in the rate of photosynthesis that occurred within the trees. Increased net photosynthesis is associated with increased tree growth and a greater ability of trees to mitigate high levels of atmospheric CO_2 associated with urbanization. The design and installation of structural soil was determined in the field during construction, so there were not details with the specific quantity of soil available. Personal communication with the material supplier revealed that in just five years the trees had already grown to the extents of the minimal amount of structural soil provided, just 1.2 m surrounding the root ball (Fig. 2).

Reduces surface temperatures by providing 2,806 m^2 of turf that is 20.8 °C cooler than hardscape surfaces and 2.6 °C cooler than typical landscape surfaces measured mid-day. Turf also positively contributes to heat island mitigation reaching a temperature of only 19.6 °C on a summer evening.

Parks in desert cities must attempt to improve human comfort by mitigating hot summer temperatures. To evaluate how this was accomplished in Civic Space Park, the research team measured both surface temperatures and air temperatures. The research team used a scaled site plan to overlay a 15.2 m grid on the site. In the field, a walking tape measure was used to identify

Table 1. Rate of Net Photosynthesis Recorded for Selected Trees From 1000-1200 hr, June 5, 2014 at Civic Space Park in Phoenix, AZ USA.

Planting Conditions	Tree Species	Rate of Photosynthesis ($umol/m^2/s$)
Trees in Landscape	*F. velutina*, *P. kawakammii*	16.4
Trees in Structural Soil	*P. chinensis*	18.6
Trees in Typical Urban Condition	*P. chinensis*	9.9

Table 2. Mean Surface Temperature in Full Sun for Each Surface Type at Civic Space Park Recorded at 1230 hr and 2200 hr on June 5, 2014 in Phoenix, AZ USA

Surface Type	Surface Temperature (°C)	
	1230 hr	2200 hr
Hardscape	52.1[Z]	33.4
Groundcover	33.9	28.8
Turf	31.3	19.6

[Z] Values are means, n=72

Table 3. Mean Surface Temperature Difference Between Data Recorded at 1230 hr and 2200 hr in Full Sun for Each Surface at Civic Space Park on June 5, 2014 in Phoenix, AZ USA.

Surface Type	Surface Temperature Difference (°C)
Hardscape	8.7[Z]
Groundcover	5.1
Turf	11.7

[Z] Values are means, n=72

the grid points and the temperature, material type, and presence of shade for each point was noted. This method of collection allowed the team to compare how temperatures changed due to material type or shade coverage. Surface temperature records were taken mid-day at 1230 hr and late evening at 2200 hr to evaluate how surface materials contributed to the overall heat island effect.

Surface temperature data of park surfaces in full sun were referenced for this performance benefit (Table 2 and Table 3). Turf grass lawn surfaces were the coolest at 1230 hr and 2200 hr. At mid-day, turf areas were 20.8 °C cooler than hardscape surfaces and even 2.6 °C cooler than landscape areas planted with drought-adapted groundcover. Likely this effect was due to evaporative cooling provided by turf transpiration and release of water from the soil. The greatest decline in surface temperatures between 1230 hr and 2200 hr were recorded on the hardscape surfaces where the differential was 18.7 °C. Although hardscape surfaces cooled the most at night, their surface temperatures at 2200 hr were still 13.8 °C higher than the surface temperature of the turf grass lawn.

Reduces mid-day hardscape surface temperatures by 13.0 °C by providing shade with the use of broadleaf trees and shade structures.

Surface temperature data of park surfaces in shade and full sun were referenced for this performance benefit (Table 4 and Table 5). During the day, shade provided a significant reduction in temperature across all surfaces measured and this was particularly evident for the turf grass lawn and hardscape surfaces. However, an interesting observation was that shade generally inhibited heat loss and subsequent cooling during the evening. The surfaces with the greatest difference between afternoon and evening were unshaded. Turf grass lawn areas provided the coolest spaces during both the day and night. The conclusion was that lawn areas in Civic Space Park contributed to the goal of providing an area of respite within a hot, urbanized area.

Surface temperature data were recorded on June 5, 2014 at 1230 hr and again at 2200 hr. Weather during this interval was normally clear and hot. Measurements were taken with a hand-held infrared thermometer, 7° angle of view. Civic Space Park was divided into a 15.2 m

Table 4. Mean Surface Temperature for Each Surface Type in Shade and Full Sun at Civic Space Park Recorded at 1230 hr and 2200 hr on June 5, 2014 in Phoenix, AZ USA.

Surface Type	Surface Temperature (°C) at 1230 hr		Surface Temperature (°C) at 2200 hr	
	Shade	Open	Shade	Open
Hardscape (Concrete)	39.1[z]	52.1	30.1	33.4
Groundcover	32.6	33.9	28.7	28.8
Turf	24.4	31.3	22.3	19.6

[z] Values are means, n=72

Table 5. Mean Surface Temperature Difference Between Data Recorded at 1230 hr and 2200 hr for Each Surface Type in Shade and Full Sun at Civic Space Park on June 5, 2014 in Phoenix, AZ USA.

Surface Type	Surface Temperature Difference (°C)	
	Shade	Open
Hardscape (Concrete)	9.0[z]	18.7
Groundcover	3.9	5.1
Turf	2.1	10.1

[z] Values are means, n=72

square grid matrix. A digital measuring wheel was utilized to identify each grid point on site. At each point temperature, material type, and presence of shade was recorded. A total of 72 total grid point intersections were measured.

Temperatures in the park are an average of 1.0 °C cooler when compared to a typical urban landscape.

A series of portable data loggers (Watch Dog series B button loggers, Spectrum Technologies, Inc.) were used to continuously record air temperatures at 30-min intervals for three consecutive days (June 5 to 7, 2014) in the park and at a nearby streetscape to understand of how visitors were likely to have experienced temperature in the park. Weather during the three days was seasonably hot and clear. The data loggers were installed at heights of approximately 2-3 m above the ground in orientations removed from exposure to direct insolation, either protected by tree canopy shade or placed inside white-louvered plastic micro-meteorological shelter. Air temperature data were directly downloaded to computer for analysis using JMP statistical software (JMP 8.02, SAS Institute, Cary, NC).

The mean daily air temperature in the park and at a nearby streetscape were 33.2 °C and 34.2 °C, respectively. However, there were intervals during day when these differences were more pronounced (Fig. 3). During the early morning hours (0700-1200 hr), air temperatures were cooler in the park compared to offsite. During mid-day, afternoon and into the late night hours (1300-1500 hr), air temperatures in turf landscaped areas were coolest while air temperature in paved areas of the park and offsite were similarly 1.1-2.2 °C higher. Finally from about 0400-0600 hr, air temperatures over paved surfaces in the park were highest perhaps caused by the release of long wave radiation from the paved surfaces.

Air temperature data were logged by data loggers every 30 minutes for three days from June 5 to 7, 2014. Weather during this interval was normally clear and hot. Loggers were Spectrum Technologies B series WatchDog data logger (http://www.specmeters.com/). Twelve loggers were installed at approximately 2-3 m height under canopy shade of either Chinese pistache or Arizona ash. Two of these loggers were located in similarly aged Chinese pistache

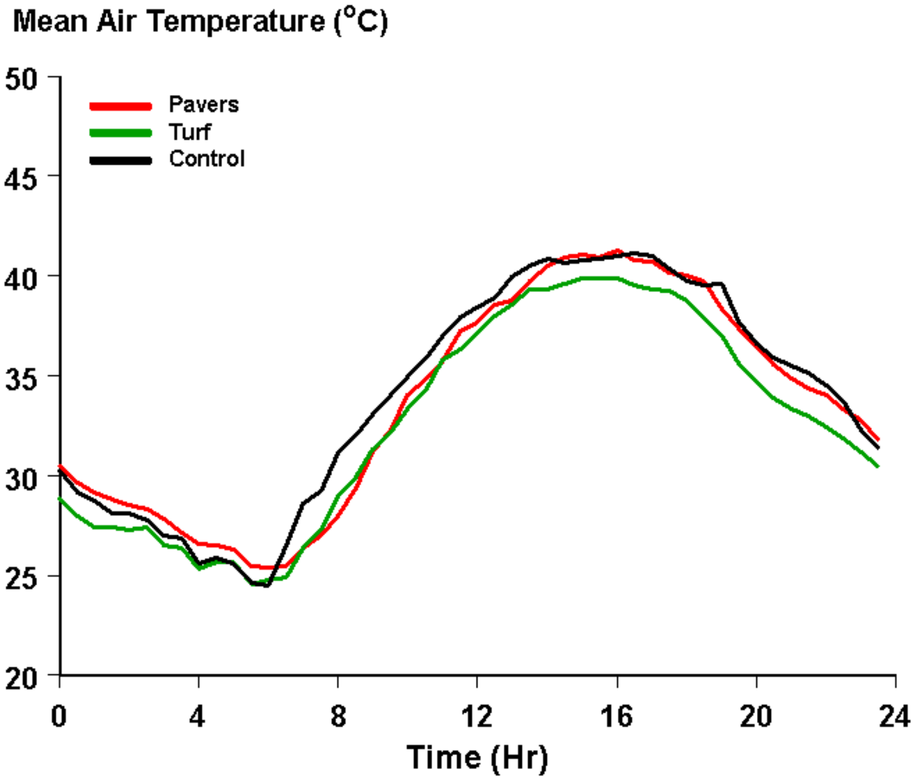


Fig. 3. Mean Daily Air Temperatures During June 5-7, 2014, Recorded 2-3 m Above Concrete Pavers and Turf Grass in Civic Space Park and a Control Planting Area Outside the Park.

Table 6. Summary of Visitors and Activity Type Recorded at Civic Space Park From 0830-1230 hr During May and June in Phoenix, AZ USA.

Date	Total Visitors	% Optional	% Social	% Pedestrian
05/30/14	638	67%	7%	27%
06/06/14	493	47%	18%	50%
06/11/14	547	74%	11%	21%
Mean	559	63%	12%	33%

trees in a nearby streetscape, and represented of a more typical urban planting condition. One additional data logger was positioned in an open location at a height of 1.2 m in a white-louvered weather shield.

Provides a location for an average of 43 free community events from each year including movie screenings, concerts, art galleries, and wellness events such as community yoga.

Regular programming and events are hosted at Civic Space Park and organized by the City of throughout the year. Events hosted by the City and their partners were advertised on the social media website, Facebook. The research team identified 68 events in 2012, 40 events in 2013, and 21 events in 2014. This resulted in a total of 129 events from the last three years and an average of 43 events per year. This list only included free public events sponsored by the city and did not incorporate privately permitted events or those solely organized by ASU.

Attracts an average of 559 visitors on a weekday morning in the low summer season. Of these, 63% engaged in optional activities and 12% of these were also engaged in social activities.

The methodology for observing site visitors to the park was derivative of Jan Gehl's (2011) observations on public space as well as methodologies developed in previous LAF Case Studies. The basis of these types of observations is that visitors to the park will engage in necessary, optional, or social activities. Gehl argues a successful public space has a greater percentage of optional and social activities. Civic Space was most active during the week when adjacent businesses were open. For this reason observations were planned for three weekdays from 0830-1230 hr. The location and activity of each visitor was recorded and their activities were classified as necessary, optional, or social (Table 6). Over the observation days a large number of visitors were observed traveling through the park, these pedestrian (or cyclist) visitors were not identified as optional visitors as it was not practical to determine if their actions were necessary or optional. For visitors who spent an extended amount of time in the park, the LED light plaza, amphitheater, and shaded turf areas were the most popular places to linger. It was also observed that the park, including the A.E. England Building, was a frequently programmed space. On two of the three observation days special events were hosted in the building, which brought an influx of visitors to the park.

A significant limitation of this investigation was that observations were limited to the summer. The number of visitors observed during this study was probably not representative of park use throughout the year. Two factors contributed to this problem; first, high temperatures reduced the number of optional visitors, and second, many of the park users are ASU students who do not live on campus during the summer. The heat also presented a challenge to the research team, and was in part why observations occurred in the morning. To get a more complete picture of the social benefits provided by this park observations should be extended to busier times of the year.

It is also important to note that plan for site observations was reviewed and granted a waiver by the ASU Institutional Review Board. The data collected about visitors during observations was more limited than in some previous case studies; however, the research team found that streamlining the data collected allowed for a prompt review and approval process.

Cost Comparison

Details and quantities of structural soil for Civic Space Park were determined in field; therefore specific information regarding the quantity of soil used was not readily available. To project the cost of structural soil used on-site the research team used recommendations from the developers of CU Structural, a prevalent structural soil brand (Bassuk, 2008). The recommended quantity of structural soil is 0.61 m^3 for each square meter of canopy at mature growth. Only two types of trees were planted in hardscape areas, Chinese pistache and *Quercus virginiana* (Southern live oak). Chinese pistache has an expected canopy diameter of 9 m and area of 66 m^2 (Martin, 2016). Southern live oak has an expected canopy diameter of 12 m and area of 117 m^2 (Martin, 2016). The expected volume of soil per tree was calculated for each tree type. For Chinese pistache, 66 m^2 x 0.61 m^3 = 40.3 m^3; and for southern live oak, 117 m^2 x 0.61 m^3 = 71.4 m^3. The research team received an estimated cost for CU Structural soil by a local supplier and extrapolated the cost over the project site. Locally the cost, including delivery, was approximately

$0.05/kg with approximately 1788.05 kg in a cubic meter. The cost was multiplied by the quantity required for each tree and the number of each tree. For Chinese pistache, 40.3 m^3 x 1,788.05 x $0.05 x 13 trees = $46,838*;* for southern live oak, 71.4 m^3 x 1,788.05 x $0.05 x 18 trees = $114,900; and for the total cost, $46,838 + $114,900 = $161,738.

Any use of structural soil was a cost addition to the project compared with the free cost of using soil found on site. However, the additional cost did not account for the added benefits of the improved tree health. Leaf gas exchange measurements taken by the research team indicated that the trees in structural soil were twice as effective at photosynthesis than similar trees in a hardscape condition without structural soil. Healthier trees will be less expensive in the long run, require less maintenance and reduce the likelihood that they will need to be replaced.

Methodology: Pete V. Domenici US Courthouse Sustainable Landscape Retrofit

Introduction

The Pete V. Domenici U.S. Courthouse Sustainable Landscape Retrofit (Domenici Courthouse) in Albuquerque, New Mexico was a redevelopment of the 1.9 ha courthouse campus to reconnect the urban site with its historical and geographic context. Construction of the retrofit was completed in 2013 for an approximate budget of $2.8 million. The project site is located within the high desert Albuquerque Basin that is within USDA Hardiness Zone 7. During the year, over 3,418 hours of sunshine creates an arid climate. During winter, mean daily minimum temperatures are as low -3.3 °C. Albuquerque receives an average of 239 mm of rainfall each year with a significant portion of that falling during the North American monsoon season from July to October in the form of thunderstorms. The site can be found within the heavily urbanized downtown Albuquerque district with significant amounts of heat conducting materials such as asphalt and concrete. Existing landscape plantings within the district are quite limited.

Project Features

The design was intended to convert a water intensive turf landscape into one that provided a dignified setting for court operations and enhanced environmental efficiency.

