Investigating the Role of Vegetation on Mid-Afternoon Microclimates in a Residential Courtyard

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In

Geography: Resource Management and Environmental Planning

by

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San Francisco, California

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Certification of Approval

I certify that I have read Investigating the Role of Vegetation on Mid-Afternoon Microclimates in a Residential Courtyard by Jolene Marie Bertetto, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requirement for the degree Master of Arts in Geography: Resource Management and Environmental Planning at San Francisco State University.

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San Francisco, California
2022

Vegetation has been found to provide localized cooling for pedestrians, but the irrigation demands required to keep such vegetation alive may contradict long-term city planning in areas where water supply is limited. This research investigates the relationship between type of vegetation, irrigation, and microclimate at the scale of a large, residential courtyard located in Walnut Creek, California using a portable micrometeorological station to compare mid-afternoon microclimates and lower 2 m temperature profiles of a well irrigated lawn and water-efficient garden (with and without overhead tree cover) and an asphalt parking lot. Variability in surface cover resulted in distinct microclimate differences, with the largest temperature differences closest to the surface. At 0.1 m height, overhead tree cover resulted in temperatures significantly different from the parking lot on 100% of transects while the exposed lawn and garden were different on 94% and 79% of transects respectively. Temperature differences between the asphalt surface and the vegetated surfaces were used to estimate a 'vegetation cooling index' (VCI), which was most pronounced on warmer days and under less windy conditions. The shaded water-efficient garden provided the greatest average VCI of 2.93 °C and was the most cooling efficient, as it provided the greatest surface and air VCI with the least amount of estimated irrigation.

Acknowledgements

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1. Introduction

The global mean temperature has increased by more than 1 °C since 1880 and will continue to rise (GISTEMP, 2020) with an increase in the frequency and severity of heat waves impacting health and human thermal comfort (Guo et al., 2018). A heatwave is defined as hot outdoor temperatures that are outside the normal range of ambient temperatures and last for several days (Robinson, 2001). Guo et al. (2018) examined heat and mortality relationships under future climate change scenarios and estimated that, with no adaptation to climate change, heat wave related deaths in California may increase 400-500% over the next 50 years. To reduce heat wave related deaths and increase human thermal comfort, regulating temperatures is a priority for many cities, where warming has been widely shown to be exacerbated by the urban heat island (UHI) effect.

The UHI effect describes the phenomenon of warmer surface and air temperatures in cities compared to surrounding rural areas (Oke, 1982). The UHI is defined as:

$$\mathrm{UHI} = \mathrm{T_{urban}} - \mathrm{T_{rural}}\ (\mathrm{Deg\ C}) \qquad (1)$$

Where $\mathrm{T_{urban}}$ is the measured air temperature of an urban area and $\mathrm{T_{rural}}$ is the measured air temperature of a surrounding rural area for comparison. The difference in temperature is primarily a result of land use changes during urbanization, when vegetation is removed and replaced with buildings and other impermeable surfaces. Urbanization modifies the surface energy balance (SEB), altering how the urban surface interacts with the atmospheric boundary layer.

The urban SEB is commonly expressed as:

$$Q^{*} + Q_{F} = Q_{H} + Q_{E} + \Delta Q_{s} + \Delta Q_{A}\ (Wm^{-2}) \qquad (2)$$

where Q* is net all-wave radiation, Q_F is the anthropogenic heat flux, Q_H is the sensible heat flux, Q_E is the latent heat flux, ΔQ_S is the net stored heat flux and ΔQ_A is net horizontal advective heat flux (Grimmond et al., 2010).

With a lack of vegetation and permeable soil to store water, the urban energy balance is dominated by $Q_{H \text{ and}}$ ΔQ_s, relative to Q_E. In urban city centers, with sealed surfaces and little to no vegetation, the net uptake or release of energy in the urban canopy air layer, buildings, vegetation, and ground can account for up to 50% of the net urban energy balance because of the high heat capacity and low albedo (reflectivity) of building materials such as concrete and asphalt (Grimmond & Oke, 1999). Energy is released as Q_H from exterior building surfaces to the atmosphere as well as outgoing longwave radiation, and in densely built areas with low sky view factors, radiation can become trapped in the urban geometry, contributing to the UHI effect.

Q_F is unique to the urban energy balance and represents the heat generated from burning fuels for human use such as vehicles, manufacturing, and heating and cooling buildings. Q_F increases the available energy for heating the atmosphere above and makes a positive contribution to the urban heat island. The size of anthropogenic heat flux varies widely based on a city's energy use but is relatively small compared to Q_H and Q_E (Offerle et. al, 2006).

UHI magnitude depends on the local background climate, weather (i.e. cloud coverage and wind) and characteristics of the built environment (Souch & Grimmond, 2006). At the regional scale, Zhao et al. (2014) modeled that geographic variations in daytime temperature differences between urban and rural areas is largely explained by convection efficiency, which typically decreases as a result of urbanization. Convection efficiency describes the efficiency through which urban and rural areas redistribute heat between the surface and the atmospheric boundary layer, with efficiency increasing with surface roughness. The difference in convection efficiency between cities and rural landscapes is correlated to precipitation and humidity. In humid environments where precipitation supports dense and tall vegetation, cities have a smoother surface roughness compared to rural areas and will be less efficient at dissipating heat (Zhao et al. 2014). The opposite is true for "dryland" environments which include arid, semiarid, steppe, and Mediterranean landscapes typically characterized by low humidity. In these areas, cities may be aerodynamically rougher than surrounding rural areas where vegetation is adapted to periods of little to no precipitation and dominated by low shrubs, sagebrush, and grasses. Cities in these environments may actually experience daytime cooling from enhanced convection efficiency. Cooling effects are relative, however, as even reduced daytime temperatures can still threaten human health, and these areas may still experience nighttime UHIs which offer no relief for residents and place a high demand on energy systems to cool buildings.

In an analysis of 419 large cities across the globe, Peng et al. (2012) found that annual surface daytime and nighttime UHIs ranged from .3 to 2.7 °C and 0.6 to 1.6 °C respectively. At the neighborhood scale, UHIs vary widely with surface temperatures found to be 2-3 °C hotter than the urban mean for areas with maximized pavement, or up to 6 °C cooler for areas with heavy vegetation. Vegetation modifies the urban energy balance primarily through direct shading and evaporative cooling (Marchionni, Revelli, & Daly, 2019). Tree canopies can reflect solar radiation upward away from the canopy and prevent energy from being stored, while evaporative cooling is achieved through energy diverted to evapotranspiration (ET). ET requires energy for the phase change of water (Q_E in Eq. 2). Thus, ET partitions energy away from the sensible heat flux of the air above the surface and the storage of heat in the building fabric (Q_H and ΔQ_s respectively in Eq. 2). For this reason, increasing vegetation is often cited as a potential strategy for mitigating the UHI effect and improving human thermal comfort.

Pockets of vegetation throughout urban areas can create what is known as the Park Cool Island (PCI) effect, expressed as:

$$\mathrm{PCI} = \mathrm{T_U} - \mathrm{T_P} \qquad (3)$$

Where T_P is the surface air temperature within a park and T_U is the air temperature of the urban area within which the park sits. The resulting difference in temperature is used to assess the magnitude to which a park or other landscape can reduce temperatures and is the focus of a growing body of literature, especially for dryland environments (Wheeler et al., 2019), susceptible to periods of extreme heat. While cooling potential is highly variable due to the complexity of urban landscapes, generally a landscape's cooling potential will depend on vegetation type, plant characteristics, and water availability, with multilayer plant diversity (Zhang et al., 2013) and high foliage density (Chen & Wong, 2006) resulting in the largest temperature decreases.

Vegetation type refers to plant metabolism, which varies by species and affects transpiration. Plants with C3 photosynthetic metabolism, common in cool and wet climates, will regularly open leaf stomata to transpire water, whereas plants with C4 photosynthetic metabolism, common in warmer, drier climates, will conserve water through closing stomata to reduce transpiration. For most plant species, stomata are closed in the absence of radiation, which means latent cooling through transpiration is most effective for reducing daytime temperatures (Gunawardena, Wells, & Kershaw, 2017).

Reducing daytime temperatures through modifying the SEB with vegetation is a challenge for dryland environments, where solar radiation is high and water is a limiting factor (Dialesandro, Wheeler, & Abunnasr, 2019). In Mediterranean climates like the Bay Area with little to no rainfall in the summer months, periods of drought place pressure on regional water supplies and local utilities may enact restrictions to irrigation. For landscapes to provide cooling, climate regulation needs to be maximized, while water and energy use are minimized.

1.1 Ecosystem Services Framework

The Millennium Ecosystem Assessment (MEA), a landmark study initiated by The United Nations in 2001, is an approach for understanding how ecosystem processes translate into environmental benefits for cities. Still widely used today, the MEA categorized the benefits of ecosystems into provisioning services (providing essential goods), cultural services (providing non-material, social and psychological benefits), and regulating services (which moderate environmental quality and conditions) while identifying the supporting ecosystem processes that enable these services (Millennium Ecosystem Assessment, 2003).

Supporting ecosystem processes including nutrient cycling, soil formation, and primary productivity have been well studied, but primarily in natural or agricultural systems and findings are not as commonly applied to understanding urban ecosystems. Climate regulation, for example, is intimately linked to biogeochemical processes that cycle and exchange water, carbon, and energy (Grulke et al., 2011), but research about how these processes help regulate the climate of urban areas are often overgeneralized and lack empirical data to evaluate the performance of real-world implementation (Pincetl, 2007, 2010). Identifying this gap in knowledge about urban ecosystems, Grulke et al. (2011) proposed a framework based on the MEA for incorporating ecosystem services and disservices (benefits and costs of green space, respectively) into improving environmental outcomes in cities (Figure 1). This framework defines the desired environmental outcome, identifies the relevant ecosystem services and disservices, and links these services and disservices to measurable ecosystem processes. In the context of this study, we focus on the desired outcome of providing cooling through maximizing climate regulating services while minimizing water use in a residential landscape.

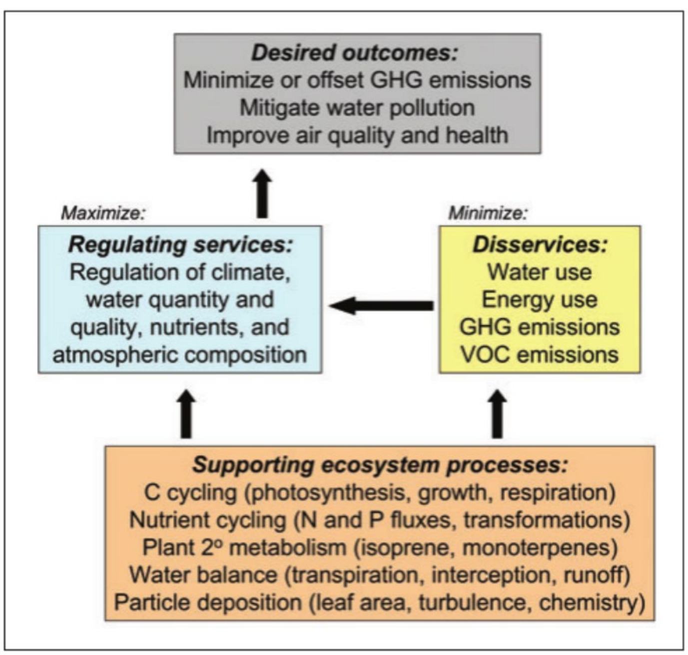


Figure 1. Framework based on the Millennium Ecosystem Assessment for incorporating ecosystem services into improving environmental outcomes in cities (Grulke et al., 2011).

Across the United States, more than half of residential water use is for outdoor irrigation (DeOreo et al., 2011) and turfgrass lawns are the largest irrigated crop (Milesi et al., 2005). In California's Mediterranean climate, turfgrass requires 70% more water than plants adapted to arid and Mediterranean climates (Hayden et al., 2015), which is why water utilities in areas susceptible to drought and water shortages incentivize residents and businesses to convert lawns to water-efficient landscapes. A water-efficient landscape, sometimes referred to as "water-wise", "water-smart", or "drought-tolerant landscape" refers to a landscape with limited turf, efficient irrigation, and native or low-water use plants (EPA, 2002).

In 2015, the California Department of Water Resources updated its Model Water Efficient Landscape Ordinance (MWELO) to promote water-efficient landscaping principals that go beyond water conservation to include additional ecosystem services (Department of Water Resources, 2015). While numerous studies have documented the water savings from water-efficient landscapes (Chesnutt, 2020; Seapy, 2015; Sovocool et al., 2006) few studies have quantified additional purported benefits and ecosystem services such as regulating air temperatures. Many studies focused on landscapes in dry climates were in places such as Arizona, where there might be a comparison of the cooling potential of a lush lawn compared to a landscape of rock and desert plants, and not representative of common Bay Area Landscapes that include a large diversity of plants.

Mesic landscaping, which is moderately moist and typically includes lawns planted with cool season turfgrass, has been shown to provide cooling benefits for dryland cities, but only in the presence of irrigation (Chow et al., 2011; Hall et al., 2016). Xeriscaping, a term sometimes interchangeable with water-efficient landscaping where very little to no water is used, also has the potential to mitigate the UHI effect when low-water use plants provide shade. However, when the effect of converting existing mesic landscaping to xeriscaping in Phoenix, Arizona was modeled by Chow et al. (2012), they found that lawn conversions increased temperatures, likely resulting in greater thermal discomfort to residents. In a similar study modeling impacts of urban vegetation on outdoor thermal comfort and microclimate in Phoenix, Song et al. (2015) found that irrigated lawns (representing mesic landscaping) had lower surface temperatures compared to non-irrigated trees (representing xeric landscaping) but higher street canyon air temperatures. These results are understood through the different cooling mechanisms of each vegetation type, with urban lawns reducing surface sensible heat fluxes and trees reducing thermal stress through shading. Trees have the added benefit of also shading pavement and walls, reducing heat storage and energy demand for buildings (Song & Wang, 2015).

While several studies suggest that parks and urban green infrastructure can contribute to cooling within cities, especially downwind, other studies suggest that the extent of cooling is highly localized and limited to microclimates (Shashua-Bar et al., 2011). Microclimate refers to the climate of a small local area that is modifiable and influenced by a variety of regional landscape elements including vegetation, soil, and topography (Xiong et al., 2020). The site/block scale was found to be especially relevant for human thermal comfort, as strategic landscape design can modify wind speeds and decrease solar and terrestrial radiation to directly reduce air temperature and energy used by nearby buildings (Demuzere et al., 2014). However, if the vegetated area is small, and turbulent mixing of the air in the urban canopy layer is efficient, air temperature reductions may be indistinguishable among different types of surface cover.

Although UHI have been widely investigated in the past half century (Arnfield, 2003) and PCIs increasingly so in the past few decades (Bowler et al., 2010; Wheeler et al., 2019), relatively little work has been done at the site scale, particularly in hot dry summer Mediterranean climates. The objective of this study is to investigate the relationship between type of vegetation, irrigation, and microclimate at the scale of a large, residential courtyard. In particular, the air temperature profiles in the lowest 2m as well as radiation, wind, and humidity differences will be compared between a well-irrigated lawn, a water-efficient landscape, and a paved parking lot within a single courtyard. These sites will be analyzed to understand how different configurations of the built environment impact the thermal environment at the scale of individual humans.

Quantifying these microclimate differences between a lawn and water-efficient landscape will help provide information on the relative trade-offs between water-use and cooling mechanisms. A water-efficient landscape may save water when compared to a lawn, but if the water-efficient landscape increases temperatures there could be unintended consequences. Understanding the tradeoffs between water use and climate regulating ecosystem services can help water agencies design programs for maximum benefits, such as requiring the addition of trees in lawn conversion projects.

2. Methods

Urban microclimate research utilizes a variety of methods depending on scale and study length to investigate microclimate variability. Studies focused on microclimates across different areas of a city commonly take sequential measurements using mobile transects (Hann, 2020; Leconte et al., 2015; Szegedi & László, 2012), whereas a comparison of the diurnal and seasonal climatic data of singular urban parks and city blocks are more likely to use fixed automatic meteorological stations (Cohen, Potchter, & Matzarakis, 2012). As scale decreases to courtyards or small gardens, researchers have utilized sensors for continuous synchronized observations over different types of vegetation (Alkhatib & Qrunfleh, 2018; Li et al., 2020), fixed stations set up around different landscapes elements (Limor Shashua-Bar et al., 2011), or portable measurement stations manually moved from site to site (Bonan, 2000; Zoulia, Santamouris, & Dimoudi, 2009). The scale of this current study was small enough that a portable measurement station was utilized to measure climatic data over different types of vegetation.

2.1 Study Area

This research was conducted in the city of Walnut Creek, California, USA located at 37 °N and -122 °W in the East Bay region of the San Francisco Bay Area (Figure 2). Walnut Creek is an economic center for Contra Costa County with an estimated population of 70,860 as of January 2019 (State of California Department of Finance, 2019). Integrated into the suburbs and surrounding the city is over 1214 Hectares (3,000 acres) of hilly oak woodland, savanna, and chaparral open space. The climate of Walnut Creek is warm-summer Mediterranean according to the Köppen Climate Classification, characterized by hot, dry summers and cool, wet winters. Located in the Diablo Valley and east of the Berkeley Hills, Walnut Creek is protected from the marine layer and consequentially warmer during summer months than nearby coastal cities. Average daily temperatures range from 12-31°C in the summer months and 2-13°C in the winter months. July, August, and September are typically the warmest months. The average maximum daily temperature for September and October is 28°C and 23°C respectively. Increasing frequency and enhanced magnitude of heat waves as a result of climate change are expected to have a major impact on public health, impacting the elderly and vulnerable populations, as identified in the City of Walnut Creek's Climate Action Plan (City of Walnut Creek, 2012).

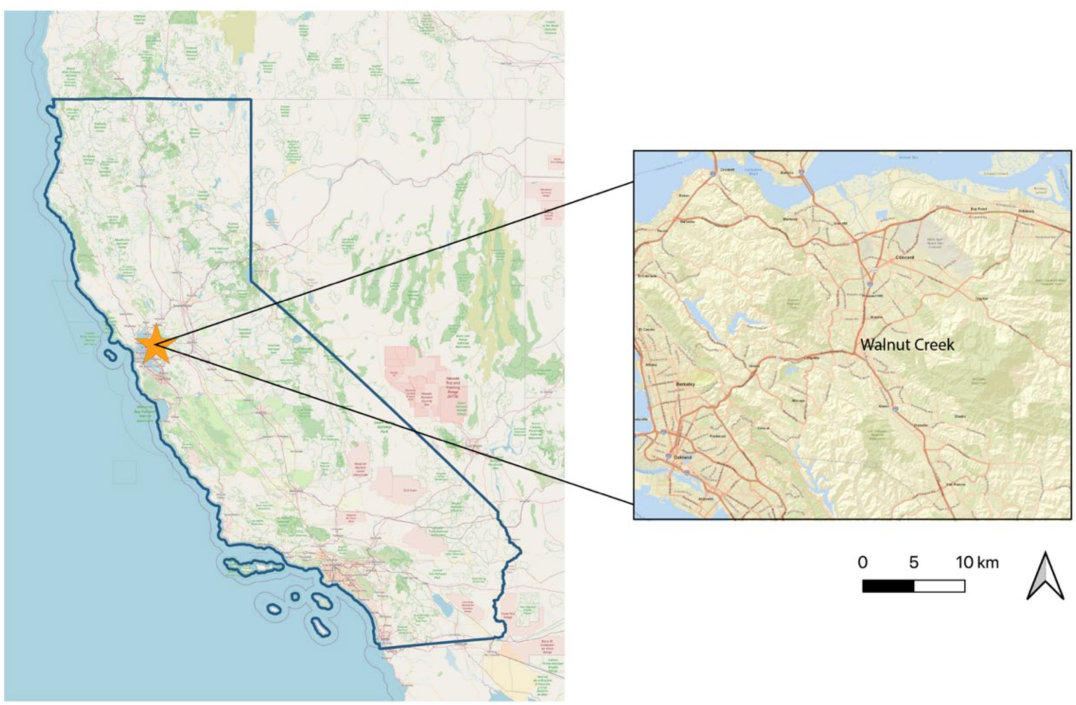


Figure 2. Map of Walnut Creek, California in the East Bay region of the San Francisco Bay Area.

Within the city of Walnut Creek, this research took place in a single courtyard located in a suburban residential "active adult" community. For the purpose of this research, the exact location is confidential. Using the local climate zones (LCZ) from Stewart and Oke (2012), the community consists primarily of open low-rise buildings. The courtyard is around 1,600 square meters surrounded by a parking lot, sidewalks, and residential units. The courtyard includes a well irrigated, green lawn; a mature sycamore tree; and a water-efficient garden with a mix of shrubs, trees, and a dry creek bed. A pathway of decomposed granite separates the lawn from the garden. Figure 2 shows an aerial view of the courtyard and the sites selected for this research. The courtyard was chosen because it features a diversity of landscapes with various water needs in close proximity of one another, which allowed for measurements to be taken over each landscape configuration within a short period time without having to correct for a change in the background temperature.

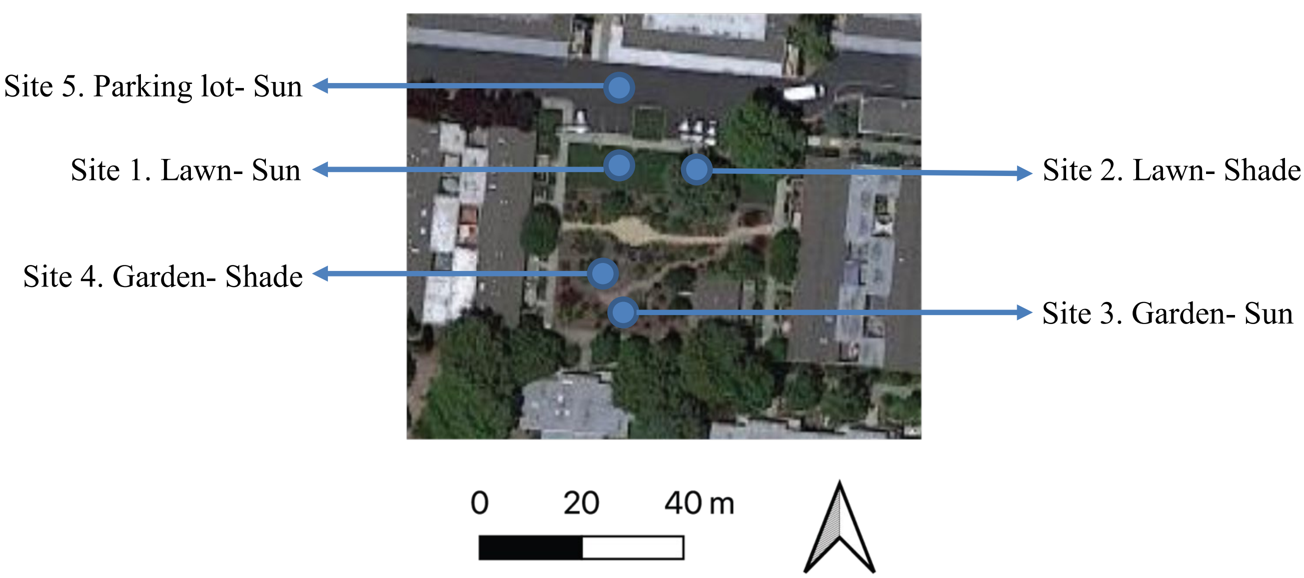


Figure 3. Aerial view of the residential courtyard and selected sites for this research in Walnut Creek, CA. Aerial imagery obtained from QGIS (2021).

2.2 Site Selection

Four vegetated sites were chosen representing a high and low water use landscape, while the nearby parking lot was used as a control site representing the urban fabric. The literature emphasizes the importance of trees and shade in affecting localized temperatures, which is why for each landscape type, a site was chosen in the sun and the shade. Figure 4 shows a close up of the measurement equipment over each site.

Site 1: Lawn- Sun Site 2: Lawn- Shade Site 3: Garden- Sun Site 4: Garden- Shade Site 5: Parking lot

Figure 4. Close up of the five selected sites for this research in Walnut Creek, CA.