Sustainability strategies incorporated into the design included rainwater harvesting, stormwater management, energy-efficient lighting, on-site solar panels, native and drought-tolerant plants, and extensive use of repurposed materials. The project was designed as a model for future sustainable landscape retrofit projects for the Government Services Administration that would demonstrate how a municipal site could more efficiently use public and natural resources. The sustainable features include:

- *Over 1,951 m^2 of existing concrete paving was harvested from the site to create new walls and benches*
- *The hardscape materials palette includes 2,159 m^2 (31.9%) of materials with an SRI value greater than 29 and provides shade for 2,883 m^2 (42.6%) of hardscape surfaces*
- *Provided a prevailing wage per Davis-Bacon Act for 100% of the 45 construction workers and a living wage per Living Wage Calculator for 58% of workers (Glasmeier, 2012).*
- *Salvaged 25% of building materials and plants for reuse in the landscape renovation, preventing the addition of materials to the landfill*
- *Power for the landscape is provided by 27.5 kWh solar panel array installed on the lower levels of the courthouse roof*
- *Stormwater management strategy features bioswales, and terraced rock gardens*
- *Irrigation water sources supplemented by rainwater collected in two underground cisterns with a total capacity of 60,567 L*
- *Over 40% of the project materials were sourced from within 805 km of the site*
- *Organic and locally sourced pecan shell mulch improves water holding capacity of soil*
- *Plant palette is made up of 58% native plants*
- *87 established Honey Locust and Sycamore trees were preserved in place*
- *Three percent of parking is reserved as preserved parking for Green Score Rated reduced emissions vehicles*

Performance Benefits

The goals of the project were to minimize the use of potable water for irrigation, slow the flow of stormwater, and increase availability of urban habitat through a combination of water conserving and native plants. These goals were evaluated when the park was certified as part of the Sustainable Sites Initiative (SITES) Pilot Program. This provided the research team with a wealth of baseline information regarding the documented sustainable features of the park. However, many of the credits for SITES were written to emphasize sustainable decision-making in the design process; whereas, the goal of the LAF Case Study Investigation was to evaluate the performance of design decisions. The research team focused on utilizing calculations and estimates from SITES as a platform to validate or improve upon when performance benefits were developed.

Reduces potable water use for irrigation by 86%, when compared to an established baseline through the use of a low-water plant palette, efficient drip irrigation, and rainwater harvesting via 60,567 L of underground storage cisterns.

In arid regions such as Albuquerque, water is a limited resource and requires careful management. Yet irrigation, usually from potable water supplies is a common and widely distributed practice to water designed landscapes. In recognition of this concern the Government Services Administration (GSA) desired a water system for the landscape retrofit that would minimize use of potable water resources for landscape irrigation. The design team achieved this reduction by utilizing drought tolerant and native plant species, installing efficient drip irrigation water delivery systems, and by supplementing potable irrigation water with rainwater harvested from the courthouse rooftop.

Documentation quantifying the percentage of water reduction was generated by the design team as part of their submittal to SITES (Rios Clementi Hale Studios [RCHS], 2013). The method and calculations are reproduced in Appendix A. Overall the reduction was quantified by calculating a baseline water demand that was compared to the water demand of the new design, accounting for offsets provided by non-potable water sources.

This methodology for estimating how much a designed landscape can reduce potable water use for irrigation is endorsed by SITES (Sustainable Sites Initiative, 2009) and other sustainability rating programs. However, there are a few caveats associated with this method. First, the evapotranspiration rate utilized represents the most extreme summertime condition (month of July); this value will fluctuate throughout the year and would not be truly representative of the entire year. Second, this method relies on a baseline condition from which to compare the designed condition. In this case, the amount of water required by the fictional baseline assumes a very consumptive landscape plant palette (comparable to an all turf lawn). The comparison could be more accurate by calculating the water use for a more realistic baseline case. Finally, a fluctuation in the amount of water collected by the rainwater cisterns is certain to occur. The quantity of rainwater collected would be affected by the timing and size of storm events in cooperation with the amount of water used by the landscape. Ultimately the best way to determine how much water is collected and how much water is used throughout the year would be to meter water use.

Reduces the volume of stormwater runoff by 90% when compared to existing conditions. A combination of rain gardens, bioswales, rock gardens, and filtering devices treat stormwater for pollutants of concern for 95% of the site area.

Managing stormwater on-site was a unique challenge for the design team. This was due to regulations established by the state of New Mexico that restricted developments from detaining stormwater on site, with the intention of ensuring downstream water rights. Therefore, the design team had to focus on strategies that would increase site permeability and slow water flow through the site. Calculations using the TR-55 Method from the civil engineer were provided for SITES documentation (RCHS, 2013) to confirm the percentage reductions of runoff volume and are reproduced in Appendix A. The method involves calculating and comparing the curve number for the existing and post-development conditions (Sustainable Sites Initiative, 2009).

A majority of the stormwater that falls on site is treated by bio-infiltration methods involving soil and vegetation (Fig. 4). In the parking lot, vegetated bioswales slow water flow and allow sediments to settle out (Fig. 5). The rock garden at the entry acts in a similar fashion allowing water to percolate through the rock garden before being transported to the municipal stormwater system (Fig. 5). Stormwater that falls on the roof is treated by a RINKER-Stormceptor, Model STC 900 prior to entering the rainwater cisterns. Both of these methods have been shown to reduce total suspended solids to a concentration of less than 25mg/L, a value recommended in the SITES Guidelines and Performance Benchmarks (2009). Of the total site area, 16,347 m^2, only 728 m^2 of the site, located in the parking lot, is directed straight to the stormwater system without treatment. This equates to a total of 95% of the total site stormwater treated to remove pollutants of concern.

Reduces net energy use for outdoor lighting by 99% by generating 27.5 kWh of on-site solar power. This saves approximately $3,749.09 in energy costs each year.

Rios Clementi Hale Studios (RCHS) originally generated the documentation supporting the reduction of energy use for SITES documentation (RCHS, 2013). The results were achieved by comparing the annual energy consumption of the utilized fixtures with the annual energy output of the renewable energy source and are reproduced in Appendix A.

To offset power used to operate electrical fixtures on-site the Courthouse includes renewable power generated by photovoltaic solar panel system. A total of two solar arrays were installed on the lower level roof, one 12.81 kW array on the southeast corner and one 14.04 kW array on the southwest. The Courthouse is an excellent example of a way to incorporate renewable energy in a retrofit scenario. The lower roof areas were selected because there were fewer conflicts with existing equipment and because there was enough area to provide an array large enough to offset the exterior landscape demand.

The overall reduction in energy by percent was calculated by dividing the solar energy output by the total energy demand, 43,093 kWh/43,229.14 kWh = 99.69% Energy Reduction. Results were based upon estimates for actual conditions throughout the year. To improve upon this information it would be ideal to have monitoring in place. It is also important to note that these calculations represent annual net energy generation and would vary if calculated monthly.

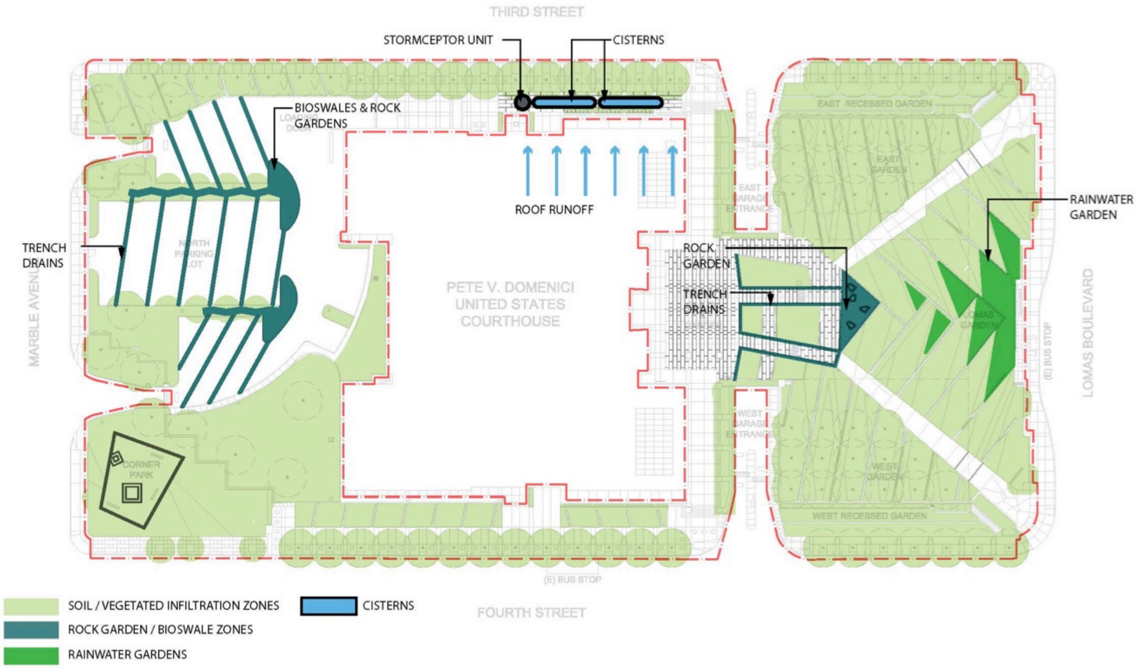


Fig. 4. Diagram of Stormwater Treatment Processes Utilized at Domenici Courthouse in Albuquerque, NM USA (RCHS, 2013).

Fig. 5. Bioswale in Parking Lot (Left) and Infiltration Rock Garden in Entry Plaza (Right) at Domenici Courthouse in Albuquerque, NM USA.

Reduces energy consumption on-site by 30% by utilizing energy efficient fixtures when compared to the lowest cost alternative fixture.

The energy reduction achieved by the selected fixtures on site was originally calculated by RCHS for SITES documentation (RCHS, 2013) and is reproduced in Appendix A. The results were achieved by comparing the annual energy consumption of the utilized fixtures with the annual energy consumption of the lowest cost comparable fixture. Calculations accounted for the quantity of each fixture, wattage of each fixture, and hours of operation.

Diverted 200,448 kg of demolition and construction waste from the landfill by repurposing materials on site and recycling unused materials. This saved $10,022.40 in landfill fees.

To prevent excessive waste generation the design team created a strategy for diverting waste generated during demolition and construction from the landfill. When possible waste was diverted to recycling centers where it would eventually be reused. Reuse of existing materials in the design was part of the strategy that minimized waste generation. Concrete that would otherwise have been removed was instead utilized as a building material. A summary of materials diverted is reproduced in Appendix A (RCHS, 2013).

The use of existing concrete on site and recycling materials when possible greatly reduced the amount of concrete that was disposed of during demolition. This also eliminated the costs associated with disposing concrete. A report from the Waste Business journal estimates the average cost of disposing waste in U.S. landfills at $0.05/kg (Thompson, 2014). Multiplying the disposal cost per ton by the quantity of waste diverted from the landfill provided an estimate of total disposal cost savings, 200,448 kg waste x $0.05/kg = $10,022.40.

Cost Comparison

One of the most highly visible sustainable features of the Courthouse is the series of site walls constructed of repurposed concrete blocks. Existing concrete sidewalks were cut into block size modules to create 547 linear meters of site walls. The design team was able to utilize three different colors of concrete and the method of saw cutting the blocks exposed a concrete aggregate finish. Records of actual costs for installing the concrete block walls were difficult to uncover given the time elapsed since construction. Instead the research team determined the cost from a replacement cost estimate provided by the contractor (RCHS, 2013). Due to the finish and quality of the blocks the contractor estimate was based on an integral color, exposed aggregate finish CMU block. The contractor provided a replacement cost of $12/block for the recycled concrete block walls. To get the cost of the recycled concrete walls the cost per block was multiplied by the total number of blocks harvested used for wall construction, $12/block x 8,500 blocks = $102,000.

A typical alternative to the recycled concrete walls would be a standard finish concrete site wall. The contractor also provided an estimate of the cost for a natural grey, concrete wall at $278.60/m. To estimate the cost of all new concrete walls the total linear meters of walls built was multiplied the cost per linear meter, $278.60/m x 547.4 = $152,505.64. In this instance a standard concrete wall was slightly more expensive than the recycled concrete block walls. This cost would certainly increase if a finish and color similar to that achieved by the recycled concrete walls were utilized. Recycling the concrete allowed the design team to increase permeable surfaces on site without generating an excessive amount of waste and provide a site wall with a premium finish.

A challenge of this calculation was the ability to establish a firm cost per linear foot of the recycled concrete walls. One could consider demolition, storage, relocating, and construction all part of the costs associated with constructing the walls. However, it was difficult to uncover actual expenditure data from construction and so the more accessible replacement costs provided by the contractor were utilized.

Methodology: George “Doc” Cavalliere Park

Introduction

George “Doc” Cavalliere Park (Doc Park) is a 13.8 ha neighborhood park constructed in 2012 for an approximate budget of $4.3 million. Doc Park is located at the northeast fringe of the greater Phoenix Metropolitan area, in north Scottsdale. The region is located within the Sonoran

Desert Biome, in the more mountainous “Arizona Upland” typology. Climate within this region is typically hot and dry with over 90 days a year above 37.8 °C. Local annual precipitation and potential evapotranspiration are about 200 mm and 2280 mm, respectively. Rainfall patterns are bimodal and typically occur within the summer North American monsoon or winter rainy seasons. During the summer monsoon, sudden, high velocity storms are frequent in the region and flooding is a concern, especially in undisturbed desert areas. While there is significant development surrounding the park, it is largely low-density residential use. The north Scottsdale area is still significantly influenced by the indigenous Sonoran Desert landscape, and that aesthetic is maintained at many developments. The park is also located in close proximity to the McDowell Sonoran Preserve, a large protected area of desert habitat that is now mainly used for recreation and conservation of native flora and fauna.

Project Features

A portion of the site for Doc Park had been previously developed to provide a regional stormwater management facility. Early site analysis revealed the existing detention basins needed to be increased in size to adequately manage the expected flows. The design solution ensured adequate stormwater management functionality while providing a community park for the nearby residents with limited disturbance to existing desert habitat. The park design included amenities such as a covered playground, artificial turf play areas, basketball courts, covered ramadas, and hiking trails. Sustainable features of the park include:

- Off-site stormwater from the regional watershed and stormwater runoff generated by the park is detained in large basins and slowly released downstream when storm events are large enough
- Over 300 native plants were salvaged for reuse or preserved in place
- The landscape design utilized a completely native plant palette diversified with Arizona Upland and riparian plant communities
- Site disturbance was limited during construction by locating fencing within 3.4 m of grading limits and staging construction within the previously disturbed portions of the site

- The top four inches of soil was harvested and stored on-site during construction and redistributed at the end of construction to restore soil quality
- A total of 30% of paved surfaces are permeable, including the parking lot that is paved with stabilized decomposed granite harvested from material found on-site.
- A total of 63% of materials including granite topdress, gabion rocks, concrete, and landscape materials were purchased from sources within 483 km of the site
- The park features 1,337 m of compacted decomposed granite hiking trails, including ADA accessible trails
- A drip irrigation system with smart controller efficiently irrigates plants for an establishment period of three years for trees and one year for shrubs, after which the landscape will be weaned off irrigation
- An array of 61 photovoltaic panels on the shade canopy is designed to provide an output of at least 24,000 kWh of power each year

Performance Benefits

The goals of the project were to minimize the impacts of development, preserve upland Sonoran Desert habitat, minimize the impact of high summer temperatures on park visitors, reduce long term maintenance costs, improve stormwater management, and to utilize a design aesthetic that fits within the desert surroundings. Many of these goals were evaluated and documented when the park was of the certified as part of the SITES Pilot Program. This provided the research team with a wealth of baseline information regarding the sustainable benefits of the park. Many of the credits for SITES emphasized sustainable decision-making in the process of design and construction; whereas, the case study was intended to evaluate ongoing benefits of the park. This created an opportunity to build upon calculations and estimates from SITES and to focus on performance benefits, such as microclimate modification, that are particularly relevant in the Phoenix Metropolitan Area.

Captures and infiltrates 100% of on-site stormwater generated from a 100-year/2-hr storm event. The park also manages runoff from several upstream developments, with the ability to store 6.1 ha/m in vegetated detention basins.

Prior to the construction of Doc Park the site was utilized as a regional stormwater management site, and this function was to remain in tact after construction of the Park. The design team was therefore challenged with providing the required park amenities without preventing the functionality of the stormwater management systems. Additionally, early on in the project it was discovered that the original storm water detention basins were undersized. The capacity of the largest basin had to be increased within the site boundaries to accommodate the expected volume of stormwater.