Prior to the installation of the garden, the courtyard was only planted with lawn, which is the dominant landscape type in the community. In 2016, after stress from reduced irrigation during California's historic drought, the courtyard was relandscaped. The remaining lawn is roughly 1/3 of its original size, irrigated with rotor sprinklers on a more frequent irrigation schedule than the garden (Table 1). The garden area, four years old at the time of this research, takes up approximately 2/3 of the courtyard. While water conservation was a factor in its design, the main consideration for the new landscaping was whether residents would be satisfied. Satisfaction is subjective but refers to design elements that may affect mental and physical health such as color, seasonal interest, shade, and accessibility. The primary plant list was drought tolerant and deer resistant, and irrigation is a mix of bubblers and high-efficiency sprinklers. The bubblers were chosen rather than drip irrigation due to issues with gophers and for ease of troubleshooting leaks (Pollan, personal communication, 2020). Table 1 describes each site's vegetation, irrigation type, and irrigation frequency.

Table 1. A description of vegetation, irrigation type, and irrigation frequency for the five selected sites.

Site	Vegetation	Irrigation Type	Irrigation Frequency
Site 1. Lawn-Sun	• Kentucky bluegrass (Poa pratensis)	Rotor sprinklers	3x a week for 22 min
Site 2. Lawn-Shade	• Kentucky bluegrass (Poa pratensis) • Sycamore tree (Platanus occidentalis)	Rotor sprinklers	3x a week for 22 min
Site 3. Garden-Sun	• Splitlawn sedge (Carex tumulicola)	Bubblers	1x a week for 17 min
Site 4. Garden-Shade	• Olive tree (Olea europaea) • Azure blue sage (Salvia azurea) • Russian sage (Perovskia atriplicifolia)	• Bubblers • High-Efficiency sprinklers	3x every two weeks for 21 min
Site 5. Control-Sun	none	none	N/A

2.3 Estimated Water Use

Water use was estimated using the California Department of Water Resource's Model Water Efficient Landscape Ordinance water budget worksheet. The water budget worksheet estimates a landscape's water use based on plant factor, irrigation method and efficiency, local climate, and landscape area. Plant factors range from 0 (needs no irrigation) to 1.0 (needs high amount of irrigation) and changes based on local climate as determined by the Water Use Classification of Landscape Species (WUCOLS) developed by the University of California. Irrigation efficiency is also a range with .75 efficiency for bubblers and overhead spray.

2.4 Instruments and Experimental Design

Measurements were made from a portable micrometeorological station designed to be easily reassembled immediately prior to taking measurements and dissembled once the measurements were complete. Instruments were attached to a vertical metal pole, held in place by a bicycle repair stand. Attached to the pole were 5 type-E fine-wire thermocouples at 0.1, 0.25, 0.5, 1, and 2 m to measure air temperature close to the surface and at pedestrian level. Table 2 describes the full instrument set up and corresponding measurements.

The instruments were connected to a CR1000 Campbell Scientific data logger (Campbell Scientific Inc. Logan, Utah) programmed with Loggernet software. The datalogger was stored out of direct sun in an insulated plastic container in a travel bag and transported with the measurement station from site to site. Measurements were taken every second for three-minute periods for a total of 180 samples at each site during one transect. A transect refers to a full cycle of measurements taken for the three-minute period over each of the five measurement sites. A full transect took around 30 minutes, with the portable station manually carried from site to site. Measurements were taken over 17 days from Sept. 18-Oct. 15, 2020, between the hours of 2:00 and 4:00 pm to capture peak afternoon temperatures. Two transects were completed a day for a total of 34 transects. As one transect was restricted to a 30-minute period, diurnal temperature change over time during each transect was considered to be negligible and not corrected for in post-processing.

Table 2. Instruments used and measurements taken during the course of the study period.

Measurement	Instrument
Air temperature at .1, .25, .5, 1, 2 m	E-Type fine wire thermocouple (0.2 mm diameter)
Surface temperature	Apogee thermal infrared radiometer
Wind speed and direction (2 m)	Young WindSonic 2-D sonic anemometer
Soil temperature (5 cm)	CS107 thermistor
Air temperature/Relative humidity (1 m)	Vaisala HMP60 thermistor/hygristor
Albedo	Handheld albedometer
Net radiation (1.5 m)	Campbell Scientific Q7.1-L REBS Net Radiometer
Datalogger	CR1000, Campbell Scientific

2.5 Data Analysis

Data analysis was conducted using MATLAB, a programming and numeric computing platform. Raw data was analyzed first for each transect using all 180 one second measurements over each site to observe distributions and to test for statistical differences. Statistical differences were tested using an Analysis of Variance (ANOVA) and posthoc Tukey test. To investigate differences between transects, means for air temperature, wind speed, soil temperature, relative humidity, and net radiation were calculated. The difference between a site's mean and the control mean (Parking Lot) was used to compare air temperature across transects and determine cooling potential of the different landscape configurations.

To compare humidity between sites with differences in air temperature, relative humidity (RH) was converted into vapor pressure (VP), or absolute humidity. Where RH is a measure of how much moisture is in the air relative to how much can be held and is function of temperature, VP is the measure of water vapor (moisture) in the air, regardless of temperature. VP was calculated as:

$$VP = \frac{RH}{100} SVP \qquad (3)$$

where SVP is saturated vapor pressure, expressed as:

$$SVP = 0.61365^{\frac{17.502\mathrm{T}}{240.97+\mathrm{T}}} \qquad (4)$$

where T is air temperature (°C) measured with the thermistor at 1m.

2.6 Limitations

The location of the measurement station at each site varied slightly from transect to transect. The location at each site was marked, but variations occurred when the station was manually carried from site to site. Variations most likely affected the sites in the shade, where dappled sunlight coming through the tree canopies impacted incoming solar radiation.

For the majority of the study, the thermocouple measuring air temperature at 1 meter was located inside the radiation shield with the thermistor measuring relative humidity, resulting in warmer temperatures recorded at this height, as it was not as effectively exposed to airflow. The thermocouple was removed and attached to the outside of the pole for transects 25-34.

The advantage of the experimental design is that any systematic instrument errors are eliminated using the same instruments for all sites. This is because the relative temperature difference is the key determinant of microclimate variability in this study. On the other hand, the fact that the sites were sampled at different times in this experimental design poses the main limitation to accuracy. This is because any temporal changes in the microclimate during the transect would be represented as spatial variability. To reduce the potential effects of temporal changes, a full transect of measurements was completed within 30 minutes and carried out during the peak temperature of the day, when change over that time period was minimal.

Another limitation is that this study did not quantitatively measure water use for each of the landscape configurations. Water use was estimated based on plant factor and irrigation equipment rather than actual water applied with each irrigation event. Despite this limitation, the estimated water use still provides a general idea of each landscape’s water demands, while irrigation run times and frequency for similar landscapes may differ based on who is managing the landscape.

3. Results

3.1 Meteorological conditions

Meteorological conditions varied over the course of the study period with temperatures falling within and above the average temperature range for September and October in Walnut Creek. Temperatures during measurements ranged from 20 to 37 °C. Elevated heat conditions often coincided with higher net radiation and lower vapor pressure, as seen in Figure 5. These conditions are typical of Walnut Creek with variations in day-to-day meteorology most strongly driven by the influence of marine air from the coast, with limited frontal activity or influence from low pressure systems at this time of year. Net radiation ranged from 54 W/m^2 to 615 W/m^2 with variability most strongly driven by the presence of clouds (typically marine stratus from the coast) or smoke from regional wildfires. Net radiation also declined as the study progressed due to solar declination change.

Lower temperature days such as transects 25 & 26 (Oct. 9) and 27 & 28 (Oct. 10), were overcast with higher vapor pressure and low net radiation. This occurred due to strong incursion of the marine layer bringing overhead stratus clouds and cool moist marine air. Transects 17-22 (Oct. 1-3) are notable for high temperatures with mid-levels of net radiation, which occurred under the influence of smoke from nearby wildfires. Wind speed was also at its lowest on these days and would have contributed to poor air quality.

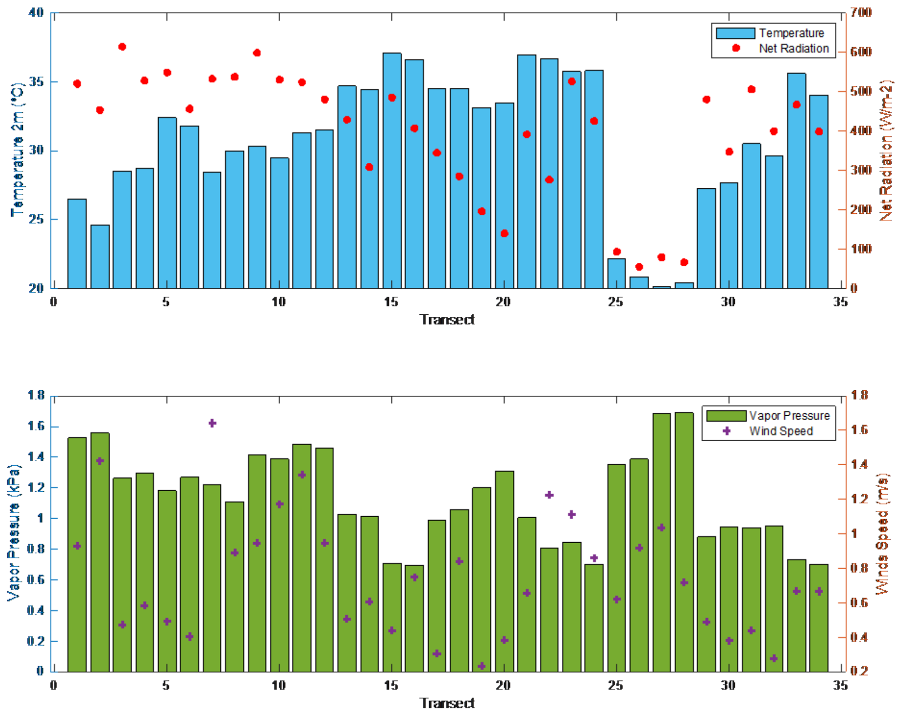


Figure 5. Average net radiation, temperature, vapor pressure, and wind speed for all 35 transects**.** Measurements were taken from the same site (Parking lot) for each Transect. Temperature is air temperature at 2 meters.

3.2 Spatial patterns

Temperature, net radiation, vapor pressure, and windspeed varied spatially based on location within the courtyard, as seen in Table 3. There was an overall difference in mean temperatures of 2.93 °C between sites, with the asphalt parking lot warmest and the shaded garden coolest. Net radiation was essentially bimodal and greater than 350 W/m^2, with local shading causing a reduction of around 97%. For sites where tree canopy reduced solar radiation, temperatures were an average of 1.6 °C cooler than their sunny counterparts, and all four irrigated vegetated surfaces were cooler than the non-irrigated asphalt surface by 1.9 °C on average. Vapor pressure varied by less than 4% among the five sites, suggesting relatively good mixing within the courtyard, also indicated by the site and transect-average wind speed of approximately 0.7 m/s. Wind speed variability across the courtyard was a little larger (up to 18%) with the lowest wind speeds (0.50 m/s) in the garden area where shrubs and trees around the measurement site added surface roughness.

Table 3. Average air temperature (averaged from all five heights), net radiation, vapor pressure, and wind speed for each site using all 35 transects.

	Lawn-Sun	**Lawn-Shade**	**Garden-Sun**	**Garden-Shade**	**Parking Lot-Sun**
Temperature (°C)	29.94	28.99	30.91	28.63	31.56
Net Radiation (W/m^2)	402.10	10.92	372.63	10.53	395.05
Vapor Pressure (kPa)	1.21	1.16	1.18	1.21	1.14
Wind Speed (m/s)	0.75	0.79	0.64	0.50	0.75

3.3 Vertical temperature profiles

To visualize the distribution for each site's surface and air temperature, we used a kernel density estimation with the raw data. The density estimate was performed with a Gaussian kernel made from 180 one-second measurements for each site, and a default bandwidth to exclude irregularities and outliers. The differences between sites were most pronounced for surface temperature, where distributions were least variable and observations rarely overlapped, as seen in Figure 6, which shows surface temperature distributions for a characteristic transect. At the surface, the vegetated sites were cooler than the parking lot, though Garden-Sun, with its limited vegetation coverage, bark mulch, and reduced irrigation, was closer in surface temperature to that of the parking lot than the other sites. The openness of the sites in the sun meant they were exposed to more radiation, which was absorbed and reradiated throughout the day, increasing temperatures. Parking Lot-Sun and Garden-Sun, for example, were an average of 28.7 °C and 22.2 °C warmer at the surface than Garden-Shade respectively. The exception was Lawn-Sun, which was an average of 0.8 °C cooler than Lawn-Shade, likely cooled by enhanced transpiration due to higher photosynthesis rates in full sunlight. In addition, Lawn-Shade, despite less radiation exposure, may have been slightly warmer at the surface than the other shaded site because the roots of the large sycamore tree extended into the lawn and reduced surface moisture.