The stormwater managed at Doc Park included run-off created by the construction of the park as well as run-on originating from the surrounding neighborhoods. Four drainage channels located north of the park discharge stormwater from surrounding development into a large detention basin where it is temporarily stored and slowly released into downstream waterways. In addition to stormwater run-on originating off-site, standards established by the City of Scottsdale and Maricopa County required that runoff from a 100-year/2-hour storm generated by the park be managed on-site. All calculations provided in the drainage report demonstrated those standards were accommodated by the design (Argus Consulting, 2009). For calculations Argus Consulting utilized the, computer program HEC-1 and the Rational Method. When combined the two detention basins can store 6.1 ha/m easily accommodating the 0.30 ha/m generated by Doc Park.

Saves 88% of potable water use for irrigation, when compared to an established baseline, by utilizing a native plant palette that does not require long-term irrigation.

The primary strategy for reducing irrigation use at Doc Park was to utilize native plantings adapted to the region's low rainfall and high potential evapotranspiration rates. After an establishment period, three years for trees and one year for shrubs, the new plantings would be weaned off irrigation until the system would be turned off completely. Documentation submitted to SITES for reduced irrigation water use, accounted for the temporary irrigation system

(SmithGroupJJR, 2013). However, during the summer research program the City of Scottsdale installed a *Cynodon dactylon* (L.) Pers. (Bermuda grass) lawn with that was not addressed by the initial SITES documentation. Therefore, it was necessary to update the irrigation estimates so the new Bermuda grass lawn was accounted for. To arrive at the percentage of reduced water use for irrigation the research team used the method developed by SITES that compared an estimated baseline water use to the designed water use (Sustainable Sites Initiative, 2009).

First, the Baseline Landscape Water Requirement was calculated (Table 7) using equation one:

$$\text{BLWR} = \text{ET0} \times \text{A} \times \text{Cu} \tag{1}$$

Where, BLWR is Baseline Landscape Water Requirement (gal/month), ET0 is average evapotranspiration for the site's peak watering month (June) in in/month, A is area of irrigated landscape in sf^2 and Cu is conversion factor (0.6233 for results in gal/month). BLWR was then converted into L/month. In the second step the Designed Landscape Water Requirement (Table 8) was generated using equation two:

$$DLWR = RTM \times [(ET0 \times KL) - Ra] \times A \times Cu \tag{2}$$

Where, DLWR is Designed Landscape Water Requirement (gal/month), RTM is Run time multiplier, equal to 1/low quarter distribution uniformity (D_U), ET_0 is average evapotranspiration for the site's peak watering month (June) in inches/month, K_L is landscape coefficient for type of plant in that hydrozone, R_A is allowable rainfall (25% of average monthly rainfall for June), A is area of hydrozone (sf), and C_U is conversion factor (0.6233 for results in gal/month). DLWR was then converted into liters (L)/month. In the last step was to determine the percentage reduction (Table 9) using equation three:

$$\textit{Percentage Water Use Reduction} = (BLWR - (DLWR\text{-}NPS))/BLWR \tag{3}$$

For these calculations a KL of zero was used for the hydrozones associated with all of the plants on the temporary irrigation system. This was the most efficient way to account for the future irrigation use. Values for the distribution uniformity and turf landscape coefficient were provided by the SITES documentation.

Ultimately the reduction in potable water use for irrigation is dependent on the

Table 7. Values Used to Calculate Baseline Landscape Water Requirement (BLWR) for Doc Park in Scottsdale, AZ USA.

ET0 (in/month)	A (sf)	Cu	BLWR (gallons)	BLWR (liters)
10.9	427,640	0.6233	2,905,373	10,998,033

Table 8. Values Used to Calculate Designed Landscape Water Requirement (CLWR) for Doc Park in Scottsdale, AZ USA.

Hydrozone	DU	KL	RA	A	Cu	CLWR (gallons)	CLWR (liters)
Trees	0.7	0	0.01	19,952	0.6233	0	0
Shrubs	0.7	0	0.01	53,598	0.6233	0	0
Accents	0.7	0	0.01	10,364	0.6233	0	0
G.C.	0.7	0	0.01	40,102	0.6233	0	0
Reveg	0.7	0	0.01	262,667	0.6233	0	0
Turf	0.7	0.8	0.01	40,957	0.6233	357,092	1,351,740
Total						357,092	1,351,740

Common Values; ET0 = 10.9; RTM = 1.43

Table 9. Values Used to Calculate Irrigation Water-Use Percent Reduction for Doc Park in Scottsdale, AZ USA.

BLWR(liters)	DLWR (liters)	BLWR-DLWR (liters)	Percent Reduction
10,998,033	1,351,740	9,646,293	88%

physical shutdown of the irrigation system. At the time of research the irrigation system was still engaged as many trees were still within the establishment time period. Correct management to reduce dependence on supplemental irrigation water will determine if the percentage reduction is actually realized in the future.

Reduces energy consumption on-site by 97% by utilizing energy efficient fixtures when compared to the lowest cost alternative fixture.

The energy reduction achieved by the selected fixtures was originally calculated by SmithGroupJJR for SITES documentation (2013) and is reproduced in Appendix B. The results were achieved by comparing the annual energy consumption of the utilized fixtures with the annual energy consumption of the lowest cost comparable fixture. Calculations accounted for the quantity of each fixture, wattage of each fixture, and time of operation.

Generates 24,000 kWh of on-site solar power reducing energy costs by approximately $2,993 each year.

The contractor selected to design and install the photovoltaic system provided informative calculations as part of their submittal (SmithGroupJJR, 2010). Data provided by the solar system engineer estimated the system to provide 24,945 kilowatt-hour (kWh) of power each year. Using an estimate of $0.12/kWh also provided by the engineer, the estimated value of the annual power generated was calculated: 24,945 kWh (power generated) x $0.12 (power cost per kWh) = $2,993.40. These data were based on estimates generated by the engineer and would vary depending on actual conditions throughout the year. At the time of research a method for tracking the actual performance of the system was not available.

Provides habitat with 16 species of arthropods observed in addition to rabbits, quail, lizards, snakes, and birds.

A primary goal of Doc Park was to preserve natural desert habitat and limit disturbance caused by the construction of the park. Casual observations of the park indicated that there was quite a bit of wildlife activity occurring. Sightings of rabbits, quail, lizards, and birds were quite common during fieldwork. Quantifying and confirming those observations was not necessarily a straightforward task.

To get this information the research team used pitfall traps arthropods to be collected and indicated arthropod activity distributed through the site. This is a data collection method used frequently at ASU by the National Science Foundation sponsored Central Arizona Phoenix Long-term Ecological Research program, and the research team was able to use their experiences as a basis for the protocol. Briefly, the method utilized 0.03 L plastic cups mounted in the ground with the top of the cup installed flush to the adjacent grade (Fig. 7). After three days in the field, the traps were collected and results observed and recorded by photograph. The location of each installed pitfall trap was documented in Fig. 6. Some advantages to this method include: simplicity of installation, minimal site disturbance, limited on-site monitoring required, and streamlining the process to observe only groups of ground dwelling animals at a lower biotrophic levels. After completing the fieldwork some disadvantages to the method were discovered including: difficulty counting the number of specimens, difficulty identifying the specimens, extreme soil temperatures as high as 60 °C damaging portions of some plastic cups, and some specimens were lost or destroyed by predators (Fig. 7). Results from pitfall collection are presented in Table 10. The highest numbers and diversity of animals were observed in PT1 and PT11, both located in close proximity to the park's large Ramada area and irrigated turf lawn. Animals observed in these traps included a lizard and gecko. It is likely the higher numbers and diversity of animals captured in these traps were because of the favorable microclimate conditions of cooler temperatures from the live and structured shade and higher ground moisture conditions from the nearby irrigated turf panel. Surprisingly, many of the traps installed in the undisturbed desert areas contained few animals and portions of the cups had melted from the extreme surface temperatures. This was not the case for the traps closer to the cooler and moister developed areas of the park. These results demonstrated how developed park infrastructure within an arid undisturbed area could locally create habitats of increased structural

Fig. 6. Locations for Pitfall Traps Installed for Arthropod Data Collection at Doc Park in Scottsdale, AZ USA in June 2014.

Fig 7. Image of Installed Pitfall Trap (Left) and Contents of Pitfall Trap PT11 (Right) at Time of Collection at Doc Park in Scottsdale, AZ USA.

complexity and resources that benefit an increase in the numbers and diversity of lower biotropic level organisms that in turn provide a food resource for higher level biotrophic organisms.

Reduces hardscape surface temperatures under live tree shade and structured by 16.9 °C and 24.9 °C, respectively, when compared to unshaded areas of the site. The steel canopy helps to maintain playground surface temperatures under 27.8 °C.

Temperature and how it is managed, plays a large role in the success of an arid region public space. To evaluate how this was accomplished in Doc Park, the research team recorded both surface and air temperatures. Surface temperature data reveal how materials impact temperature and air temperature data reflects how those materials influence human comfort. Tree (live) and structured (hard) shade reduced mid-day hardscape surface temperatures by 16.9 °C (Table 11) and 24.9 °C (Table 12), respectively, when compared to unshaded areas of the site. The mean reduction was calculated by comparing the mean temperature of concrete and stabilized decomposed granite (D.G.) surfaces in the open, under live shade, and under hard shade. Where possible the research team attempted to capture data for each surface type in the open, under live shade, and under hard shade. The analysis compared concrete and stabilized D.G. because these were the primary hardscape surfaces utilized at the park and research team was able to measure these two surface types under all three conditions.

While Doc Park utilizes both live shade and hard shade, the large steel shade canopy at the center of the park is key to the park's microclimate heat mitigation strategy. During the day it provides consistent shade for the playground, one of the most used areas of the park. In comparison to the live shade, the hard shade of the large ramada structure provided a very consistent and significant reduction in surface temperatures (Table 13). The highest temperature recorded under the canopy was stabilized D.G. at 27.4 °C, the same surface under live shade reached 36.1 °C (Table 11 and 12). Conversations with visitors confirmed this fact as many visitors felt that this park provided a comfortable playground for summer use.

The research team recorded a series of temperature readings from each surface type in random locations (Table 14). These surfaces included: undisturbed native soil, vegetated

Table 10. Contents of Collected Pitfall Traps at Doc Park in Scottsdale, AZ USA After Three Days of Installation During June 2014.

Pitfall Trap #	Location	Number of Species
PT1	Shade Structure	6[Z]
PT2	Trail Ramada	3
PT3	Trail	4
PT4	Trail	4
PT5	Trail	4
PT6	Basin	2
PT7	Basin	3
PT8	Playground	2
PT9	Parking Lot	2
PT10	Turf	2
PT11	Turf	2[Z]

[Z] Observed Lizards among species collected

Table 11. Mean Surface Temperatures of Hardscape Surfaces at Doc Park in Open and Live Shade Conditions Recorded at 1230 hr in Scottsdale, AZ USA.

Surface Type	Surface Temperature (°C)		
	Open	Live Shade	Difference
Concrete	54.4[Z]	36.1	18.3
Stabilized D.G.	48.6	33.1	15.5

[Z] Values are means, n=297

Table 12. Mean Surface Temperatures of Hardscape Surfaces at Doc Park in Open and Hard Shade Conditions Recorded at 1230 hr in Scottsdale, AZ USA.

Surface Type	Surface Temperature (°C)		
	Open	Hard Shade	Difference
Concrete	54.4	25.9	28.5
Stabilized D.G.	48.6	27.4	21.2

[Z] Values are means, n=297

Table 13. Surface Temperature of Materials in Playground Area at Doc Park Recorded at 1230 hr on June 19, 2014 in Scottsdale, AZ USA.

Surface Type	Surface Temperature (°C)
Play Rubber	24.8
Play Sand	23.8
Concrete	25.9
Gabion Basket	20.7
Stabilized D.G.	27.4
Concrete Bench	22.4

Table 14. Mean Surface Temperatures Recorded at 1230 hr at Doc Park in Scottsdale, AZ USA, June 19, 2014 a Seasonally Hot and Clear Day.

Surface Cover Type	Mean Surface Temperature (°C)	Std. Error
[Hard Shade]Artificial Turf	23.5[Z]	0.67
[Hard Shade]Concrete	25.9	0.83
[Hard Shade]Concrete Bench	22.4	0.72
[Hard Shade]Gabion Basket	20.7	0.61
[Hard Shade]Play Rubber	24.8	0.72
[Hard Shade]Play Sand	23.8	0.67
[Hard Shade]Stable DG	27.4	0.72
[Live Shade]Asphalt	37.6	1.06
[Live Shade]Bare Desert Soil	29.4	0.72
[Live Shade]Concrete	33.1	1.17
[Live Shade]Stable DG	36.1	1.06
[Live Shade]Vegetated Surface	26.1	0.61
[Open]Artificial Turf	58.8	0.50
[Open]Asphalt	55.1	0.89
[Open]Bare Desert Soil	51.7	0.61
[Open]Concrete	48.6	0.56
[Open]Concrete Bench	43.5	0.72
[Open]Gabion Basket	46.7	0.72
[Open]Stable DG	54.4	0.56
[Open]Steel Bridge	31.3	0.50
[Open]Turf	22.7	0.56
[Open]Vegetated Surface	26.5	1.06

[Z] Values are means, n=297

surfaces, stabilized decomposed granite, natural turf, artificial turf, play sand, rubberized play surface, concrete, and asphalt. Hottest surface temperatures ranged from 48.3-58.3 °C and were recorded on unshaded surfaces such as impervious asphalt and concrete, bare desert soil, landscaped surfaces covered with impervious decomposing granite, or artificial turf grass. The coolest mid-day surface temperatures ranged from 20.6-27.8 °C and were recorded on ground surfaces covered by structured shade or unshaded live turf grass.

Surface temperature data were recorded on June 5, 2014 at 1230 hr when sunlight was most directly attenuated. Weather during this interval was normally clear and hot. Surface temperatures were recorded with a hand-held infrared thermometer, 7° angle of view. Surface temperatures of each of the park's 12 surface types were recorded for full sun and shaded conditions. Data collection points were randomly assigned and a total of 297 data points were recorded.

Reduces air temperatures on the natural turf field and the playground by 1.8 °C and 1.3 °C, respectively, when compared to air temperatures in the undisturbed desert areas.

The portable data loggers were positioned at nine locations within the park to enable an understanding of how visitors were likely to experience temperatures throughout the park. This allowed the research team to compare air temperatures in the designed areas of the park with natural desert areas, which indicated how design decisions impacted microclimate mitigation. During the four days, the mean air temperature on the natural turf field was 30.1 °C and the mean air temperature on the playground was 30.6 °C. These were the two coolest locations recorded in the park. The mean air temperature on the natural desert trail was 31.9 °C and the mean air temperature in the parking lot was 31.2 °C.

Results from the portable data loggers showed some larger temperature trends throughout the park (Fig. 8). The turf field was consistently one of the coolest spaces in the park during both the daytime and nighttime hours, and sharp drops in temperature caused by the latent heat of vaporization were observed at discrete times when overhead irrigation was

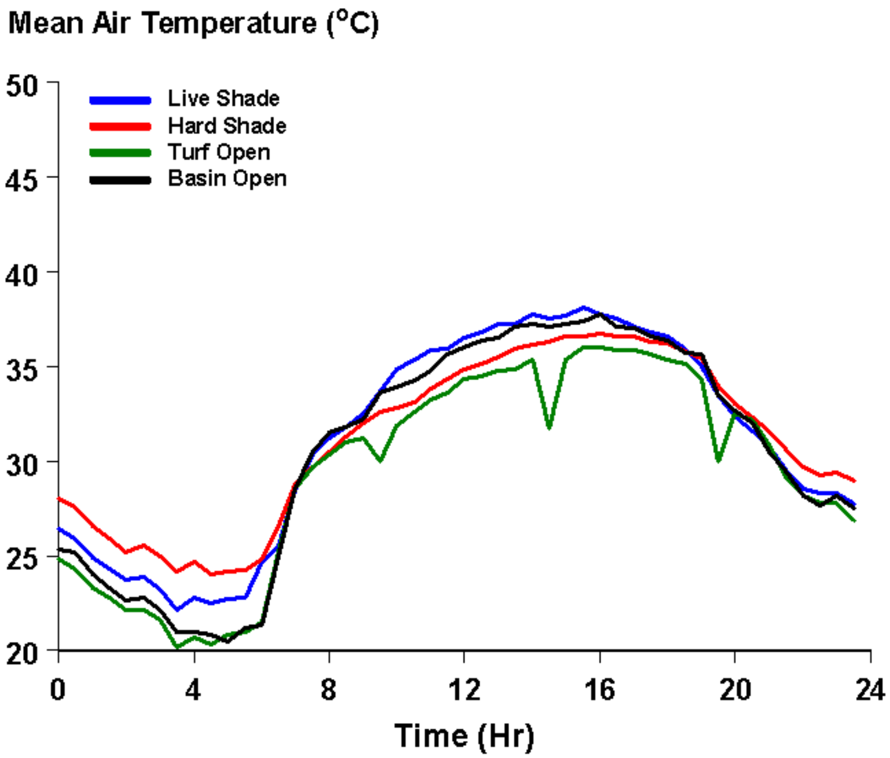


Fig. 8. Mean Patterns of Daily Air Temperatures From June 19-22, 2014, Recorded Under Live Tree and Structured Hard Shade, and in the Open Over Turf Grass or Exposed Soil Basin in Doc Park.

Fig. 9. Locations of Installed Portable Data Loggers at Doc Park in Scottsdale, AZ USA.

running. During the warmest parts of the day from about 0900-1900 hr, spaces under the structured shade caste by the large central park Ramada were among the coolest in the park. However, during the nighttime hours, spaces under the central Ramada were the warmest in the park due to the Ramada's entrapment of long wave radiation. Although the Ramada's structured hard shade did exacerbate the impacts of extreme desert heating at night, it did provide substantial human comfort benefits during the day through shading.

Portable data loggers recorded air temperature data every 30 minutes for four days from June 19-22, 2014. Weather during this interval was seasonally hot and clear. The portable data loggers were WatchDog B series 2K button loggers from Spectrum Technologies, Inc. (http://www.specmeters.com/). Nine data loggers were installed at approximate heights of 1.2 m to 2.4 m above ground throughout the site. The data loggers were installed in orientations removed from exposure to direct insolation; either protected by tree canopy shade, structured hard shade, or placed inside a white-louvered plastic micro-meteorological shelter. Locations were selected to optimize the variety of park conditions. Data loggers were located in the natural turf field, parking lot, restroom, playground, hiking Ramada and in several trees located in the basins and trails (Fig. 9). The data loggers located in the turf and basin bottom, where they could not be hung on a nearby tree or structure were placed in the white-louvered shelters. Air temperature data were directly downloaded to computer for analysis using JMP statistical software (JMP 8.02, SAS Institute, Cary, NC).

Attracts an average of 32 visitors on a weekend morning, in the low season of summer. Of these, an average of 91% engaged in optional activities and 72% of these were also engaged in social activities.

The methodology for observing site visitors to the park were derived from Jan Gehl's (2011) observations on public spaces as well as methodologies developed in previous LAF Case Studies. The basis of these types of observations is that visitors to the park will engage in three general types of activities: necessary, optional, and social. Gehl argues a successful public space has a greater percentage of both optional and social activities. Doc Park is a rather suburban park that was more active on the weekends when visitors had more leisure time. For this reason observations were planned for three days over a weekend (Friday, Saturday, and Sunday) from 0830-1230 hr. The location and activity of each visitor was recorded and their activities were classified as necessary, optional, or social.

Visitors to the park were overwhelmingly there for optional activities (Table 15). The park was not connected to other urban activities therefore a majority of visitors drive to the park were treating it as a destination. The summer temperatures may have influenced this trend; in cooler times of the year pedestrian (or cyclist) visitors may be more numerous. Visitors who did make it to the park were often engaged in unplanned social activities. This was most frequently observed with children playing together on the playground and their parents who talked while watching them play. There were also several visitors who utilized the trails for hiking and walking dogs.

A significant limitation of this investigation was that observations had to occur within the summer. The number of visitors observed during this study was probably not representative of park use throughout the year. The heat also presented a challenge to the research team, and is in part why observations were limited to the morning hours. It is also possible that the timing effected when the park was most used, due to children being out of school for the summer. When the research team was completing other environmental measurements during the week, the park was busier than expected. To get a more complete picture of the social benefits provided by this park observations should be extended to other, busier times of the year.

It is also important to note that the research team submitted plans for site observations of park visitors to the ASU Institutional Review Board for review and approval. The data collected about visitors during observations was more limited than some previous case studies, ultimately a waiver was granted for approval. The research team found that streamlining the data collected allowed for a prompt review process.

Cost Comparison

Wherever it was practical, the design team elected to use permeable stabilized decomposed granite (D.G.) paving in lieu of more traditional impermeable materials. The parking

Table 15. Summary of Visitors and Activity Type Recorded at Doc Park From 0830-1230 hr During June in Scottsdale, AZ USA.

Date	Total Visitors	Percent Optional	Percent Social
06/20/14	31	87%	67%
06/21/14	31	87%	89%
06/22/14	35	100%	60%
Average	32	91%	72%

Table 16. Material Cost for Installing Stabilized Decomposed Granite (D.G.) Paving at Doc Park in Scottsdale, AZ USA.

	Material Area	Unit Cost	Total Cost
Stabilized D.G. Path (610 mm Depth)	2,229 m^2	\$24.02/m^2	\$53,540.58
Stabilized D.G. Drive (1,219 mm Depth)	698 m^2	\$48.42/m^2	\$33,826.37
Total Cost			\$87,366.95

Table 17. Material Cost for Installing the Traditional Concrete Paving Method at Doc Park in Scottsdale, AZ USA.

	Material Area	Unit Cost	Total Cost
Natural Grey Concrete Path	2,229 m^2	\$64.62/ m^2	\$144,037.98
Asphalt Paving	698 m^2	\$89.74/ m^2	\$62,638.52
Total Cost			\$206,676.50

lot, most of the entry drive, and pathways were constructed from stabilized D.G. harvested from the site. The cost of paving these areas in stabilized decomposed granite totaled approximately $87,366. The cost of paving these same areas in with standard impermeable surfaces such as asphalt and concrete would be approximately $206,571. In this application the more rugged material did not present maintenance concern and was a cost effective option for a permeable paving material.

The research team was provided with a cost estimate of Doc Park generated by SmithGroupJJR (2010). This estimate was the last one prepared prior to contractor selection and represents an accurate idea of costs at the time of construction. The organization of the estimate also allowed the research team to compare costs quite easily. Total quantities of each paved surface type and unit costs were provided allowing an easy comparison between the materials. The difference in cost between the designed solution and a more traditional solution was $119,310.

Discussion

A successfully designed sustainable landscape provides ecosystem services in response to the particular areas of concern for the project type and location. All three of these projects were located in hot and arid cities where the primary regional concerns are extreme temperatures and limited availability of water. The research team elected to put emphasis on data collection to identify performance benefits that related to the capacity of each project to balance microclimate mitigation to improve human comfort with water conservation. The Civic Space Park in downtown Phoenix, Arizona, was designed with human comfort as the highest priority. George “Doc” Cavalliere Park in Scottsdale, Arizona, was designed to strike a balance between the amenity needs of a local park with water conservation. Domenici Courthouse in Albuquerque, New Mexico, was designed to achieve water conservation as its highest priority. Each project struck a different balance, influenced by the individual project goals and constraints, and displays a range of strategies for balancing ecosystem services tradeoffs in an arid region.

For the Civic Space Park design team the primary goal was microclimate mitigation of extreme urban desert heat. To achieve the goal a combination of shade structures, large shade trees, and expansive turf grass lawns were used to provide shade and increase convective cooling through evapotranspiration. Air and surface temperature data recorded in the park revealed some trends affected by the cooling strategies implemented in the park. Shaded surfaces in the park at mid-day were an average of 7.1 °C cooler than those without cover. While temperatures under shade were significantly lower than those without shade, data also showed that turf grass lawns were highly effective at lowering surface temperatures. Lawn surfaces in the park were an average of 17.3 °C cooler during mid-day and at night than paved surfaces.

Large shade trees and turf grass lawns mitigate urban microclimates through shade and evapotranspiration, but in arid regions require extensive supplemental irrigation water. The Civic Space design team had initially considered strategies ways to supplement irrigation water supplies. However, they found that the amount of water collected by a rainwater harvesting system in Phoenix only satisfied a small percentage of the landscape’s annual water demand, and in the end the cost of installation and maintenance was not justified.

With several acres of undisturbed desert habitat on site it was important for the Doc Park to embrace the surrounding native habitat while also providing traditional park amenities that neighbors were eager to use. The initial design strategy was to consolidate the amenities under a large shade structure to improve thermal comfort and to limit turf to two strategically placed lawns. During the Park’s construction phase however it became apparent that the cost of maintenance for the two turf lawns would be a fiscal constraint for the city. The selected solution was to replace one lawn with artificial turf for one lawn.

For most of the day, air temperatures over the natural turf lawn were the lowest air temperatures observed in the park. The playground, one of the most highly used features of the park, was located adjacent to the artificial turf field and directly under the large shade structure. The shade structure was highly effective at lowering surface and air temperatures on the playground. At Doc Park, the costs of maintenance and water for natural turf were balanced by phasing construction, limiting turf areas, providing structured shade, and utilizing artificial turf.

It is important to note that there were some additional tradeoffs associated with the use of artificial turf in a desert environment. When exposed to the summer sun, artificial turf became an extremely hot surface; surface temperatures as high as 62.8 °C were recorded at solar noon. In fact, the City of Scottsdale, Arizona, provided an automated sprinkler system (operating during limited hours on the weekend) to cool the artificial turf surface and visitors used it as a popular play feature. Additionally, there were some soft benefits associated with park's natural turf area that were not achieved by the artificial turf. For example, cooler temperatures and availability of irrigation water run-off increased wildlife activity around the natural turf lawn area.

At Domenici Courthouse water conservation was the primary sustainability concern. The pre-existing turf dominant, water intensive landscape created many technical difficulties for facility management because much of the landscape was planted over-structure. Implementing a low water demand landscape improved sustainability and was essential for reducing risk to long-term damage of the below ground structure. The design team achieved their goal of water conservation by both lowering landscape water demand and supplementing irrigation water supply. To lower landscape water demand the pre-existing turf grass lawn was replaced with a diverse mixture of native and drought-adapted species. These plants were regionally adapted and able to perform well when irrigated with an efficient drip system.

State regulations prevented the design team from collecting rainwater in passive systems such as catchment basins, but they were not prevented from collecting rainwater that fell on a roof surface. An automated rainwater collection system was designed to catch water from the roof surface and store it in two underground tanks with an overall capacity of 60,567 L. Due to the low water demand of the landscape, a rainwater collection system was a practical solution for this project.

These three arid region projects highlight the need for designers to customize sustainable solutions to the particular objectives and constraints of a given project site. Solutions and strategies should respond not only to the prominent environmental concerns of the region, but also to specific opportunities and constraints of an individual site. A firm understanding of the individual project context is necessary to determine the appropriate tradeoffs.

CHAPTER 2

EFFECT OF TREE SPECIES AND ARTIFICAL SHADE ON HUMAN THERMAL COMFORT IN PHOENIX, AZ USA

Introduction

The cooling potential of urban vegetation in the form of parks, urban forests, and green walls or roofs has been demonstrated in many climates (Bowler et al., 2010). Urban vegetation has been explored as a strategy for mitigating the impacts of the urban heat island or as a method for modifying thermal comfort in urban microclimates (Coutts et al., 2015). Human thermal comfort is an especially important consideration for the design of outdoor spaces in hot, desert cities where there is a significant risk for heat related illness and mortality in the summer months (Harlan et al., 2006). The risk is exacerbated by the lack of vegetation and high quantity of surfaces absorbing radiation that increases temperatures in urban areas (Akbari et al., 2001). Trees, in particular, positively contribute to improving human thermal comfort in summer by attenuating direct solar radiation and by modifying latent and sensible fluxes (Oke et al., 1989, Akbari et al. 2001). Attenuation of direct solar radiation is often more significant, as the effect of evapotranspiration is mainly felt immediately above the canopy and not within the pedestrian realm (Oke et al., 1989). Additionally, trees in urban areas provide a host of environmental and cultural benefits such as reducing energy use and improving property values (McPherson, 1992).

In response, many municipalities in desert climates have launched efforts to provide more shade with urban tree planting initiatives such as *Million Trees LA* (McPherson, 2011) and the *Phoenix Tree and Shade Master Plan* (City of Phoenix, 2011). A study by Middel et al. (2014b), predicted that the 15% increase in tree coverage proposed by the *Phoenix Tree and Shade Master Plan* could result in a 2.0 °C air temperature reduction. The authors point out that implementation of such a plan requires further research into influential factors such as tree type, arrangement, and combined use with architectural shade structures (Middel et al., 2014b). Evidence from studies in desert cities suggests the degree to which microclimate cooling is achieved can vary with the type of vegetation utilized. For example, Middel et al. (2014) and Chow and Brazel (2012) utilized the ENVI-met model to compare the effect of xeric, mesic, and oasis landscape types on urban temperatures. Their results indicate that xeric landscape types may be effective for cooling; however, greater air temperature reductions can be achieved with mesic or oasis landscape types. It should be noted that these previous works were modeling exercises and were not isolated to the effects of trees. The objective of this research is to better understand how shade type affects thermal comfort in hot, desert climates by comparing several tree species with shade structures in an empirical study.

This research extended the question of landscape type and asked if all tree species are similarly effective at improving thermal comfort? Several empirical studies have explored the impact of trees on thermal comfort in complex urban environments (Gulyas et al., 2006, Ali-Toudert et al., 2007, Lin et al., 2010, Coutts et al., 2015), but few have made distinctions between the species of trees observed. Georgi and Zafiriadis (2006) compared the discontent index under the shade of 21 species of trees in Thessaloniki, Greece and found that percent reduction from full sun varied from 1.5-15.8%. De Abreu-Harbich et al. (2015) observed afternoon thermal comfort in full sun and under shade of 12 tree species and the amount thermal comfort was improved varied from 7.1-16.0 °C due to species. Similar studies are needed in hot, arid climates, to confirm if these results are also found under shade of desert adapted tree species. Differences must also be evaluated with statistical analysis to determine if they are significant enough to warrant the recommendation of specific species. In desert cities consumption of water resources to support shade trees is concerning (Gober et al. 2010), but before low water-use options are widely promoted the efficacy with which they achieve the goal of improving thermal comfort must be evaluated.

Another line of questioning of this research asked if shade from structures and trees are similarly effective at improving thermal comfort? Architectural shade structures such as ramadas, pergolas, arbors, and canvas shades are also commonly utilized to create shade in outdoor urban environments (van Uffelen, 2013). However, little is known about how well structures perform the function of thermal comfort cooling when compared to trees. An experimental study by Shashua-Bar et al. (2011) compared thermal comfort under tree shade to shade from a mesh cloth, and found there was actually a slight heating effect underneath the shade of the mesh shade cloth.