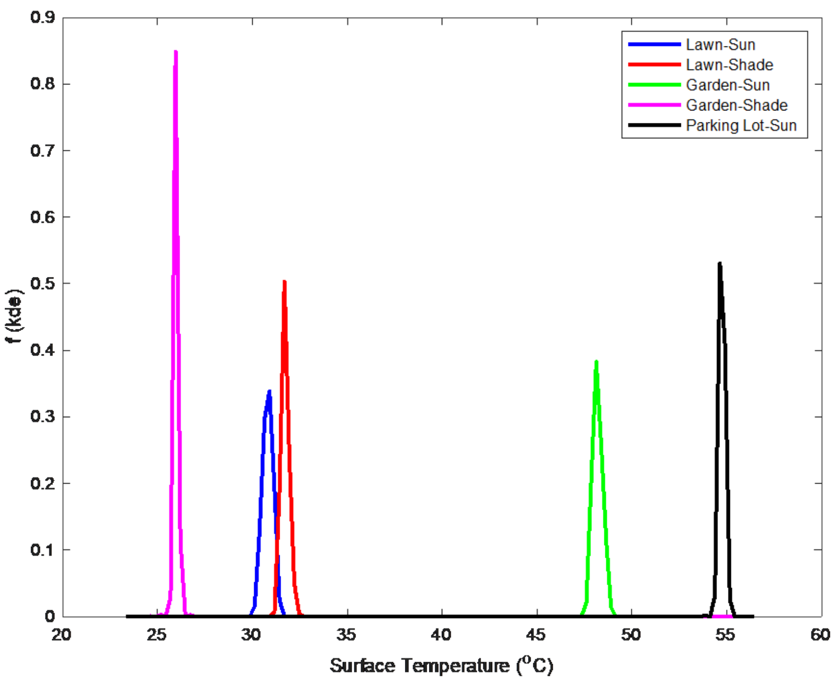


Figure 6. Surface temperature distributions for all five sites. Measurements were taken during the second transect on 10/4/20.

By comparison to surface temperature, the surface layer air temperature distribution was more variable with overlapping distributions between sites (Fig. 7). The air temperature differences between sites decreased with height, although the relative position of the five site temperature distributions remained consistent with height and also matched the surface temperature distributions. This suggests the variability in surface cover produced distinct microclimate differences in the lower 2m, but these differences diminished with increasing height due to mixing in the atmospheric surface layer. At 0.1, 0.25, and 0.5 m, the differences between sites were easily distinguishable, with the mean, median, and mode of Garden-Shade consistently cooler than other sites and Garden-Sun and Parking Lot-Sun distinctly warmer. At 2 m, the total range of temperatures decreased with all modes falling between 34 and 36 °C. Garden-Shade was no longer easily distinguishable from Lawn-Shade, as both had modes around 34.5 °C. However, the mean temperature for Garden-Shade was still the coolest, as data was negatively skewed. Parking Lot-Sun was still the warmest but followed a similar distribution to Garden-Sun across all heights.

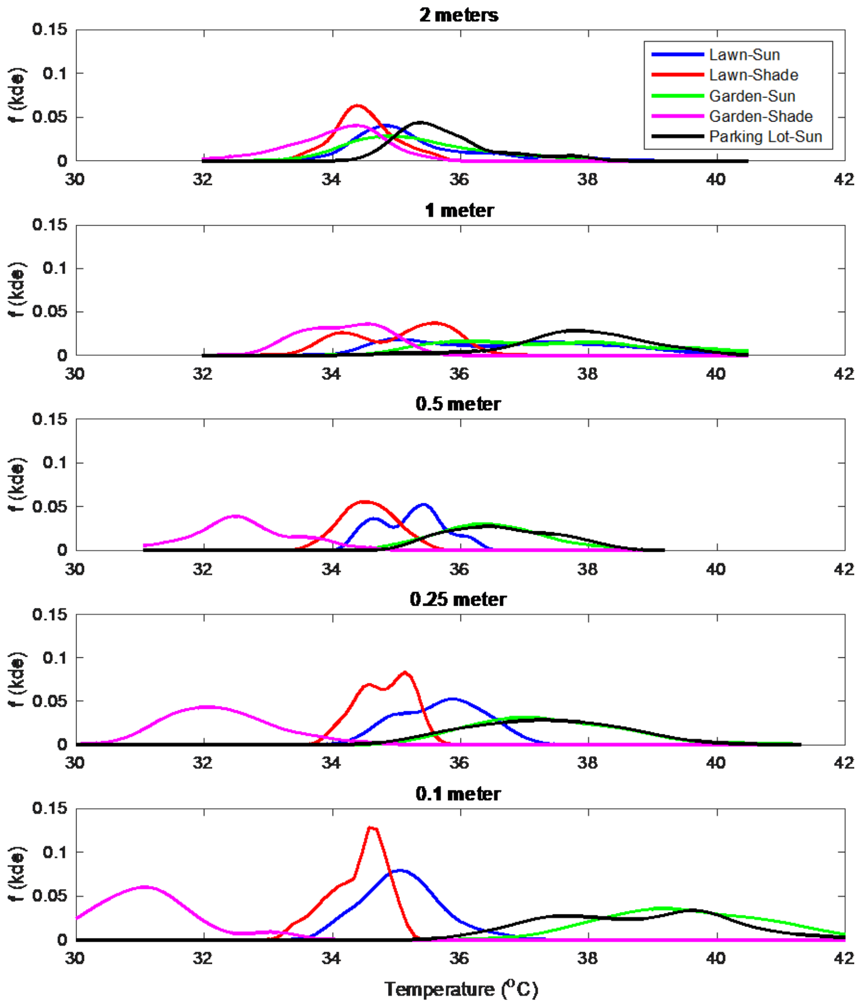


Figure 7. Air temperature distributions for all sites across five heights during second transect of 10/4/20.

Across heights, the majority of measurements were mostly normally distributed, with some evidence of bimodal, and multimodal distributions. Bimodal and multimodal distributions possibly resulted from the occurrence of wind gusts and lulls during the course of the three-minute measurement period over each site. For all sites, the width of the confidence interval decreased with height, suggesting that the upper measurement levels are connected to larger scale eddies that more effectively mix air and maintain greater consistency in temperature across small spatial scales. At the lower levels, temperature measurements were more connected to the surface and more closely indicative of the surface energy balance (SEB) of the immediate local surroundings. The exception to this rule appears to be the Lawn-Shade site, which was the least variable. This might be due to shelter from broader mixing by the site's large tree canopy, as well as greater consistency in the SEB due to the uniform grass surface and irrigation, at least compared with the garden sites.

From Figure 7, it is clear that some populations of air temperature observations were different from each other based on the site (e.g. Garden-Shade and Parking Lot-Sun) while the differences between other sites were difficult to ascertain (e.g. Garden-Sun and Parking Lot-Sun below 0.5 m). To compare which sites had statistically significant different temperatures from each other across transects, we conducted Tukey's multiple comparison test. In Tukey's test, the null hypothesis is that all means are equal, and the alternative hypothesis is that not all means are equal. A p-value under 0.05 is considered statistically significant to reject the null hypothesis at the 95% confidence level.

When conducted for all transects, the largest temperature differences occurred closest to the surface at 0.1 m. Garden-Shade and Lawn-Shade were significantly different from the non-vegetated Parking Lot-Sun at the 95% level (p-value < 0.05) on 100% of transects while Lawn-Sun and Garden-Sun and were significantly different from Parking Lot-Sun on 94% and 79% of transects respectively (Figure 8). By comparison, at the 2 m level, Garden-Shade, Lawn-Shade, Lawn-Sun, and Garden-Sun were significantly different (p-value < 0.05) from Parking Lot-Sun on 97%, 94%, 85%, and 75% of transects respectively.

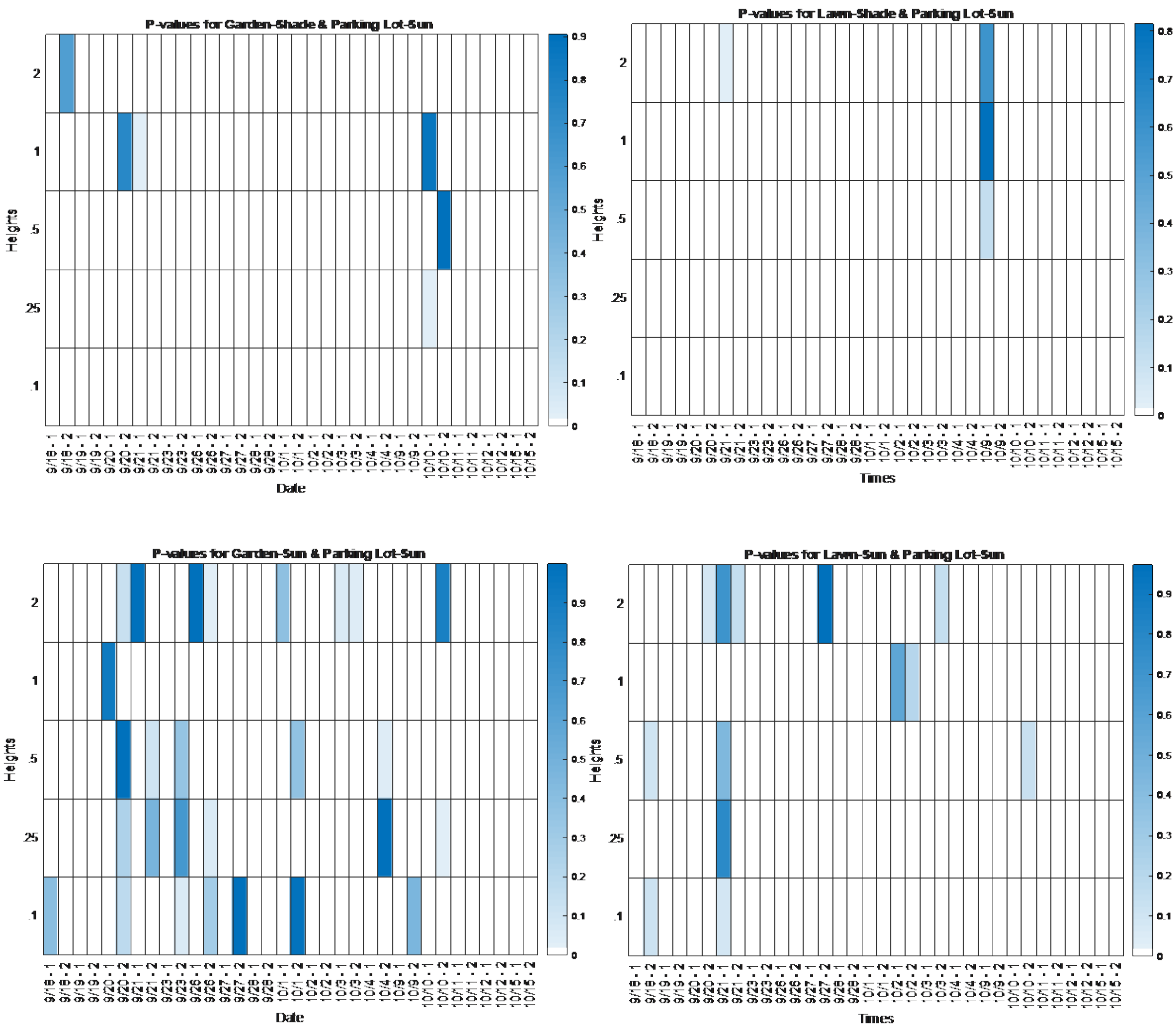


Figure 8. Colormap comparing Tukey's Test P-Values for each vegetated site to the non-vegetated parking lot. P-Values and corresponding colors are identified in the colorbar.