Finally, this research asked if tree species and shade structures exhibit differing capacities to improve human thermal comfort, what are the most significant factors causing the differences? Previous empirical studies comparing thermal comfort under tree species, suggested that differences observed under various tree species were correlated to the amount of solar radiation attenuated by the tree canopy (Georgi and Zafiriadis, 2006, de Abreu-Harbich et al., 2015). Solar radiation in tree canopies is attenuated through reflection, absorption, and transmissivity, and the degree to which these processes occur is dependent upon branching patterns and leaf cover inherent to the tree species (Shahidan et al., 2010). In the Negev Desert the amount of direct solar radiation reduced under native and exotic tree species varied from 40-68% (Kotzen, 2003), yet in Malaysia tree species reduced solar radiation by 93% and 79% (Shahidan et al., 2010), and in Sweden percent of global radiation reduced by five tree species ranged from 85.5-91.6% (Konarska et al., 2014). Since radiation has a significant impact on thermal comfort (Ali-Toudert and Mayer, 2006) these differences should translate to thermal comfort; however, it appears as though the degree of impact tree species has on radiation could vary widely in alternate climates. In this research the density of branching patterns and leaf cover canopies was characterized by sky-view factor (SVF). SVF is the proportion of sky obscured at a given location and is reported as a dimensionless ratio from zero to one, with zero representing the least sky visible and one representing the most sky visible (Grimmond et al., 2001). The hypothesis was that tree species and shade structures would vary in their capacity to improve thermal comfort, based upon their respective abilities to attenuate solar radiation.

Human Thermal Comfort

To arrive at a reliable representation of human thermal comfort it is necessary to utilize an integrated index that is capable of capturing the effects of factors such as radiation, which would not be accounted for by recording air temperature (Shasua-Bar et al., 2011, Ali-Toudert and Mayer, 2006). The physiologically equivalent temperature (PET) is an index that has been used extensively for evaluating thermal comfort in complex urban environments, including hot and arid climates (Lee et al., 2016, Mayer et al., 2008, Ali-Toudert and Mayer, 2007, Johansson, 2006). The index is based upon a human energy balance model and is able to account for physiological response to the integrated effects of the surrounding meteorological environment accounting for personal characteristics such as clothing and activity level (Höppe, 1999). PET is defined as the air temperature at which, in a typical indoor setting, the energy balance of the human body is the same as it would be under the conditions of the environment being evaluated. PET has the benefit of being reported in degrees Celsius and is therefore easily interpreted by academic and nonacademic audiences.

Several thermal comfort indices, including PET, can be calculated using the easily accessible radiation and human-bioclimate modeling software, RayMan (Matzarakis et al., 2007, Matzarakis et al., 2010). Requiring relatively few input parameters, RayMan is a practical tool that has successfully estimated the thermal qualities of complex urban environments (Cohen et al., 2012, Lin et al., 2010, Ali-Toudert, 2007, Gulyas, 2006). The software requires recorded meteorological data, descriptions of the physical environment, and characteristics of human activity as parameters to calculate thermal comfort. The required meteorological data include air temperature (Ta), wind speed (WS), relative humidity (RH), surface temperature (Tsurf), and mean radiant temperature (Tmrt). Tmrt is defined as the equivalent temperature of a hypothetical sphere surrounding a human body that would result in the same radiant heat transfer as the actual environment (Thorsson et al., 2007). Under sunny conditions Tmrt is the most important parameter effecting thermal comfort for indices that utilize the human energy balance method (Mayer and Matzarakis, 1998). The primary function of RayMan is to provide an accurate estimate of Tmrt based on radiation flux densities and a description of the physical environment. For this study the physical environment is described with a fish-eye lens photo, that RayMan utilizes to calculate SVF. Once meteorological data and fish-eye photos have been input, settings for human activity, clothing, age, and sex can be modified and the model will output results for PET, Tmrt, and sky-view factor (SVF).

Research Objective

A relative dearth of empirical studies comparing the varying abilities of different shade types to modify thermal comfort presents a challenge for the successful implementation of tree and shade programs in hot, desert climates. The purpose of this research was to undertake such a study, evaluating how the goal of improving human thermal comfort in hot, desert climates is effected by tree species and shade structures. Motivating the research was the hypothesis that tree species and shade structures will vary in their capacity to improve thermal comfort due to their respective abilities to attenuate solar radiation. The objective was to test the hypothesis by calculating PET in full sun and under shade of six commonly used landscape tree species and typical park ramada structures during pre-monsoon summer afternoons in residential parks of Phoenix, AZ USA. Residential parks are recognized as 'cool islands' where the cooling effect of vegetation is already well documented (Chow et al., 2011, Declet-Barreto et al., 2013) and are one of the few urban locations with enough trees and shade structures to meet selection requirements. Measuring during pre-monsoon summer insures hot and dry synoptic weather conditions when the need for shade to mitigate heat stress is high.

Materials and Methods

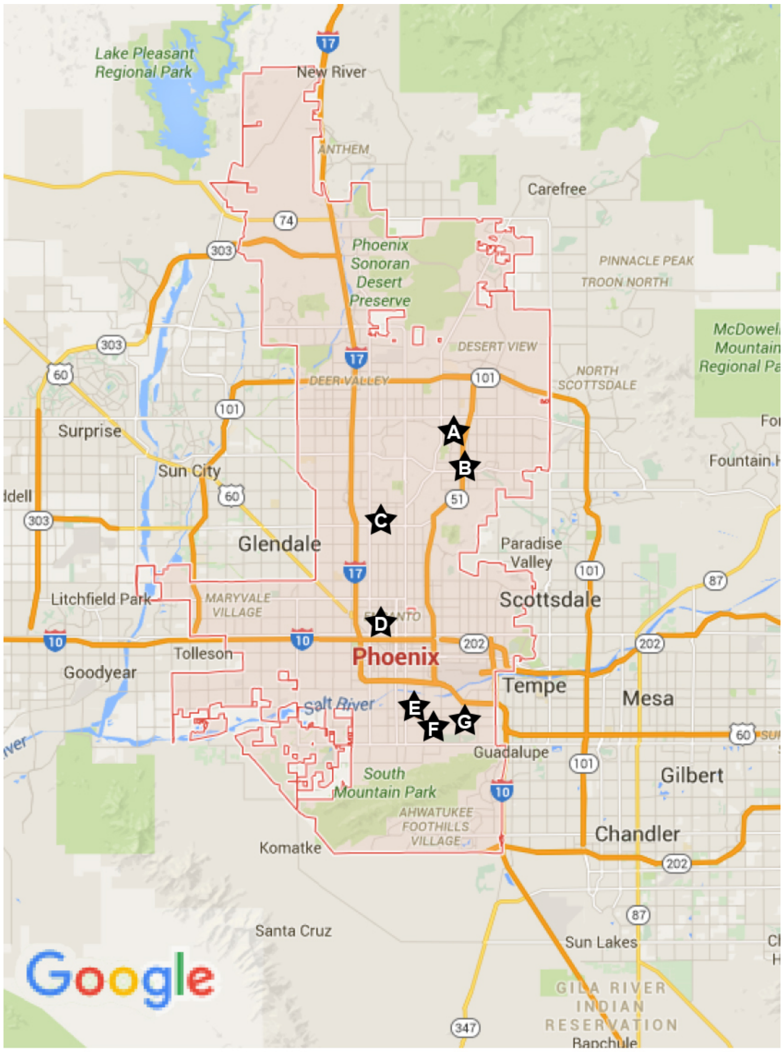
During June and July 2015, a study was conducted to determine effects of six landscape tree species and ramada structures on human thermal comfort in urban residential parks in Phoenix, Arizona. Phoenix is a desert city located in the southwestern United States (33.4° N 112.0°W) at an approximate elevation of 340 m. Sited at the northern region of the Sonoran Desert, Phoenix has an arid, subtropical climate with mild winters and hot summers. During June and July of 2015, the daily maximum and minimum air temperatures were 38.6 °C and 24.7 °C, respectively (AzMET, 2015). A majority of rainfall is distributed between cool, winter rains and humid, monsoon rains in late summer. During 2015, total monthly precipitation and potential evapotranspiration was 7.6 mm and 236.2 mm in June, and 15.5 mm and 231.1 mm in July. Phoenix landscape vegetation is typically provided with supplemental irrigation water during summer months to make up the deficit between precipitation and evapotranspiration.

Meteorological data were collected in full sun and under tree canopy and ramada shade at seven urban residential parks in Phoenix (Fig. 1). Each park was embedded within a residential community and ranged in size from 3.7 ha to 47.5 ha. The design of each park was predominately a mixture of Bermuda grass (*Cynodon dactylon* (L.) Pers.) surface cover and scattered mature landscape shade trees. Bermuda turf grass was clipped to a standard height of 2.5 cm. In addition, each park had ramada shade structures and recreational amenities such as playgrounds and barbeque grills. To limit the impact of topography and location on the data collected, all seven parks were selected across a 25 Km, north-south transect distributed in the northern, central and southern regions of Phoenix. The City of Phoenix Parks and Recreation Department managed all parks similarly. Bermuda turf grass and trees in each park were given regular supplemental irrigation by surface flooding or overhead sprinkler systems.

Tree Selection

Within the seven parks, six species of commonly used shade trees and park ramadas were selected for this study. The six shade tree species included: Arizona ash (*Fraxinus velutina* Torr.), Mexican palo verde (*Parkinsonia aculeata* L.), Aleppo pine (*Pinus halepensis* Mill.), South American mesquite (*Prosopis spp.* L.), Texas live oak (*Quercus virginiana for. fusiformis* Mill.), and Chinese elm (*Ulmus parvifolia* Jacq.). This selection represents a variety of trees including desert-adapted species (*Parkinsonia* and *Prosopis*), deciduous (*Fraxinus* and *Ulmus)*, evergreen *(Quercus),* and conifers (*Pinus*). Five replications for each tree species were selected for study, except for *Ulmus* (n=6). The distribution of tree species within the seven parks is summarized in Table 1. The following rules were applied during the selection of individual tree species replicates:

1) The tree canopy will not intersect with adjacent tree canopies, unless the adjacent tree is of the same species and the canopy of the selected tree is not significantly deformed.
2) No buildings or solid walls more than 2-m in height within 20 m of the selected tree.
3) Each tree must have a minimum crown base height above ground of 2.5 m.



Map data ©2016 Google 5 mi

Fig. 10. Location of Neighborhood Parks in Phoenix, AZ USA Where Micrometeorological Data was Recorded; A. Palomino Park, B. Roadrunner Park, C. Royal Palms Park, D. Encanto Park, E. Nueve Park, F. Hermoso Park, and G. Esteban Park

Table 18. Summary of City of Phoenix Parks Selected for Measurements and Their Address, Size, and Trees or Ramadas Selected for Measurement Within the Park.

Name	Address	Size	Trees species and/or ramadas selected
Encanto	2605 N. 15th Avenue	47.5ha	*Fraxinus*, *Parkinsonia*, *Prosopis*, *Quercus*, Ramada
Esteban	3345 E. Roeser Road	25.9ha	*Fraxinus*, *Quercus*, *Ulmus*, Ramada
Hermoso	2030 E. Southern Avenue	9.9ha	*Fraxinus*, *Pinus*, *Ulmus*, Ramada
Nueve	4445 S. 9th Street	3.7ha	*Parkinsonia*
Palomino	15815 N. 30th Street	4.5ha	*Prosopis*, Ramada
Roadrunner	3502 E. Cactus Road	14.4ha	*Pinus*, *Quercus*, Ramada
Royal Palms	9405 N. 15th Avenue	10.8ha	*Pinus*, *Ulmus*

4) Each tree must have an average minimum crown projection of 4 m, determined by the average of three measurements.
5) The ground cover surface underneath all selected trees must be Bermuda grass turf.
6) Trees must be a minimum of 20 m from park water feature.

For each tree the following measurements were taken: overall tree height, crown base height, diameter at breast height (DBH), and crown projection. Crown base height, the height of the lowest part of the crown above ground surface, and tree height were measured with a clinometer (Brunton, Louisville, CO). The DBH was measured using a metric diameter tape (Apex Tool Group, Sparks, MD) at a height of 1.4 m. If scaffold branches formed below 1.4 m, measurements were taken at narrowest point on the trunk below the first scaffold branch. Crown projection was determined through the average of three measurements of the distance from the trunk to the extent of the canopy.

Ramada Selection

Five replicates of ramada shade structures in residential parks were also selected for observation. The following rules were utilized for ramada selection:

1) The structure must be a stand-alone metal, concrete, or masonry structure without walls built for the purpose of providing shade.
2) The structure roof cannot be more than 7.6-m above the ground and must cover an area of 50 to 200 m^2.
3) The structure shall not be shaded by an adjacent tree or structure.
4) The surface cover underneath all ramadas must be consistent and surrounded by Bermuda grass turf when possible.

For each shade structure the following characteristics were identified: height of the ramada roof above the concrete surface pad, thickness of roof, length and width of structure, and ramada construction material. The surface cover under the selected ramadas was concrete, as there were no ramadas with Bermuda grass turf surface cover due to the difficulty of growing grass under dense shade and the desire to provide recreational amenities. In most cases the concrete area was limited to the exact dimensions of the ramada and was then surrounded by Bermuda grass turf. Several of the ramadas were equipped with tables, benches or barbeque grills. Two of the parks, Roadrunner and Esteban, utilized the same construction detail for the ramadas. When several structures were available at the park the structure with the most Bermuda grass turf surrounding it was selected.

Sky View Factor

Sky view factor (SVF) was used to describe the canopy characteristics for each tree canopy and ramada. SVF was determined by analyzing the pixels of a hemispherical image (Fig.3.) captured with a fish-eye lens under tree canopies and ramadas (Matzarakis et al. 2007, Matzarakis et al. 2010). Images were taken using a digital camera (EOS 6D, Canon, Melville, NY) fitted with a fish-eye lens (EF 8-15mm f/4L Fisheye USM Ultra-Wide Zoom Lens, Canon, Melville, NY) and then processed with photo editing software (Photoshop CS6, Adobe, San Jose, CA). The camera was set on a level surface at a 1.1-m height, directly north of the tree trunk and approximately one-third of the distance between the trunk and canopy edge. For structures, the camera was placed as close to the center of the structure as possible.

Meteorological Data

Mid-day micrometeorological data were recorded in shade under each tree canopy and ramada and in an adjacent full sun location. All micrometeorological data were recorded on 14 days between June 12, 2015 and July 8, 2015 (Julian Day 163 and 189) between the hours of 1200 hr and 1400 hr. The dates selected for data collection exhibited similar hot, dry conditions with clear skies and above normal geopotential heights typical of pre-monsoon weather in Phoenix, AZ (Table 2). Mean daily air temperature averaged 34.3 °C, relative humidity averaged 21%, and wind speed averaged 3.2 m/s. In comparison, normal synoptic weather conditions at Encanto Park, Phoenix, AZ for the month of June are mean daily air temperature 30.0 °C,

Table 19. Mean Daily Synoptic Weather Conditions During Measurement Days in Phoenix, AZ, USA During June and July 2015; Air Temperature (Tave), Maximum Air Temperature (Tmax), Relative Humidity (RH), Wind Speed (WS), and Sea Level Pressure (SLP).

Julian Day	Tave[Z] (°C)	Tmax[Z] (°C)	WS[Z] (%)	RH[Z] (m/s)	SLP[Y] (kPa)
163	30.7	38.3	2.0	22.7	100.2
165	33.5	40.1	2.7	18.8	100.2
166	35.0	41.7	2.9	17.5	100.6
167	34.7	41.7	2.9	20.0	100.6
168	35.4	42.7	3.1	20.5	100.6
169	35.2	43.5	2.9	19.9	100.6
170	33.5	42.3	2.9	20.2	100.9
172	34.6	40.1	3.4	23.2	100.9
173	34.0	40.3	3.1	22.1	100.6
174	35.2	42.4	3.6	18.7	100.6
175	35.1	42.5	2.9	19.0	100.9
176	35.2	41.2	4.5	24.0	100.6
188	33.8	39.8	2.9	30.3	100.6
189	33.7	40.3	4.9	19.8	100.6

[Z] Phoenix Encanto 2015 Daily Report. Phoenix (AZ): AZMet. [cited 2016 Jan 27]. Available from http://ag.arizona.edu/azmet/. Data are daily mean values recorded at Encanto Park, Phoenix, AZ; [Y]Weather History for KPHX. Phoenix (AZ): Weather Underground. [cited 2016 Jan 27]. Available from http://www.wunderground.com/history/airport/KPHX. Data are daily mean values recorded at Phoenix Sky Harbor International Airport, Phoenix, A relative humidity 25%, and wind speed 3.7m/s (AzMET, 2015). Of the 19 days in June when maximum air temperatures exceeded 40 °C, twelve coincided with micrometeorological measurement dates for this study (AzMET, 2015). Due to the number of tree species selected and the distance between park locations data were collected at one park location per day.

At each park, under tree canopies, micrometeorological data were consecutively recorded at three locations at a distance of one half of the crown projection from the tree trunk. These three locations were at cardinal degrees of 0, 120, and 240 (Fig. 2). Under ramadas, micrometeorological data were recorded three consecutive times at one location at the center point of the ramada's shade projection. Concurrently, three consecutive recordings of micrometeorological data were made in a nearby full sun location.

Under tree canopy and ramada shade, and in adjacent full sun locations, air temperature (Tair), globe temperature (Tg), relative humidity (RH) and wind speed (WS) were recorded with two portable Kestrel meters (4400 Heat Stress Tracker, Kestrel, Boothwyn, PA). Each Kestrel meter was mounted on a tripod at a height of 1.1-m. Surface temperature (Tsurf) was recorded with a hand-held infrared thermometer with a 7° field of view, held approximately 1.1-m above grade (Cen-Tech Infrared Thermometer, Camarillo, CA). Photosynthetically active radiation was recorded using a hand-held quantum sensor held at approximately 1.1-m above grade (LI-189, LI-COR, Inc., Lincoln, NE) and converted to total global radiation (Rad).

Normalization

All recorded air temperatures at each park were normalized to a nearby single reference air temperature within the park to eliminate variation caused by daily weather patterns, as data was not recorded at all parks simultaneously. Reference air temperature was recorded at one-hour intervals with portable dataloggers (WatchDog 100-Temp 2K, Spectrum Technologies, Plainfield, IL) mounted at the crown base height under the canopy shade of a nearby shade tree or similar dimensions and shade density. Reference temperatures were recorded from June 12,

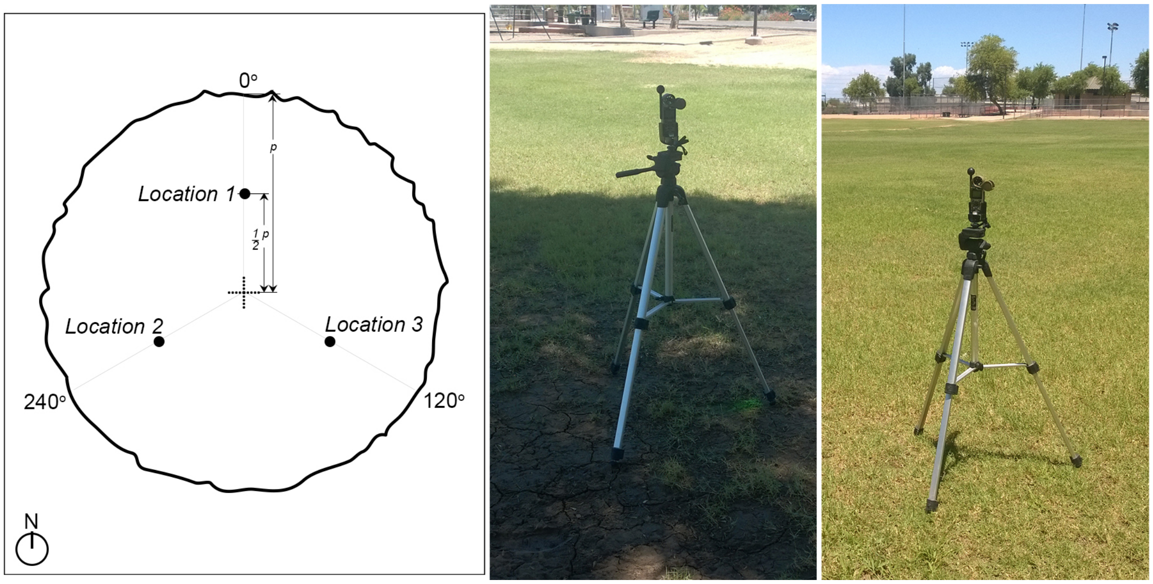
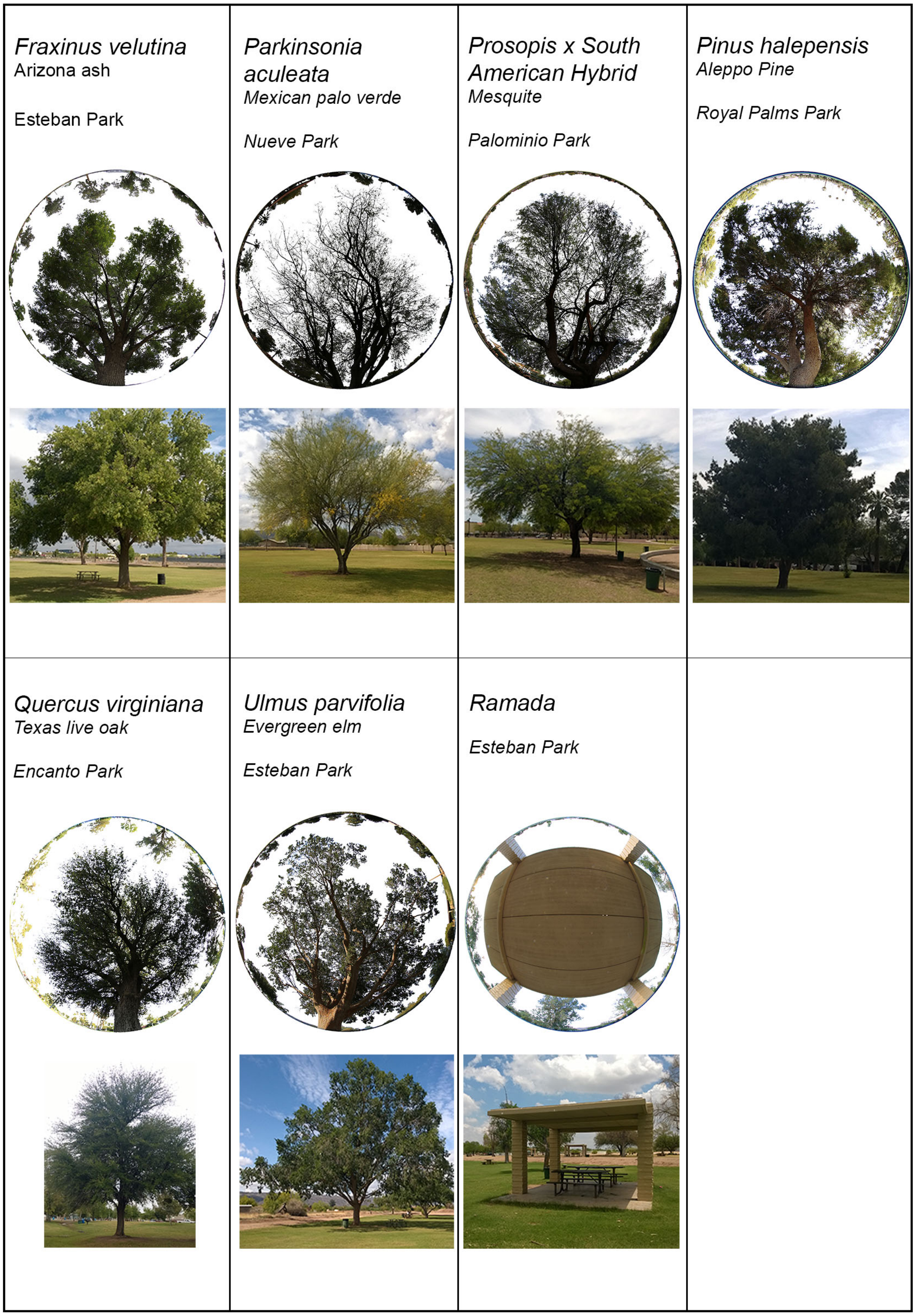


Fig. 11. Description of the Three Locations for Micrometeorological Data Collection Under Tree Canopy Shade (Left) and Images of Kestrel Heat Stress Meters Utilized for Micrometeorological Data Collection Under Shade and in Full Sun (Right).



Fraxinus velutina
Arizona ash

Esteban Park

Parkinsonia aculeata
Mexican palo verde

Nueve Park

Prosopis x South American Hybrid
Mesquite

Palominio Park

Pinus halepensis
Aleppo Pine

Royal Palms Park

Quercus virginiana
Texas live oak

Encanto Park

Ulmus parvifolia
Evergreen elm

Esteban Park

Ramada

Esteban Park

Fig. 12. Representative Standard and Fish-Eye Lens Photographs of the Selected Tree Species and Ramadas at Their Respective Locations in Residential Parks of Phoenix, AZ USA Taken in June 2015.

2015 to July 8, 2015 (Julian Day 163 to 189). The normalized air temperature (Tadj) for each recorded air temperature reading was calculated using the following formula:

$$Tadj = Tair - (Tmref - Tref) \quad (1)$$

where, Tair is the air temperature recorded by the Kestrel Heat Stress meter; Tmref is the park-specific reference air temperature at 1300 hr calculated as the mean of values recorded during Julian Day 163 to 189; Tref is the park-specific reference air temperature recorded at 1300 hr on the same day that Tair was recorded. Tmref was derived using only the 14 days on which micrometeorological data were collected (Table 2). The mean air temperatures from 1300 hr were selected as they represented a time during the middle of the microclimate measurement window. The same formula was used to adjust both sun and shade micrometeorological measurements.

Thermal Comfort Calculation

A combination of micrometeorological data (Tadj, WS, RH, Tsurf and Rad) and digital fish-eye images from shade and sun locations within each park were used by the RayMan model as input variables to calculate PET. Except for clothing, default model parameters were used for the personal data categories: 1.75m height, 75.0 kg weight, 35 years age, male, and 80.0 standing condition. The clothing setting used was 0.57 corresponding to trousers and a short-sleeved shirt, a more applicable clothing value for summer weather in Phoenix, AZ (ASHRAE, 2013). Additional data were calculated from PET; PETsun-PETshade is the difference between PET recorded in full sun and PET simultaneously calculated in shade, PETshade-Tadj is the difference between PET calculated under shade and Tadj recorded under shade.

RayMan Model Validation

Precision of the RayMan model was validated by comparing Tmrt calculated from observational micrometeorological data (*O*) with the Tmrt values predicted by the RayMan model (*P*). Observed Tmrt was calculated using the ISO Standard 7726 (1998) equation, which required recorded data for air temperature (Tair), globe temperature (Tg), and wind speed (WS) and has been utilized previously to validate RayMan results (Thorsson, 2007, Lin et al., 2010). This validation procedure was conducted under full sun and shade conditions. This validation methodology was based on calculations of the root mean square error (RMSE), the index of agreement (*d*), and other relevant descriptive statistics (Wilmot, 1982). RMSE is a favorable descriptor of model performance as it relates directly to the size of the differences between *O* and *P*. The degree to which the modeled values are error free is represented by *d* and reported as a value from 0.0 to 1.0, the higher the number the closer *P* is to *O*.

Statistical Analysis

Several linear model procedures were used to compare effects of tree or ramada shade on micrometeorological data (PET, Tmrt, Rad, Tadj, RH, WS). Mean values for PET, PETsun-PETshade, Tsurf, Tadj, Tmrt, Rad, and RH were evaluated for significant difference by shade element using Tukey's LSD Test, P<0.05. Values of SVF, Tadj, Tsurf, and RH were analyzed for correlation to PET using Bivariate analysis of fit tests, P<0.05. All analysis were completed with JMP Software (JMP 8.02, SAS Institute, Cary, NC).

Results

Physical Characteristics of Tree Species and Ramadas

For each tree species, mean crown height, crown base height, crown projection, shade projection and diameter at breast height (DBH) are summarized in Table 3. Mean crown heights of all trees were similar, except for *Parkinsonia,* which was ca. 15-20% less. Crown height was most variable for *Ulmus*. Crown base height was similar for all tree species. Mean crown and shade projections of *Ulmus* and *Prosopis* were greater than *Parkinsonia* and *Pinus*. Mean DBH of *Pinus* and *Fraxinus* was greater than *Parkinsonia*. *Quercus* trees had the most variation in crown projection, shade projection, and DBH. Mean height of ramada roof cover was 3.4±0.96 m above the concrete ground surface. Mean shade projection observed for ramadas

Table 20. Crown Height and Base, Crown Projection, Shade Area, and Diameter at Breast Height (DBH) of Selected Tree Taxa (*Fraxinus*, *Parkinsonia*, *Pinus*, *Prosopis*, *Quercus*, and *Ulmus*) Within Seven Residential Parks, Phoenix, AZ USA.

Species	Crown Height (m)	Crown Base Height (m)	Crown Projection (m)	Shade Projection (m^2)	DBH (cm)
Fraxinus	9.8 ± 0.6[Z]	3.7 ± 0.5	6.3 ± 0.9	125.7 ± 34.6	56.3 ± 7.7
Parkinsonia	8.2 ± 0.6	3.5 ± 0.2	5.4 ± 0.9	94.8 ± 30.7	46.6 ± 6.4
Pinus	10.7 ± 1.1	3.2 ± 0.4	5.8 ± 1.0	108.0 ± 40.6	66.4 ± 10.3
Prosopis	8.8 ± 1.1	3.4 ± 0.5	7.0 ± 1.0	154.3 ± 41.3	50.0 ± 11.6
Quercus	10.3 ± 1.4	3.4 ± 0.5	7.3 ± 2.2	181.2 ± 119.9	66.0 ± 19.8
Ulmus	10.7 ± 2.2	3.5 ± 0.3	7.8 ± 1.5	195.8 ± 70.5	54.4 ± 14.7

[Z] Mean values ± SD; n=5, except n=6 for *Ulmus* was 108.9±45.4 m^2, these values were similar to the mean shade projection of *Fraxinus, Parkinsonia, Pinus, and Prosopis*.

Mean sky-view factor (SVF) results are reported in Table 4. Mean SVF under trees and ramadas was generally about 72% less than full sun. Under ramadas, mean SVF was ca. 42% less than under trees. Mean SVF under *Parkinsonia* trees was higher than under the other tree species. Mean SVF of *Ulmus*, *Prosopis*, *Quercus*, and *Pinus* tended to be similar. Standard deviations for SVF under trees and ramadas ranged from only 0.01 to 0.02.

Meteorological Data

Mean values for micrometeorological data recorded under shade of ramada, six tree species, or in full sun are summarized in Table 5. Tadj was 1.2-2.6 °C higher under *Parkinsonia* than under the remaining tree species, ramada, or in full sun. Tsurf was 10.2-18.8 °C higher in the full sun than under shade. Under shade of *Prosopis* and ramada, Tsurf was higher than under *Fraxinus*, *Parkinsonia*, *Pinus*, *Quercus*, and *Ulmus*. Tsurf under *Pinus* was less than *Parkinsonia* and *Quercus* by ca. 10%. Rad in full sun was 798.3-878.4 W/m^2 higher than Rad under shade. Under *Parkinsonia* shade, Rad was higher than under ramadas and all tree species except *Prosopis*. Rad under *Prosopis* was similar to *Parkinsonia* and *Ulmus*. Although ramada had the lowest absolute value for Rad, it was not significantly different from *Fraxinus*, *Pinus*, *Quercus*, or *Ulmus*. Mean RH in full sun was similar to mean RH under shade. Under *Prosopis* and ramada shade, mean RH was lower than under *Fraxinus*, *Pinus*, *Ulmus*, and *Quercus*. WS was similar under ramadas, all tree species, and in full sun.