When Tukey's Test was applied to compare vegetated sites amongst each other, the null hypothesis was more likely to be accepted closer to the surface when comparing the lawn sites to each other and when comparing the shade sites to each other. The lawn sites are irrigated at the same frequency and duration (3 times a week), while the shade sites result in less radiation exposure and less water lost to evaporation. As height increased, proximity and mixing impacted temperature and reduced differences between sites in the sun and shade. However, even at 2 m, Lawn-Sun and Lawn-Shade were significantly different from each other on 74% of transects, while Garden-Sun and Garden-Shade were significantly different on 88% of transects. For additional color charts illustrating Tukey's test results, see Appendix A.

Variability in temperature occurred from transect to transect as a result of changes to wind speed, wind direction, and radiation exposure. Another driver, though not measured, would include irrigation, as measurements were taken on days with and without morning watering. Figure 9 demonstrates how mean temperatures may vary between two transects, despite being taken within one hour of each other. For both transects, the difference between means decreased as height increased. At 2m, for the first transect, both lawn sites were the coolest, while for the second transect, both shade sites were the coolest. The first transect also shows a converging of temperatures in the garden, while the second transect shows a converging of sites in the sun.

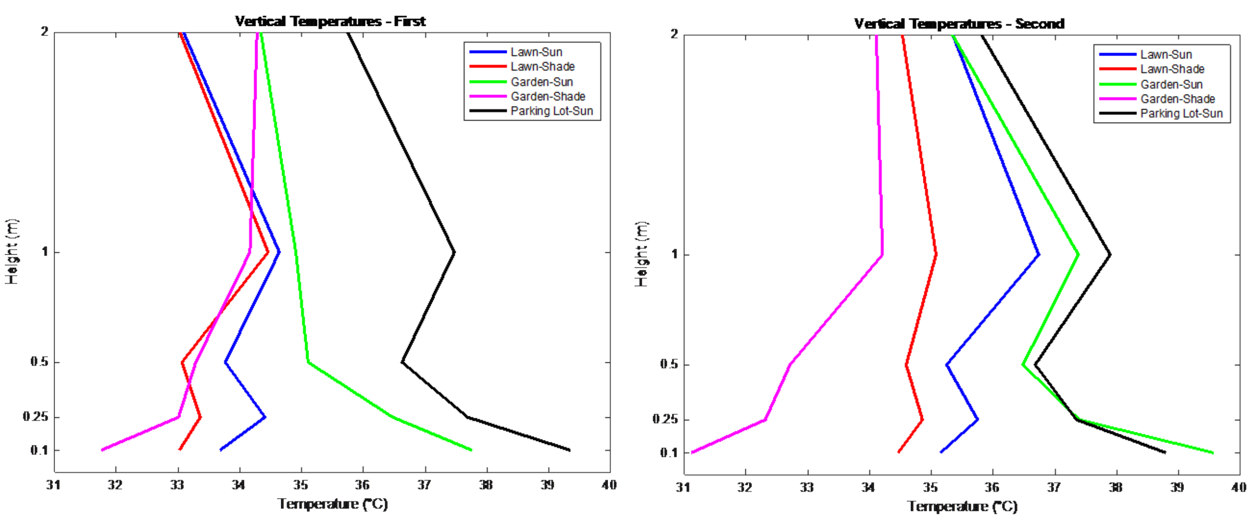


Figure 9. Comparing vertical temperatures for two transects measured on 10/4/20. Measurements for the first transect started at 2:30pm while the second transect started at 3:00pm.

3.4 Vegetation Cooling Index

Mean PCI intensity is used for comparing the air temperature within a park to the air temperature of urbanized surroundings. In this study, we compare the air temperature over vegetated surfaces to a nearby unvegetated parking lot. The difference in temperature, while similar to the PCI effect, is measured at a finer scale and is more accurately termed the Vegetation Cooling Index (VCI), defined in this study as:

$$VCI = T_{Asph} - T_{Veg-i}$$

Where T_{Asph} is the temperature measured over the asphalt parking lot and T_{Veg-i} is the temperature over four vegetated sites. The results show that the VCI effect was greatest at the surface, with Garden-Shade 25.21 °C cooler than Parking Lot-Sun (Table 4).

Table 4. Mean VCI and standard deviation for vegetated sites at all measurement heights for all transects.

Height (m)	**Lawn-Sun**		**Lawn-Shade**		**Garden-Sun**		**Garden-Shade**	
	μVCI	**σVCI**	**μVCI**	**σVCI**	**μVCI**	**σVCI**	**μVCI**	**σVCI**
Surface	20.49	4.04	24.07	5.45	9.42	5.08	25.21	5.87
0.1	3.02	2.15	4.80	1.38	0.27	1.09	5.52	1.91
0.25	1.71	1.24	2.80	0.95	0.64	0.99	3.60	1.39
0.5	1.43	0.92	2.15	0.81	0.67	0.89	2.62	1.08
1	0.80	1.10	1.54	1.22	0.85	0.96	1.26	1.13
2	1.12	1.00	1.55	0.80	0.79	1.12	1.64	1.07
Average air VCI	1.62	1.28	2.57	1.03	0.64	1.01	2.93	1.32

Across all heights, Lawn-Shade and Garden-Shade offered the greatest VCI, while Lawn-Sun and Garden-Sun produced the lowest VCI, as seen in Figure 10. VCI was greatest for all sites at the surface, with the VCI for both shades sites within 1 °C of each other, whereas the VCI for Lawn-Sun was 11.07 °C greater than Garden-Sun. While both the sun sites would have similar radiation exposure, Lawn-Sun was clearly influenced by the cool transpiring leaves of the irrigated lawn, which was irrigated more frequently than the garden site (three times a week compared to once a week). The energy used in the process of evapotranspiration from the lawn (Q_E) would mean less energy was available for heating the ground surface (ΔQ_S) and air (Q_H). In contrast, the mulch of the garden site would likely absorb solar radiation and be more directly converted to sensible heat flux given the lack of exposed water. With minimal irrigation, the garden site in the sun would be very dry, with little evapotranspiration and latent heat fluxes to disperse energy, and even when irrigated, the mulch would still slow soil evaporation. The result is that the surface of the garden, when exposed to sun, was closer in temperature to that of the parking lot than the lawn.

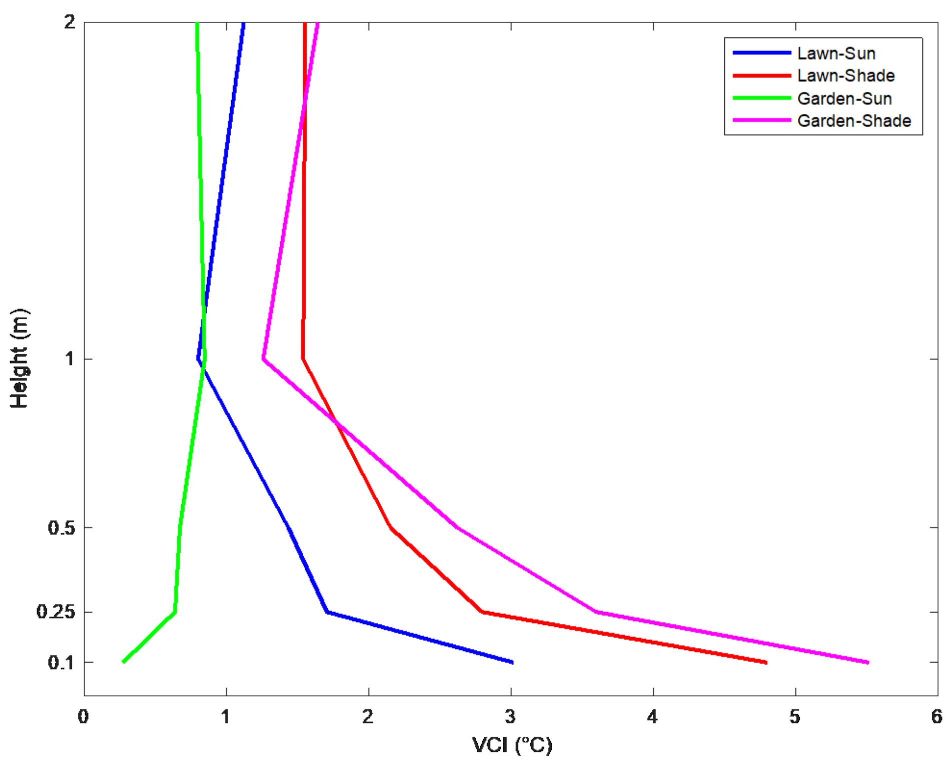


Figure 10. Mean VCI (VCI = $T_{site\ 5} - T_{site\ i}$) at five heights for each vegetated site during the study period.

3.4.1 VCI and Background Temperature

To examine the impact of background temperature on VCI, the average temperature of the control site at 2 m (30.75 °C) was used to establish warmer vs. cooler days, as seen in Table 5. Transects with temperatures higher than the average were categorized as "warmer" while transects with temperatures at or below the average were categorized as "cooler," resulting in an average temperature difference of close to 10 °C.

Table 5. Average temperature and standard deviation for the control site at 2 m across all transects. Transects highlighted in yellow cells were warmer than average, while the remainder were cooler than average.

		μ Temp		**σ Temp**	
Transect	**Date**	**First**	**Second**	**First**	**Second**
1, 2	9/18/20	26.50	24.60	1.57	1.14
3, 4	9/19/20	28.51	28.73	1.35	0.54
5, 6	9/20/20	32.39	31.80	1.18	0.43
7, 8	9/21/20	28.41	29.98	0.98	1.93
9, 10	9/23/20	30.35	29.48	1.22	1.02
11, 12	9/26/20	31.30	31.50	0.63	0.65
13, 14	9/27/20	34.69	34.41	1.12	0.76
15, 16	9/28/20	37.09	36.62	0.94	0.56
17, 18	10/1/20	34.53	34.50	0.83	0.70
19, 20	10/2/20	33.14	33.48	0.35	0.48
21, 22	10/3/20	36.98	36.69	0.83	0.53
23, 24	10/4/20	35.74	35.81	1.28	0.79
25, 26	10/9/20	22.15	20.81	0.74	0.48
27, 28	10/10/20	20.14	20.41	0.47	0.51
29, 30	10/11/20	27.26	27.64	1.16	1.38
31, 32	10/12/20	30.50	29.65	1.07	0.73
33, 34	10/15/20	35.60	34.02	2.06	1.38
All Warmer		34.46		1.18	
All Cooler		26.57		1.02	

Average VCI for cooler transects are compared with warmer transects in Figure 11. Measurements from 1 m have been excluded from the figure because of inconsistencies with the 1 m thermocouple siting. Across heights, the average VCI was greater for each site under warmer conditions. At .1 m, The VCI for Lawn-Sun, for example, was up to 3 times greater on warmer than average days than cooler than average days, pointing to enhanced evaporative cooling on warmer days, supplied with plentiful irrigation. At 2 m, the change in VCI was greatest for Garden-Shade, with an increase in VCI of 52%. On all days, the VCI for Lawn-Shade and Garden-Shade was consistently higher than the other sites, pointing to the importance of shade for cooling benefits. On cooler days, with less radiation (Figure 5), Lawn-Shade had the largest VCI at 2 m, cooled by irrigation in addition to shade.

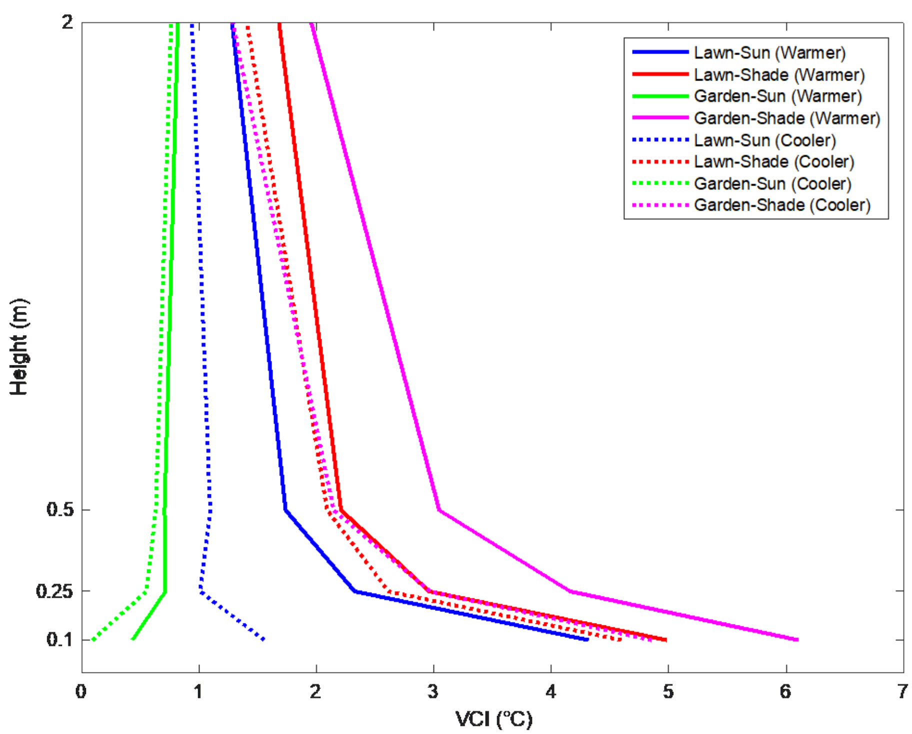


Figure 11. Mean VCI for four vegetated sites comparing conditions on warmer days (18 transects) to cooler days (16 transects.)

In a simple linear regression, temperature had a positive relationship with VCI for all sites, as seen in Figure 12. For the model, VCI was expressed as the average air temperature from 5 heights. Temperature was a significant driver (p-values <0.05) for Garden-Shade, Lawn-Sun, and Lawn-shade, with the model explaining 44, 32, and 12% of variance respectively. As temperature increased, VCI increased as shade and irrigation resulted in cooler temperatures compared to Parking Lot-Sun. Temperature was not a significant driver of VCI for Garden-Sun, as this site's sparse vegetation, dark mulch and reduced irrigation schedule produced a similar temperature profile to the parking lot. Model coefficients, R^2 and p-values are provided in Table 6.

Table 6. Linear Regression results for testing the relationship between VCI and temperature for each vegetated site (n=34).

Site	Lawn-Sun	Lawn-Shade	Garden-Sun	Garden-Shade
R^2	0.316	0.123	0.00959	0.443
P-Value	0.000547	0.0422	0.582	1.75e-05
Intercept	-2.1332	0.6233	0.11985	-1.9668
Slope	0.1262	0.065415	0.0176	0.1646

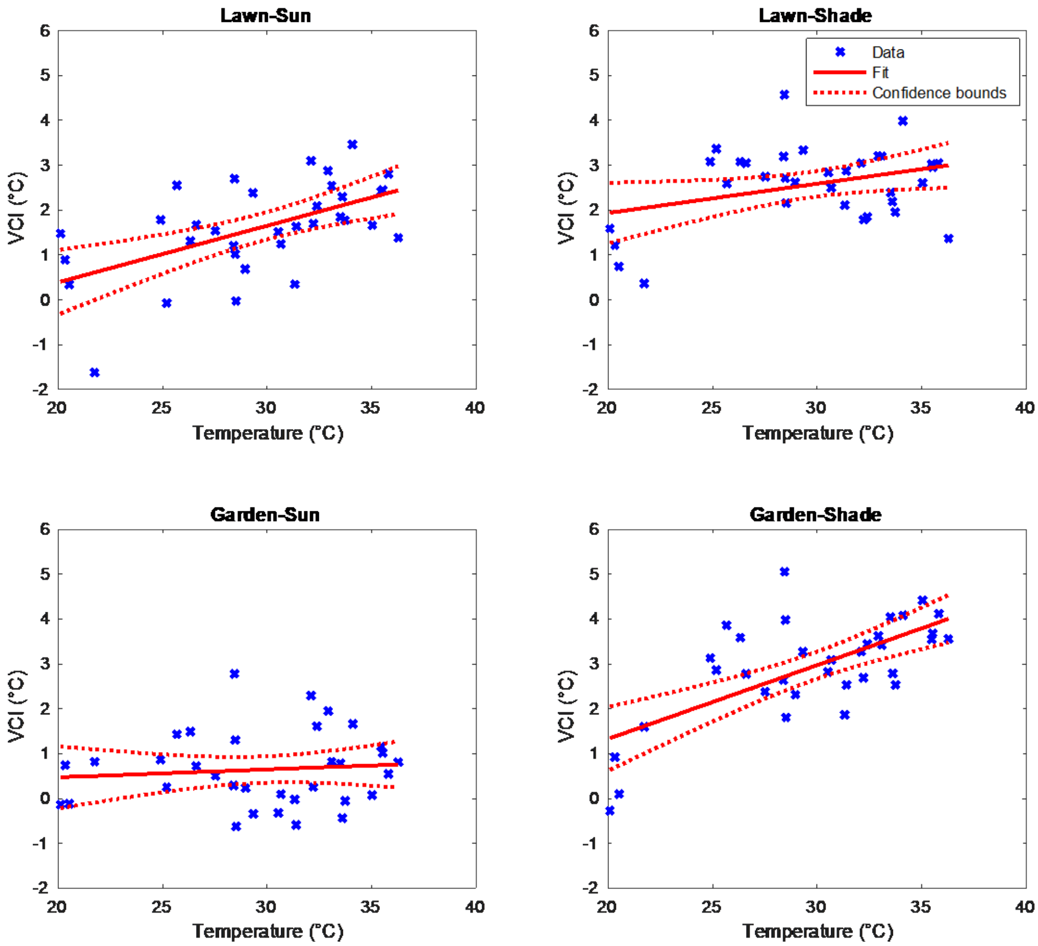


Figure 12. Linear regression model showing a positive relationship between VCI and temperature for all sites. VCI was average air temperature across heights, and temperature was the mean air temperature at 2 m for each transect.

3.4.2 VCI and Wind

To examine the impact of wind on VCI, the average wind speed of the control site was calculated (0.75 m/s) for the length of the study period. While wind speed varied amongst sites, in order to compare transects, transects with a wind speed at the control site that exceeded the average were categorized as "windier" while transects with a wind speed at the control site that was at or below the average were categorized as “less windy”. Average VCI for the windier transects are compared with less windy transects in Figure 13.

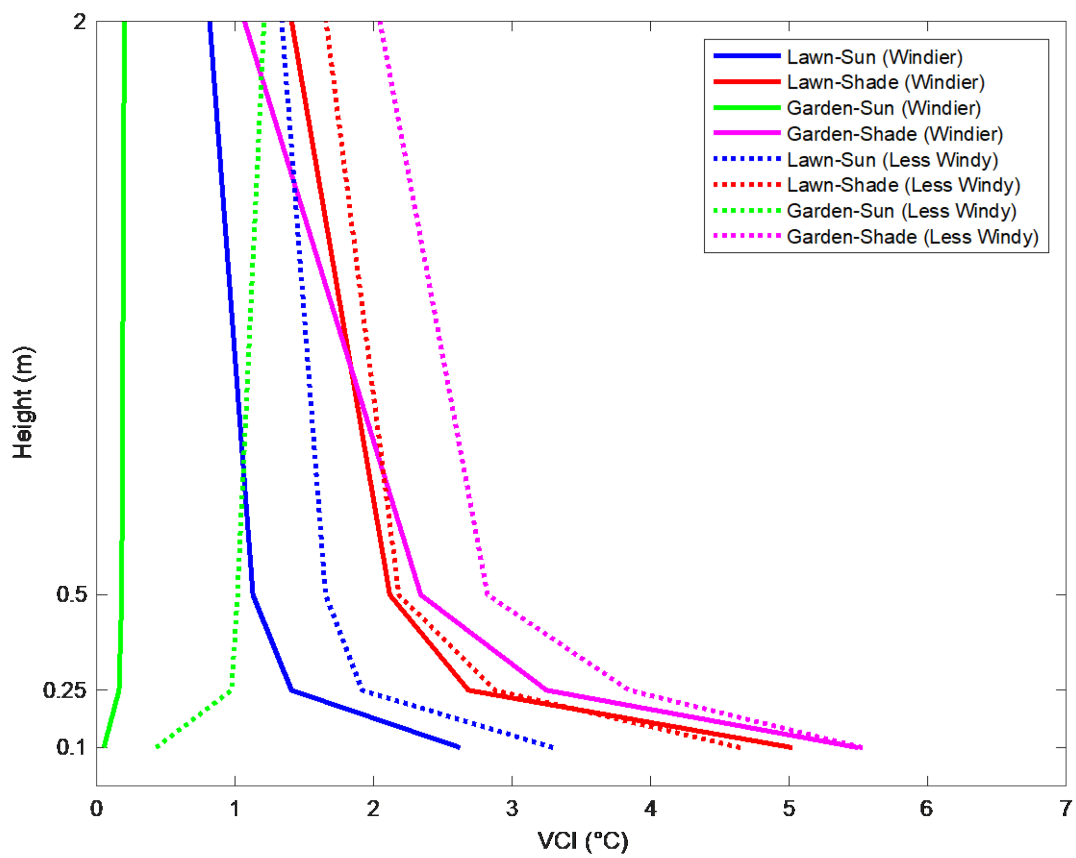


Figure 13. Mean VCI for four vegetated sites comparing less windy conditions (20 transects) to windier (14 transects).

The profiles of the VCI maintain similar shapes but shift toward lower VCIs under higher wind speeds. The largest differences occurred at 2 m and the differences generally diminished closer to the surface. This indicates the importance of mixing within the courtyard, in diminishing the VCI, and that sites closer to the surface are less affected by mixing and more driven by the immediate SEB. Therefore, under less windy conditions, Garden-Shade had the largest VCI. Under windier conditions, Lawn-Shade had the largest VCI. Wind affects VCI by mixing air above sites as well as bringing in air from surrounding sidewalks, roads, and building walls. Under windier conditions, the difference in VCI between Garden-Shade and Lawn-Sun decreased, suggesting that air above these sites were mixing, while the difference in VCI between Garden-Shade and Garden-Sun increased, suggesting that Garden Sun may have been subject to greater mixing with other nearby, exposed landscapes since it wasn't sheltered from the wind as the shaded site was.

3.4.3 VCI and regional meteorological impacts

The warmest days of the study occurred when weak easterly air masses produced low humidity, clear skies, low wind speeds and high temperatures across the region. Transects 29, 30, 31, & 32 provide a good example of these conditions. Under conditions when regional pressure gradients across the coastline dominated, cooler, windier, and more humid airmasses prevailed, often accompanied with stratus clouds extending inland as far as the study site. Transects 25, 26, 27, & 28 provide good examples of these conditions. A comparison between mean temperature profiles under these two conditions is provided in Fig. 14.

Under cooler, cloudier and more humid conditions (transects 25, 26, 27, & 28), the VCI at 2 m for all sites was less than 0.5 °C, and Lawn-Sun was 0.02 °C warmer than the parking lot, providing no VCI. When conditions returned to higher temperatures and radiation with low vapor pressure (Transects 25, 26, 27, & 28), the impact of shade once again became clear with Garden-Shade providing the largest VCI at all heights. These results suggest that vegetation as a strategy for localized cooling is most effective under conditions with higher temperature, higher radiation, and lower vapor pressure.