Thermal Comfort

A summary of Tmrt and PET modeled by RayMan are shown in Table 6. The highest values for Tmrt and PET were recorded in full sun. Tmrt and PET in full sun were 23.5-15.0 °C and 12.6-6.9 °C greater, respectively, than Tmrt under shade of ramada or trees. Tmrt under *Parkinsonia* and *Prosopis* shade was greater than Tmrt under the shade of ramadas or other tree

Table 21. Mean Sky View Factor (SVF) Under Canopy Shade of *Fraxinus*, *Parkinsonia*, *Pinus*, *Prosopis*, *Quercus*, and *Ulmus*, and Under Ramada, and in the Full Sun Within Seven Residential Parks, Phoenix, AZ USA.

Shade Type	SVF
Fraxinus	0.26 ± 0.01[z]
Parkinsonia	0.33 ± 0.02
Pinus	0.24 ± 0.02
Prosopis	0.23 ± 0.02
Quercus	0.21 ± 0.01
Ulmus	0.22 ± 0.01
Ramada	0.14 ± 0.01
Full sun	0.80 ± 0.06

[z] Mean values ± SD, n=5, except n=6 for *Ulmus*.

Table 22. Mean Meteorological Data [Adjusted Air Temperature (Tadj), Globe Temperature (Tglobe), Wind Speed (WS), Relative Humidity (RH), Surface Temperature (Tsurf), and Global Radiation (Rad)] Collected Under Shade of Ramada, Six Tree Species, or in Full Sun During June and July 2015 between 1200 and 1400 hr, Phoenix, AZ USA.

Shade Type	Tadj (°C)	Tsurf (°C)	Tglobe (°C)	Rad (W/m^2)	RH (%)	WS (m/s)
Fraxinus	38.5 ± 1.1[Z]	32.5 ± 3.0	39.3 ± 1.5	32.3 ± 7.4	20.5 ± 4.8	1.0 ± 0.7
Parkinsonia	41.1 ± 1.0	33.2 ± 2.5	43.4 ± 1.2	108.9 ± 61.5	13.6 ± 2.2	0.9 ± 0.7
Pinus	38.6 ± 1.0	30.0 ± 2.0	40.2 ± 1.2	42.9 ± 17.5	18.6 ± 5.4	1.2 ± 0.5
Prosopis	39.3 ± 1.8	38.6 ± 1.9	44.3 ± 1.8	82.3 ± 54.0	10.3 ± 2.5	1.2 ± 0.7
Quercus	39.1 ± 1.6	33.8 ± 2.7	40.3 ± 2.7	42.8 ± 39.8	17.1 ± 4.4	0.9 ± 0.6
Ulmus	39.0 ± 1.3	32.0 ± 2.9	40.2 ± 2.0	54.0 ± 22.3	17.2 ± 5.3	1.0 ± 0.6
Ramada	39.3 ± 1.0	38.6 ± 3.0	43.6 ± 1.5	28.8 ± 7.4	12.3 ± 3.4	0.8 ± 0.7
Full sun	39.9 ± 1.5	48.8 ± 7.9	53.0 ± 2.8	907.2 ± 36.7	15.7 ± 5.7	1.0 ± 0.7

[Z] Mean values ± SD; n=24 for *Fraxinus*; n=24 for *Ulmus*; n=15 for *Prosopis*; n=18 for *Quercus*; n=15 for *Parkinsonia*; n=15 for *Pinus* n=21 for ramada; and n=132 for full sun.

species. Tmrt under *Fraxinus* shade was less than Tmrt under the shade of ramadas. PET under *Parkinsonia* shade was greater than PET under shade of *Fraxinu*s, *Pinus*, *Quercus*, *Ulmus*, or ramadas. PET under ramada shade was similar to PET under all tree species except *Parkinsonia*.

Calculated differences between PET in full sun and under shade (PETsun-shade), and between PET and Tadj under shade (PETshade-Tadj) are summarized in Table 7. PETsun-shade differences of *Fraxinus* and *Quercus* were higher than *Parkinsonia, Prosopis* or ramadas. PETshade-Tadj differences of *Parkinsonia* and *Prosopis* were higher than *Fraxinus*, *Pinus*, *Quercus*, *Ulmus*, or ramadas.

Results from bivariate analysis of TAadj, WS, RH, Tsurf, Rad, and SVF against PET under shade are summarized in Table 8. TAadj and Rad were significant drivers of PET. In contrast, WS, RH, Tsurf and SVF were not strongly correlated with PET

RayMan Model Validation

Based upon Willmott (1982), an array of values including RMSE, *d*, and general descriptive statistics were determined to describe the relationship between RayMan modeled (*P*) and observed (*O*) Tmrt. The RMSE and *d* calculated for observed and modeled Tmrt were 5.49 °C and 0.94, respectively (n=264). The mean Tmrt predicted by the RayMan model (*P*=39.9 °C) was lower than the observed Tmrt (*O*=42.0 °C). In full sun RayMan (*P*=60.0 °C) tended to predict a higher Tmrt than was observed (*O*=55.5 °C). Under shade RayMan (*P*=39.9 °C) tended to predict a lower Tmrt than observed (*O*=42.0 °C). A linear regression analysis indicated a strong correlation between *P* and *O* (P=1.3O-11.9, r^2=0.79, n=264).

Discussion

In June and July 2015, thermal comfort in full sun and under shade of six tree species and park ramadas was calculated from micrometeorological data collected on afternoons in Phoenix, AZ USA. This study was initiated to determine if tree species and shade structures vary

Table 23. Calculated Mean Radiant Temperature (Tmrt) and Physiological Equivalent Temperature (PET) Under Shade of Ramada, Six Tree Species, or in Full Sun During June and July 2015 Between 1200 and 1400 hr, Phoenix, AZ USA.

Shade Type	Tmrt (°C)	PET (°C)
Fraxinus	36.8 d[Z]	38.5 d
Parkinsonia	45.3 b	44.2 b
Pinus	36.9 cd	38.9 d
Prosopis	44.5 b	42.6 bc
Quercus	39.0 cd	39.8 d
Ulmus	39.0 cd	39.9 d
Ramada	40.4 c	40.3 cd
Full sun	60.3 a	51.1 a

[Z] Mean values ± SD; n=24 for *Fraxinus*; n=24 for *Ulmus*; n=15 for *Prosopis*; n=18 for *Quercus*; n=15 for *Parkinsonia*; n=15 for *Pinus* n=21 for ramada; and n=132 for full sun.

Table 24. Calculated Differences Between Physiological Equivalent Temperature (PET) in Full Sun and Under Shade (PETsun-shade), and Between PET and Adjusted Air Temperature (Tadj) Under Shade (PETshade-Tadj) Sorted by Tree Species or Ramada as Observed During June and July 2015 Between 1200 and 1400 hr, Phoenix, AZ USA.

Shade Type	PETsun-shade (°C)	PETshade-Tadj (°C)
Fraxinus	12.6 a	-0.02 b
Parkinsonia	8.3 b	3.11 a
Pinus	11.1 ab	0.27 b
Prosopis	9.3 b	3.37 a
Quercus	12.4 a	0.66 b
Ulmus	10.8 ab	0.97 b
Ramada	9.5 b	1.04 b

[z] Mean values, n=24 for ash; n=24 for elm; n=15 for mesquite; n=18 for oak; n=15 for palo verde; n=15 for pine; and n=21 for structure. Mean values followed by the same letter within a column are not significantly different, Tukey's HSD test, α =0.05

Table 25. Results of Analysis of Variance of the Bivariate Fit of Physiologically Equivalent Temperature (PET) Under Canopy Shade of Trees and Ramada by Global Radiation (Rad), Adjusted Air Temperature (Tadj), Surface Temperature (Tsurf), Relative Humidity (RH), or Sky View Factor (SVF).

	Tadj (°C)	WS (°C)	RH (m/s)	Tsurf (%)	Rad (°C)	SVF (W/m^2)
F-ratio	134.7^Z	4.1	10.9	9.3	293.2	3.4
P-value	<0.0001	0.0438	0.0013	0.0027	<0.0001	0.0672
r^2	0.51	0.02	0.07	0.06	0.69	0.02

^{Z} Results of bivariate analysis of fit n=132 for all tests.

in their ability to modify human thermal comfort, hypothesizing that the trees and structures capable of attenuating the most solar radiation would be the most effective at improving human thermal comfort as described by PET. Results from this research showed that all of the landscape trees and ramadas were effective at lowering PET, but some more so than others. These data support the significant role of attenuating radiation in mitigating outdoor human thermal discomfort and heat stress. The exception was under ramada shade where the relationship between PET and radiation was more complex.

Thermal Comfort Differences

All the landscape trees and ramadas in this study significantly improved outdoor human thermal comfort compared with a full sun exposure. The PET difference between shaded and unshaded locations was 8.3 °C or more. Even though all trees and ramadas provided shade that significantly lowered PET compared to full sun, *Parkinsonia* and *Prosopis* trees and sometimes ramadas were less effective at mitigating outdoor human thermal comfort than the other landscape trees. Few previous studies have documented the ability of different landscape tree species to effect human thermal comfort through shading. A 2010 study in Tel Aviv, Israel evaluated three species of trees and found differences among all three that were mostly related to canopy coverage (Shashua-Bar et al., 2010). A more recent study in Campinas, Brazil evaluated 12 species of trees and found that individual plantings of those trees provided a range of PET reductions from 7.1-16.0 °C (de Abreu-Harbich, et al. 2015). PETsun-shade differences ranged from 8.3-9.5 °C under *Parkinsonia*, *Prosopis*, and ramada to 12.4-12.6 °C under *Fraxinus* and *Quercus*. The maximum thermal comfort cooling effect was recorded under shade of *Fraxinus*, which had PETsun-shade differences that were 4.3 °C more than *Parkinsonia*.

Within the context of human comfort, were the amplitude of PETsun-shade differences between tree species and/or ramadas recorded in this study physiologically significant? Previous studies have utilized PET in combination with thermal comfort scales to assign PET temperature ranges to general comfort levels, such as neutral, warm, hot, etc. (Lin and Matzarakis, 2009, Cohen et al., 2013, Mayer and Matzarakis, 1998). In these studies, each thermal comfort scale was dependent upon climate as individuals will adapt to local conditions. The thermal comfort scale most similar to the climate of this study was developed for Tel Aviv, Israel, with a 2 °C difference between neutral and slightly warm, a 6°C difference between slightly warm and warm, and a 6 °C difference between warm and hot (Cohen et al., 2013). The difference observed in this study between *Fraxinus* and *Parkinsonia* PETsun-shade 4.3 °C. Considered from another perspective, any temperature above 40 °C was considered 'Very hot' according to the thermal comfort scale used by Cohen et al. (2013). PET under *Parkinsonia*, *Prosopis* and ramada were higher than 40 °C, while *Fraxinus*, *Pinus*, *Quercus*, and *Ulmus* were lower than 40 °C. It appears from these findings that *Fraxinus*, *Pinus*, *Quercus*, and *Ulmus* are better suited to mitigate human discomfort from heat stress than *Parkinsonia*, *Prosopis* or ramadas.

Impact of Solar Radiation

Global radiation and the differential extent to which it was attenuated by tree species or ramadas appeared to be the best explanation for the differences in thermal comfort observed in this study. Bivariate analysis of meteorological data showed that radiation was strongly correlated to PET. Although Tadj was also strongly correlated to PET in a bivariate analysis, Tadj in full sun and under tree or ramada shade were similar, except for *Parkinsonia*. Other studies have found that air temperatures are not greatly altered by the presence or absence of shade (Ali-Tourdet et al., 2007). In this study, the differences that were recorded under *Parkinsonia* were likely due to the park location rather than the actual tree shade. A majority of the *Parkinsonia* trees that used in this study were from a park within a neighborhood of low socio-economic rank surrounded by industrial land use of sparse vegetative cover. Parks within neighborhoods with these characteristics were previously associated with higher air temperatures (Martin et al., 2012), which explains why higher temperatures were observed in the *Parkinsonia* locations.

WS was also an unlikely cause, as there were no observed differences in WS under shade or in full sun. Tsurf and RH also had a limited impact on PET, but variation in these values was most likely due to the effects of groundcover. Tsurf was highest under ramada and *Prosopis*, the former is explained by concrete groundcover and the latter by poor Bermuda turf grass health leading to exposed bare ground. Different thermal properties of these materials, combined with the reduced ability for Bermuda turf grass to contribute to cooling through evapotranspiration are potential explanations for Tsurf and RH differences. Additionally, irrigation practices for the parks varied between surface flood irrigation and overhead sprinklers. Measurements were not conducted during periods of irrigation, but the two irrigation methods vary in the amount of water applied to the soil, which could have still have a limited impact on measurements. The interaction of shade and groundcover can create differences in thermal comfort (Shashua-Bar et al., 2009, Shashua-Bar et al., 2011). Additional studies are needed to better understand how shade type and groundcover type combine to impact thermal comfort.

The results from this study aligned with previous work in urban environments that have demonstrated that radiation, especially in hot, arid climates, is the most significant factor impacting thermal comfort (Shashua-Bar, 2000, Gulyas et al., 2006, Coutts et al., 2015). The tree species with significantly higher thermal comfort temperatures, Parkinsonia and Prosopis, were also the species that attenuated the least amount of solar radiation. These findings supported the research hypothesis that tree species and shade structures would vary in their capacity to improve thermal comfort due to their respective abilities to attenuate solar radiation. The few studies exploring the effect of tree species on thermal comfort under have also found a negative correlation between the percent of radiation attenuated and thermal comfort (Georgi and Zafiriadis, 2006, de Abreu-Harbich, et al., 2015). Shashua-Bar et al. (2010) attributed microclimate differences to tree canopy density, a characteristic primarily determined by species type. The performance of *Parkinsonia* and *Prosopis* can be partially explained by the low levels of canopy density and leaf coverage resulting from bipinnate leaf structure, which are characteristic of these two species (Brenzel, 2001). Under ramada shade, solid canopy coverage did not result in lower thermal comfort temperatures.

The relationship between solar radiation and thermal comfort under ramada shade was not as distinct. The Rad under ramadas was 97% less than Rad under full sun and was similar to

Quercus, *Ulmus*, *Fraxinus*, and *Pinus*. SVF for ramadas was lower than the trees due to the solid nature of the ramada roofs, making it the most efficient at blocking direct solar radiation. Despite lower absolute radiation and SVF values, thermal comfort under ramada shade was not significantly lower than thermal comfort under tree shade. In fact, they are mostly similar to *Parkinsonia* and *Prosopis* rather than to the other trees. This is likely due to emission of longwave radiation absorbed by materials in the structure. A study by Shashua-Bar et al. (2011) utilized infrared thermal images to show high radiant surface temperatures on a canvas shade cloth in comparison to tree shade. Although highly efficient at blocking solar radiation, ramadas were not equally effective at improving thermal comfort. Additional research should identify the height, size, and materials for shade structures that are best for improving thermal comfort, before structures are broadly recommended as an alternative to shade trees.

RayMan Model Performance

Results from the RayMan model validation were good when compared to a recent study conducted in Glasgow, UK that explored how effective different RayMan model parameters were for calculating Tmrt, when compared to the globe thermometer method (Krueger et al., 2014). They found using RayMan with input values for global short-wave radiation and SVF from a representative location, the most similar method to approach taken by this study, RSME was 11.9°C and *d* was 0.54. Accuracy of RayMan improves when calculations are made for conditions when wind speed is low (Chen et al., 2014) and during summer afternoons when the sun angle is high (Thorsson et al., 2007), which might be explanations for the strong validation results observed in this study. Furthermore, this study used both local SVF and global short-wave radiation measurements as input parameters for RayMan.