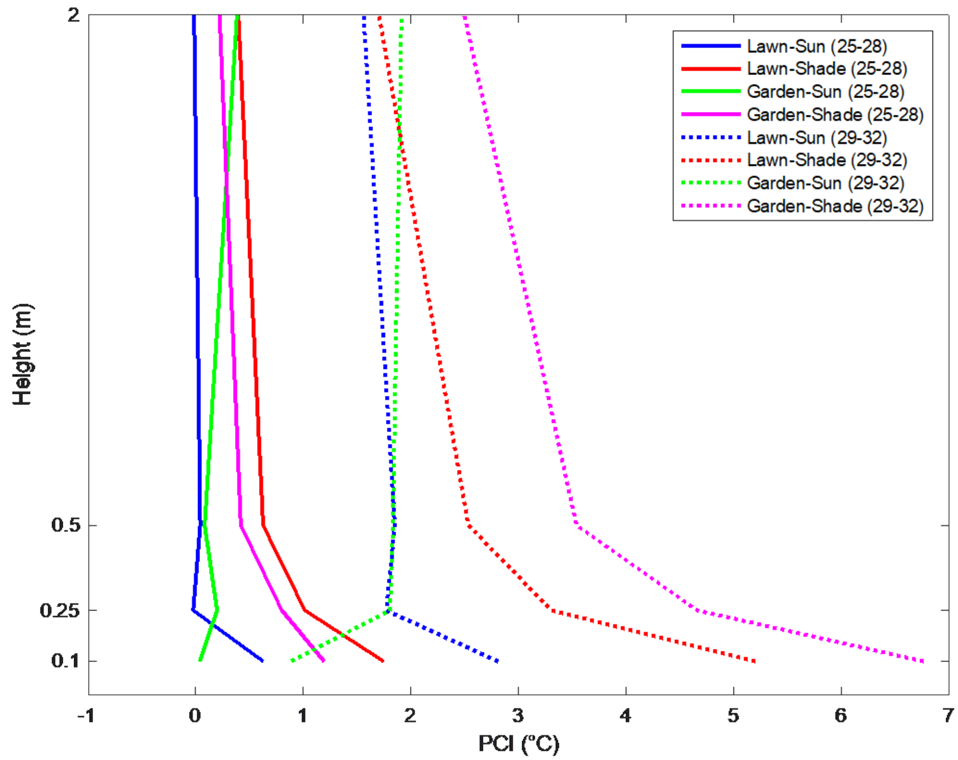


Figure 14. Comparison of the VCI effect for Transects 25,26,27, and 28 to Transects 29,30,31, and 32. Transects 25-28 had the lowest radiation and highest vapor pressure during the study period.

3.5 Estimated Water Use and Cooling Efficiency

Each site's water use was estimated for an area of 9.3 m^2 (100 sq.ft.) using the California Department of Water Resources (DWR) Model Water Efficient Landscape Ordinance (MWELO) water budget worksheet (Table 7). The water budget worksheet estimates water use based on plant factor and irrigation efficiency. Plant factor refers to a plant's water needs based on region, ranging from 0 (needs no irrigation) to 1.0 (needs high amount of irrigation) as determined by the University of California's Water Use Classification of Landscape Species (WUCOLS). Irrigation efficiency refers to the percentage of irrigation reaching the plant. Overhead spray devices such as sprinklers and bubblers are assumed to have an irrigation efficiency of 0.75, while drip irrigation is more efficient at 0.81.

Table 7. MWELO Water Use Worksheet to estimate water use based on plant factor, irrigation method and efficiency, local climate, and landscape area.

Hydrozone	Plant Factor (PF)	Irrigation Method	Irrigation Efficiency (IE)	ETAF (PF/IE)	Landscape Area (sq.ft.)	ETAF x Area	Estimated Total Water Use Gallons (Eto x .62 x ETAF x Area)	Estimated Total Water Use (liters m^2)
Lawn-Sun	1	Spray	0.75	1.33	100	133	380,965	1,552,300,000
Lawn-Shade	1	Spray	0.75	1.33	100	133	380,965	1,552,300,000
Garden-Sun	.1	Bubbler	0.75	0.13	100	13	37,237	151,730,000
Garden-Shade	.3	Spray/ Bubbler	0.75	0.4	100	40	114,576	466,850,000

Estimated water use for both lawn sites were the highest, as lawns have the highest plant factor for Walnut Creek's climate, indicating that these sites would need to be irrigated more frequently than the garden and thus would use more water. As the shade-tree over the lawn was incidentally irrigated on the same schedule and with the same equipment as the lawn, it's water use is included in the same hydrozone as Lawn-Shade. Garden-Shade, with its mix of trees and shrubs, had a lower plant factor than the lawn sites, but a higher plant factor than the other garden site. Garden-Sun, which was sparsely planted with drought tolerant bunch grass had the lowest plant factor and consequentially was estimated to use significantly less water than the other sites.

Cooling efficiency refers to how much VCI resulted from each site's estimated water use, as seen in Figure 15. When plotting cooling efficiency, the 0 point assumes that if there is no water, there can be no surviving plants. Without surviving plants, there would be no transpiration or shade, no soil water available for evaporation, and consequentially no VCI. The upper point of the line passes through the estimated maximum water found in the courtyard and the resulting maximum VCI. The results show that the presence of shade trees achieved by far the highest cooling efficiency, and Garden-Shade provided the highest VCI with the least amount water. Lawn-Shade also provided more cooling for the same amount of water as Lawn-Sun. While Garden-Sun uses the least amount of water, relatively little cooling was achieved.

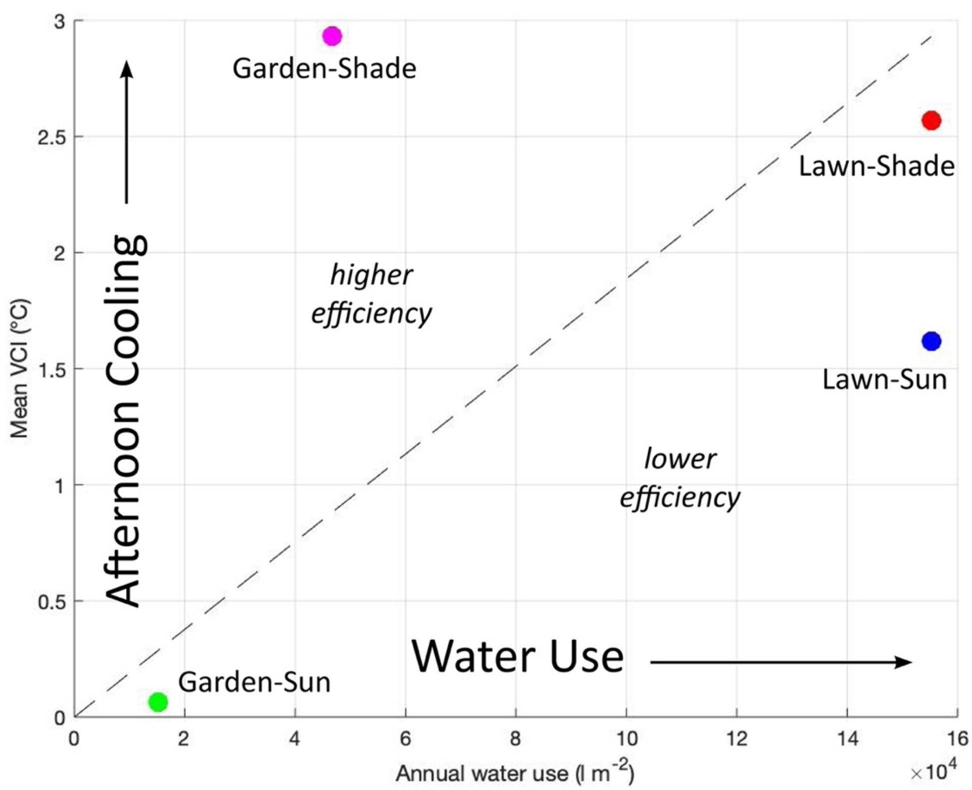


Figure 15. Scatter plot of average VCI versus estimated annual water use.

4. Discussion

4.1. Microclimate differences

Our findings show how, at the site scale, variability in surface cover resulted in distinct microclimate differences, with landscaping that included shade trees providing the maximum cooling effects. Air temperature differences between sites were more pronounced closer to the surface and diminished with height due to mixing in the atmospheric surface layer, but even at 2 m, air temperature differences were statistically significant ($p < 0.05$) between sites for the majority of transects. The site in the water-efficient garden under the olive tree (Garden-Shade) and the site over the lawn under the sycamore tree (Lawn-Shade) were consistently cooler than the exposed vegetated sites and the parking-lot, demonstrating the importance of trees in reducing air temperature whether planted in a lawn or a water-efficient garden, as long as the tree canopy provides sufficient shade. The lawn site and garden site in the sun also provided cooling when compared to the parking lot, though to a lesser extent.

Temperature differences were caused primarily by shade trees blocking radiation and moderating the convective surface-to-air heat exchange, and by direct cooling of air through evapotranspiration. The shaded sites, cooled by both shade and ET, had the largest VCIs and provided similar cooling effects within the 2m vertical air temperature profile. On warmer days with increased radiation, the shaded garden site provided the largest VCI, possibly because the mulched surface held in moisture from the morning irrigation, which meant water was still available in the afternoon to cool the air through evaporation (Singer & Martin, 2008). In contrast, the shaded lawn may have lost moisture earlier on hot days (when temperatures were above the average of 30.75 °C), as the cooling effect of irrigation over lawns has been found to disappear by noon during elevated heat events (Cowles, 2014). The shaded lawn site may also have had less water available for evaporation due to the root system of the large sycamore tree extending into the lawn and utilizing soil water. On cooler days (when temperatures were less than the average of 30.75 °C) with more cloud coverage and less radiation, the VCI for the shaded lawn site was the greatest, presumably due to cooling from the transpiring leaves of the lawn and tree canopy in addition to shade.

Across all transects, at 2 m, the mean VCI for the shaded garden and shaded lawn were 1.64 °C and 1.55 °C respectively, while the exposed lawn without shade (Lawn-Sun) and the sparsely planted garden (Garden-Sun) produced an average 2 m VCI of 1.12 °C and 0.79 °C. These results are consistent with, though a little lower than, a study by Shashua-Bar et al. (2009) measuring air temperature at 1.5 m in two adjacent courtyard spaces configured with different landscape strategies in a controlled experiment in southern Israel. When comparing vegetation to a non-vegetated, controlled courtyard, they found that the combination of trees over grass yielded the largest afternoon VCI of 2.5 °C. Our vegetation produced a lower VCI likely because the average background temperature over the exposed parking lot in our study was around 4 °C cooler than their exposed courtyard, and both shaded sites in this study had a VCI positively correlated with background temperature (Fig. 8). Microclimate effects are more pronounced on warmer days due to larger amounts of energy available for evapotranspiration, both from higher air temperature and higher solar radiation.

These results add to a large body of literature finding that urban green spaces can reduce the UHI effect at various spatial and temporal scales. However, the majority of previous studies are at the scale of urban forest or parks (Marchionni et al., 2019). As research in a single courtyard is limited, the right terminology doesn't exist to describe the cooling index of different vegetation configurations at this scale, hence, we use vegetation cooling index (VCI) as a microclimate assessment of the role of vegetation within the urban environment. At larger scales such as urban forest and parks, vegetation has been found to reduce mid-day air temperature up to 4 °C (Oke, 1989; Spronken-Smith & Oke, 1998; Shashua-Bar & Hoffman, 2000; Potchter et al., 2006; Cowles, 2014) while our results are more similar to studies at the neighborhood scale, such as in Colorado's semiarid environment, where vegetated surfaces such as urban lawns may reduce temperatures by up to 2 °C (Bonan, 2000). At smaller scales, air above different types of surface cover are subject to greater mixing with air influenced by elements of the surrounding built environment resulting in smaller temperature decreases from vegetation compared to larger urban green spaces.

4.2. Water Use

A key result from this study is the potential for water-efficient landscaping with shade trees to reduce surface and air temperatures in a residential setting. The difference in cooling between shade and no-shade was significantly larger than the cooling obtained from an unshaded irrigated lawn compared with unshaded water-efficient species. These results suggest that drought tolerant shade trees would be a good choice for residential landscaping in areas where water districts may implement seasonal restrictions to irrigation, limiting the capacity to support water-intensive landscaping. Lawns or similar open ground cover, for example, may reduce daytime surface and air temperatures through cooling from transpiration, but will likely need relatively large amounts of irrigation to maintain the growth rate required to transpire sufficient water for cooling, making irrigated lawns a less efficient choice for cooling compared to drought tolerant trees. In contrast, drought tolerant plants that are typical of water-efficient gardens will require relatively less irrigation, but if sparsely planted and exposed to the sun, the garden's microclimate may have a weaker cooling effect and the dry soil may produce a sensible heat exchange from the surface to the atmosphere that resembles impermeable surfaces (Coutts et al., 2013). In our study the exposed water-efficient garden provided a VCI of less than 1 °C and was closer in temperature at the surface to that of the parking lot than the other vegetated sites. This implies the nature and color of surface mulches could be modified to further reduce heat absorption.

The results of this study can help inform utility or municipal lawn conversion programs, where residents and businesses are incentivized with rebates to convert lawns to water-efficient gardens. If adopted on a large scale without considering how to plant to optimize cooling, water-efficient gardens could have unintended adverse effects and create warmer microclimates. Vahmani and Weiss (2016), for example, found through modeling that converting lawns to water-efficient landscaping (shrubs with no irrigation) in the Los Angeles metropolitan area resulted in daytime air temperature increases up 1.9 °C, largely due to the increase in sensible heat flux. Notably their study did not include low-water trees as part of what they considered water-efficient landscaping.