One question addressed by this study was how well SVF can predict PET. A bivariate analysis revealed a poor correlation between SVF and PET. There was little variation in SVF between tree species, while a greater difference was recorded for ramadas and full sun exposures. Since SVF must be calculated from the full 180° hemispherical photo, more than just the tree canopy is accounted for. Small spaces between branches and leaves make up a small fraction of the image. Some studies have adapted SVF to calculate SVF isolated to just the tree canopy (de Abreu-Harbich, et al. 2015, Konarska et al., 2014). The results are not adequate to calculate PET, but can be used as a ratio to describe openness in the tree canopy. However, these calculations may still be limited by the resolution of images used by RayMan and may not be detailed enough to pick up differences leaf coverage. Alternative methods such as Leaf Area Index, Plant Area Index, or direct measurements of radiation, may be better suited for quantifying the relationship between canopy density and thermal comfort.

Research Implications

Tree shade is an appealing solution to improving thermal comfort in the outdoor urban environment because in addition to the relative ease with which trees can be planted, they also provide numerous other benefits (Nowak and Dwyer, 2007). Along with the costs of planting and maintaining trees, in desert cities the additional demand planting initiatives place on water resources for irrigation must also be considered. Several findings of this study can be useful for analyzing tradeoffs between the performance benefit of microclimate cooling and water conservation. First, not all shade elements observed in this study can be considered similarly effective at improving thermal comfort during summer afternoons. This result also has implications for water use as *Parkinsonia* and *Prosopis*, often promoted as low water-use trees (ADWR, 2007), were less effective at lowering PET. Second, further research is needed to understand the relationship between outdoor thermal comfort and shade provided by an architectural shade structure. Factors such as height, size, and material should be investigated to identify how the characteristics of shade structures affect thermal comfort.

When selecting tree species to plant or developing policy to implement tree shade, the results from this study are best utilized when context is taken into consideration. In a case where mitigating outdoor thermal discomfort is a high priority, such as in urban residential parks where visitors are likely be outside during the hottest parts of the day, selecting landscape trees that give the most thermal comfort cooling may be necessary, despite the potential to use more water. However, in a residential yard where the necessity of mitigating outdoor thermal discomfort is low, there are several trees or structures that will be sufficient and water conservation can be prioritized instead. Structures must also be considered in a larger context before they are implemented. Results from this study show that the ramada type structures observed performed the benefit of microclimate cooling moderately well. However, when a structure is selected to provide shade the many additional benefits that would be provided by a tree are also lost. This may be an acceptable tradeoff for amenities that can be provided underneath a structure, such as tables, grills, etc. that would be unsuitable under a tree.

As cities continue to recognize the important roles that trees can play in addressing human comfort in urban environments it is important to also increase the knowledge base about how these benefits can be optimized, recognizing that tradeoffs that may be necessary. Careful consideration of the context for each site will lead to a more thoughtful balance of thermal comfort benefits and water conservation.

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APPENDIX A

REPRODUCTIONS FROM SUSTAINABLE SITES INITIATIVE DOCUMENTATION FOR PETE V. DOMENICI US COURTHOUSE SUSTAINABLE LANDSCAPE RETROFIT

Table 1. Values and calculations for baseline landscape water use (BLWR) at Domenici Courthouse in Albuquerque, NM.

ET0 (inches/month)	A (square feet)	C_U	BLWR (gal)	BLWR (L)
7.17	75,439	0.6233	337,142	1,276,221

Table 2. Values and calculations for designed landscape water use (DLWR) at Domenici Courthouse in Albuquerque, NM.

Hydrozone	D_U	K_L	A	CLWR (gal)	CLWR (L)
Planting Area^Z	0.9	0.20	21,345	16,357	61,918
Planting 1 – Turf	0.9	0.80	1,812	6,788	25,695
Planting 2 – Arroyo Riparian	0.9	0.20	5,130	3,932	14,884
Planting 3 – Native Shrubs/G.C.	0.9	0.20	3,944	3,022	11,440
Planting 4 – Mesa Shrubs/G.C.	0.9	0.20	9,293	7,121	26,956
Planting 5a – High Desert Shrubs	0.9	0.20	26,184	20,065	75,954
Planting 5b – High Desert Shrubs	0.9	0.20	7,731	5,924	22,425
Total				63,209	239,272

^{Z}Common Values; $ET_0 = 7.17$; $R_A = 0.3275$; $C_U = 0.6233$; RTM = 1.11

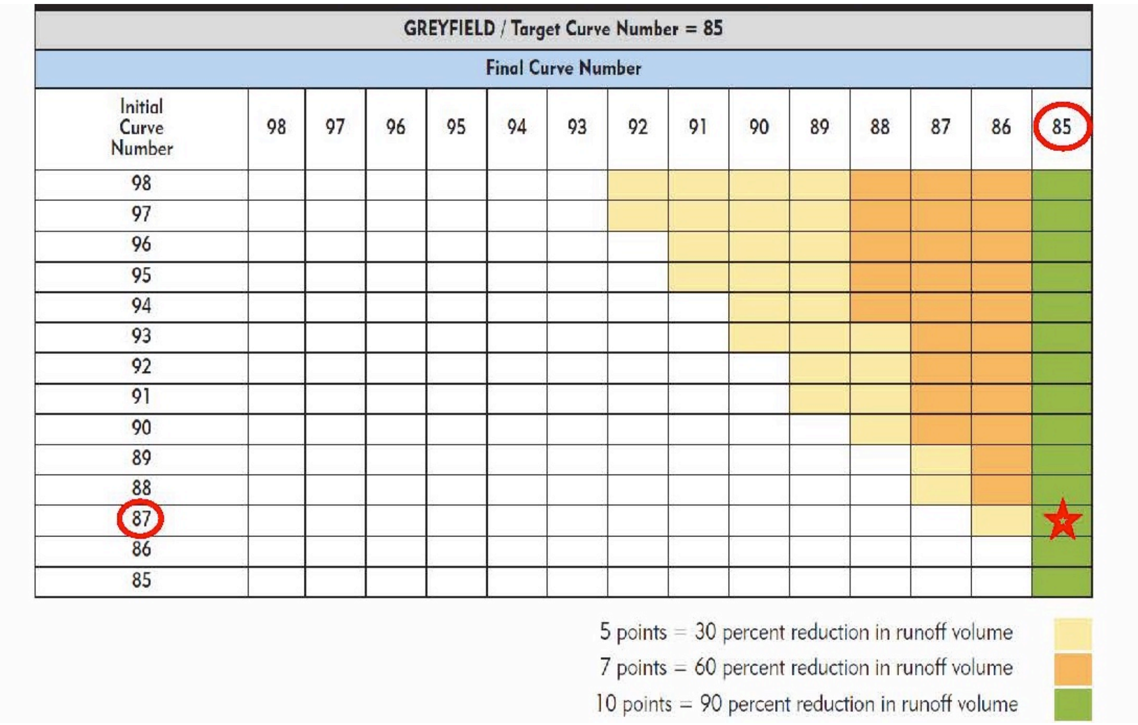
Table 3. Calculations for percentage of water use reduction at Domenici Courthouse in Albuquerque, NM.

Water Source	Water use (liters)
Baseline Landscape Water Requirement	1,276,221
Designed Landscape Water Requirement	239,272
Non-Potable Source (Rainwater Cistern Volume)	60,567
Percentage Water Use Reduction	86%

Table 4. Existing and post-development hydrologic conditions at Domenici Courthouse in Albuquerque, NM USA.

Land Use	Hydrologic Soil Group	Existing Conditions		Post-Development Conditions	
		Area (ha)	Curve Number	Area (ha)	Curve Number
Open Space; grass cover >75%	B	0.28	61	0.16	61
Paved parking lots, roofs, driveways	B	1.13	98	0.89	98
Desert shrub	B	0.23	68	0.68	68
Newly graded area (Post-development only)	B	0.00	0	0.04	86
Totals		1.64	87	1.77	85

Table 5. Initial and post-development stormwater curve numbers and percent reduction in runoff volume at Domenici Courthouse in Albuquerque, NM USA.



GREYFIELD / Target Curve Number = 85

Initial Curve Number	Final Curve Number													
	98	97	96	95	94	93	92	91	90	89	88	87	86	85
98							🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟩
97							🟨	🟨	🟨	🟨	🟧	🟧	🟧	🟩
96								🟨	🟨	🟨	🟧	🟧	🟧	🟩
95								🟨	🟨	🟨	🟧	🟧	🟧	🟩
94									🟨	🟨	🟧	🟧	🟧	🟩
93									🟨	🟨	🟨	🟧	🟧	🟩
92										🟨	🟨	🟧	🟧	🟩
91										🟨	🟨	🟧	🟧	🟩
90											🟨	🟧	🟧	🟩
89												🟨	🟧	🟩
88												🟨	🟧	🟩
87													🟨	🟩 ★
86														🟩
85														🟩

5 points = 30 percent reduction in runoff volume 🟨

7 points = 60 percent reduction in runoff volume 🟧

10 points = 90 percent reduction in runoff volume 🟩

Table 6. Annual energy demand of selected light fixtures at Domenici Courthouse in Albuquerque, NM USA.

Quantity	Fixture	Watts/Hr	Average Daily Runtime (Hrs)	Days Per Year	Total kWh
12	F-1	50	10	365	2,190.00
9	F-2	71	10	365	2,332.35
4	F-2A	71	10	365	1,036.60
1	F-2B	71	10	365	259.15
4	F-3	50	10	365	730.00
40	F-4	26	8	365	3,036.80
778 LF	F-5	6W/LF	12	365	20,445.84
9	F-6	320	12	365	12,614.40
4	F-7	50	8	365	584.00
Total					43,229.14

Table 7. Annual solar power output from photovoltaic panels installed at Domenici Courthouse in Albuquerque, NM USA.

Month	Solar Radiation ($kWh/m^2/day$)	AC Energy (kWh)	Energy Value (¢11.8 /kWh)
January	3.57	2,355	$204.88
February	4.52	2,698	$234.73
March	5.58	3,691	$321.12
April	7.01	4,327	$376.45
May	7.97	4,959	$431.43
June	8.04	4,695	$408.46
July	7.80	4,686	$407.68
August	7.09	4,295	$373.66
September	6.03	3,563	$309.98
October	5.07	3,212	$279.44
November	3.94	2,454	$213.50
December	3.31	2,157	$187.66
Total	5.83	43,093	$3,749.09

Table 8. Energy reduction between selected light fixtures and lowest cost comparable fixture at Domenici Courthouse in Albuquerque, NM USA.

Qty	Selected Fixture	Annual Energy Use (kWh/yr)	Comparable Fixture	Annual Energy Use (kWh/yr)	Percent Reduced
12	LED 40W Pole	600	High Pressure Sodium (HPS) Pole	1,200	50%
9	LED 60W Pole	639	HPS Pole	900	29%
4	LED 60W Pole	284	HPS Pole	400	29%
1	LED 60W Pole	71	HPS Pole	100	29%
4	LED 40W Pole	200	HPS Pole	400	50%
40	Compact Fluorescent 26W	1,040	Incandescent 100W	4,000	74%
778 LF	LED 6W Linear	4,668	LED 6W Linear	4,668	0%
9	Metal Halide Pole	2,880	HPS Pole	3,240	11%
4	MR-16 In Grade	200	R-20 Incandescent	400	50%
1	Orenco Pump	2,438	Comparable	3,312	26%
Total		13,020		18,620	30%

Table 9. Quantity of waste diverted during construction at Domenici Courthouse in Albuquerque, NM USA.

Material	Material Category	Name of Receiving Agent	Waste Diverted (kg)
Concrete	Road/Infrastructural	Harold Grading & Trucking	217,724
Rebar	Structural Materials	Acme Iron & Metal Group	2,722
Metal Tree Grates	Structural Materials	Born Free Scrap Metal	6,350
Concrete Paving	Road/Infrastructural	On-site	200,488
Foam Fill	Structural Materials	On-site	9,072
Total Waste Diverted			436,356

APPENDIX B

REPRODUCTIONS FROM SUSTAINABLE SITES INITIATIVE DOCUMENTATION FOR GEORGE “DOC” CAVALLIERE PARK

Table 1. Energy reduction between selected light fixtures and lowest cost comparable light fixture at Doc Park in Scottsdale, AZ USA.

Qty	Fixture	Annual Energy Use (kWh/yr)	Comparable Fixture	Annual Energy Use (kWh/yr)	Percent
22	Beta LED	5,143	Incandescent	204,905	97%
6	Visonaire	4,109	Incandescent	104,781	96%
3	Visonaire	2,055	Incandescent	52,391	96%
15	Beta LED	603	Incandescent	10,478	94%
27	Bega	888	Incandescent	9,430	91%
5	Winscape	68	Incandescent	1,746	96%
2	Winscape	27	Incandescent	699	96%
Total		12,892		384,430	97%

APPENDIX C

STANDARD AND FISH-EYE LENS PHOTOGRAPHS OF THE SELECTED TREES AND RAMADAS IN RESIDENTIAL PARKS OF PHOENIX, AZ USA

Arizona ash (*Fraxinus velutina* Torr.)


EN-Ash-1


ES-Ash-1


ES-Ash-2

ES-Ash-3

HR-Ash-1

Mexican palo verde (*Parkinsonia aculeata* L.)


ES-Palo-1


NU-Palo-1


NU-Palo-2

NU-Palo-3

NU-Palo-4

Aleppo pine (*Pinus halepensis* Mill.)



HR-Pine-1



RD-Pine-1



RY-Pine-3

RY-Pine-4

RY-Pine-5

South American mesquite (*Prosopis spp.* L.)

EN-Mesq-1

EN-Mesq-2

PL-Mesq-1

PL-Mesq-2

PL-Mesq-4

Texas live oak (*Quercus virginiana for. fusiformis* Mill.)


EN-Oak-1


EN-Oak-2

ES-Oak-1

ES-Oak-3

ES-Oak-4

Chinese elm (*Ulmus parvifolia* Jacq.)



ES-Elm-1



ES-Elm-2



ES-Elm-3

HR-Elm-3

RD-Elm-1

RY-Elm-1

Ramadas



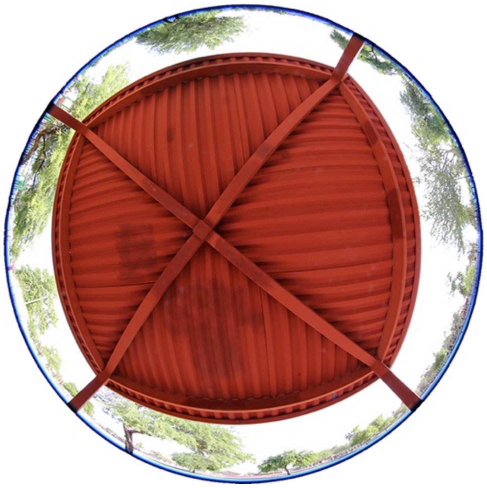
Encanto Park



Esteban Park



Hermoso Park

Palomino Park


Roadrunner Park

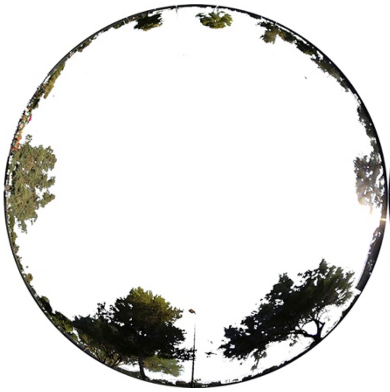
APPENDIX D

FISH-EYE LENS PHOTOGRAPHS OF FULL SUN LOCATIONS IN SEVEN RESIDENTIAL PARKS OF PHOENIX, AZ USA

Encanto Park

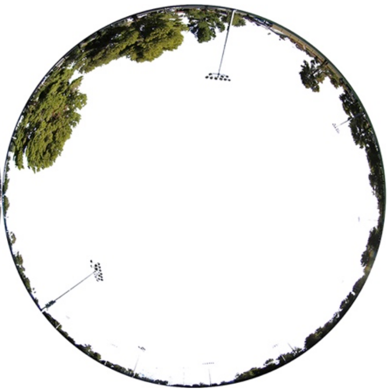
Esteban Park

Hermoso Park



Nueve Park

Palomino Park



Roadrunner Park

Royal Palms Park