Our study found that the addition of shade trees to a water-efficient garden will increase cooling efficiency of air near the surface, as they require less irrigation than a lawn while providing more cooling. This was also concluded by Chow and Brazel (2012) who evaluated the combined impact of both increased shading and evapotranspiration from low-water use plants, including shade trees adapted to desert conditions, on residential surface temperatures in two Phoenix neighborhoods. They found distinct daytime and nighttime cooling impacts when compared to heavily built-up urban centers. However, when they evaluated the effect of converting existing mesic landscaping (including lawns and large, non-native shade trees) to water-efficient landscaping, they found that lawn conversions increased temperatures, likely resulting in greater thermal discomfort to residents.

Cohen et al. (2012) also found that trees were an important factor for reducing UHIs in the Mediterranean climate of Tel Aviv, Israel. In a comparison of urban parks with different vegetation types, they found that the parks planted with a dense canopy of trees reduced daytime air temperatures by up to 3.8 °C in the summer and 2 °C in the winter. The park with dense trees was notably cooler than the park planted mainly with lawn. While the results of our study show potential cooling benefits from xeriscaping with shade trees, the tree selection options are limited as many native trees that grow without supplemental irrigation are short and have sparse canopies, and in some arid climates, no appropriate shade trees exist (Wheeler et al., 2019). Ossola et al. (2020) recommend prioritizing fast-growing tree species adapted to survive periods of extreme heat and droughts, which excludes several popular native species that may not survive future climate change scenarios without increased irrigation (Ossola, Staas, & Leishman, 2020). If stressed from high heat and radiation loads, trees may constrain stomatal conductance (Chen et al., 2011) restricting transpiration and further increasing temperature. Furthermore, stressed and unhealthy trees can also lose a proportion of their canopy coverage, reducing shade and other ecosystem services (Shashua-Bar et al., 2010a).

An approach to prevent tree stress while still encouraging water conservation in the landscape, is the implementation of Water Sensitive Urban Design (WSUD) or Low Impact Development (LID). WSUD and LID refers to strategies for stormwater reuse and capture with the goals of supplementing potable irrigation while also providing other ecological benefits including reducing stormwater pollutant loads. These strategies involve rainwater collection in tanks to be used for irrigation, and bioswales designed with berms and basins that capture rainwater in the landscape rather than allowing it to runoff onto sidewalks and streets where it enters storms drains and is discharged into waterways. WSUD and LID support climate regulating ecosystem services by promoting localized cooling at the microclimate scale through enhanced water availability and evapotranspiration (Coutts et al., 2013; Newcomer et al., 2013).

4.3. Future Research

In this study, the cooling effect of vegetation is only reflected by air temperature and surface temperature differences, not by an integrated representation of microclimatic effects on a human body. Surface and air temperature are not the only drivers of overall human thermal comfort, especially in hot-arid environments where radiation dominates and interacts with vegetation and complex features of the built environment. For example, Pearlmutter et al (2007) noted how some UHI strategies, such as the use of high-albedo materials, may result in cooler surface temperatures but the reflected radiation may raise air temperature and contribute to pedestrian discomfort. Such thermal comfort considerations would need to include an analysis of radiation, humidity, and wind effects on the human body.

While there is no single landscape design that is suitable for UHI mitigation in all areas (Gober et al., 2010), future microclimate research on residential landscaping would benefit from more detailed site descriptions to better understand how features of the built environment positively or negatively affect pedestrians. These features could include (a) surface roughness length, as it influences wind flow; (b) vegetation fraction, as it is key to energy partitioning and shading; (c) sky view factor, as it determines radiation exposure and also radiative cooling; and (d) albedo, as it influences surface heat absorption and radiation reflection.

Future research could also measure diurnal microclimate differences to see how temperatures change throughout the day and at night. While Vahmani and Weiss (2016) found that water-efficient landscaping raised temperatures during the day, at night these same landscapes caused a mean cooling of 3.2°C due to less efficient surface to air heat transfers. As UHIs are primarily observed at night, water-wise landscapes were found to be an effective UHI mitigation strategy, and the night-time cooling may offset the daytime heating (Vahmani & Ban-Weiss, 2016). A longer study showing daytime and nighttime temperature differences could also evaluate how air temperature is affected by different irrigation timing and water use.

Our study used an estimate of evapotranspiration based on plant water needs and irrigation type, which provided a generalized estimate for annual water use. This method assumes that the plants are being irrigated to their ET demands where irrigation replaces total water lost through evapotranspiration, but actual watering may vary, and it would be helpful to have more detailed information on irrigation timing and application amounts for future research. Deficit irrigation, for example, is when less than 100% of the potential ET is replaced and may be practiced to conserve water. Little data has been collected about deficit irrigation, ET, and urban landscapes. Future research could measure water vapor fluxes by eddy covariance technique or the weighing lysimeter method to analyze irrigation and water conservation's relationship to microclimates. The relationship between water use, landscape configurations, and cooling could be incorporated into models to predict heating and cooling of residential landscapes in Mediterranean climates.

5. Conclusion

In this study we analyzed midafternoon surface and air temperature profiles, radiation, wind speed, and humidity differences between a well-irrigated lawn, a water-efficient landscape, and a paved parking lot in a residential courtyard to better understand how common types of urban form and landscape designs impact microclimate heating and cooling.

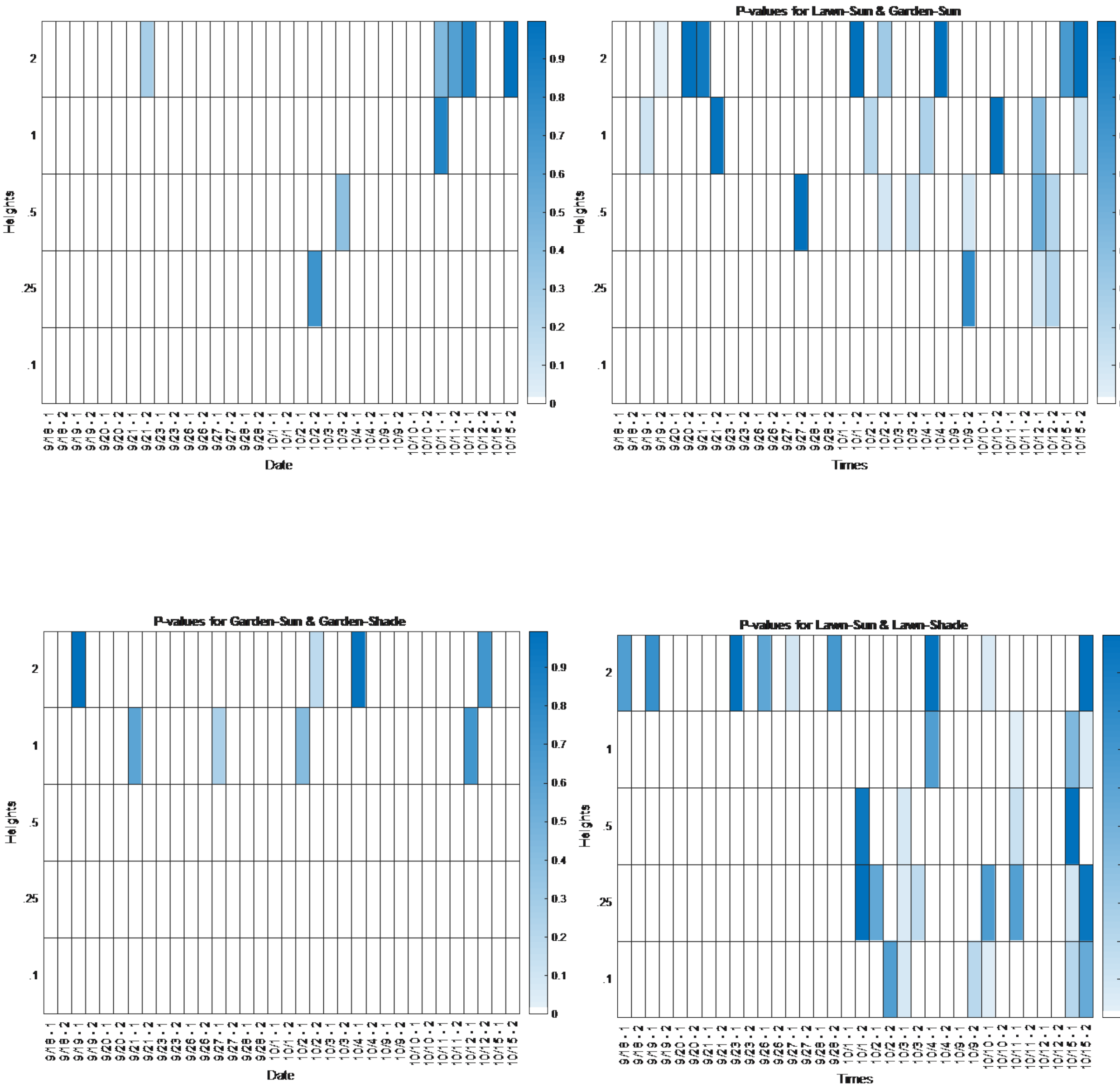
At the scale of a residential landscape, variability in surface cover resulted in distinct microclimate differences, with the largest temperature differences closest to the surface. Temperature differences were caused primarily by shade trees blocking radiation and moderating the convective surface-to-air heat exchange, and by direct cooling through evapotranspiration. The construction of the VCI allowed for a comparison between the asphalt surface and the vegetated surfaces, to estimate cooling potential from different types of vegetation at this scale. VCI's for all vegetated sites were most pronounced on warmer days due to larger amounts of energy available for evapotranspiration, both from higher air temperature and higher solar radiation, and under less windy conditions when sites were less affected by mixing in the atmospheric surface layer.

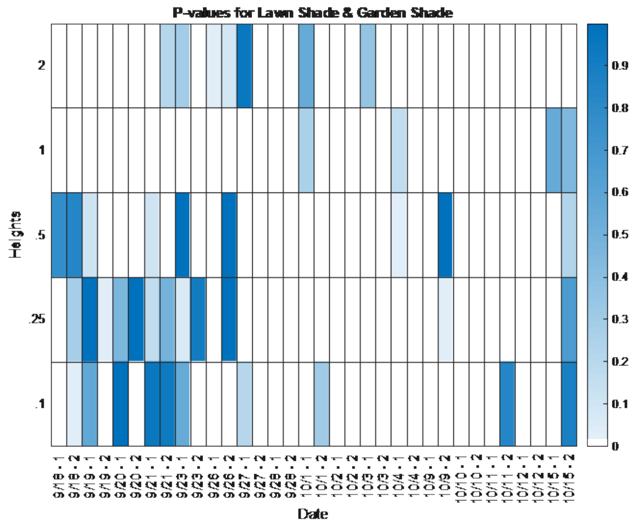
The greatest average VCI was provided by the shaded water-efficient garden, which was cooled by both shade and ET. In terms of cooling efficiency, the shaded water-efficient garden also provided the most cooling with the least amount of water. While the shaded lawn provided similar cooling to the shaded water-efficient garden, the cooling was outweighed by the lawn's high-water demand. The exposed water-efficient garden had the lowest water-use, but its sparse vegetation and exposure to radiation provided the smallest VCI and was closer in temperature to the parking lot than the other sites.

These results suggest that, when compared to a parking lot, the addition of vegetation to a residential development may provide temperature regulating ecosystem services, and a shade tree that is planted as a part of a water-efficient garden has the potential to reduce surface and air temperatures more than an exposed lawn or even a lawn/shade combination. For water district's incentivizing the replacement of lawns with water-efficient landscaping, requiring a climate appropriate low-water use tree would increase temperature regulating ecosystem services while keeping landscape water use low.

Appendix A

Appendix A. 1. Tukey Test P-Value Colormaps




P-values for Lawn Shade & Garden Shade
Heights
2
1
.5
.25
.1
Date
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

References

Alkhatib, Laila; Qrunfleh, M. M. (2018). Plants as an Element in Microclimate Modification in Jordan Landscape Courtyard Gardens. *Jordan Journal of Agricultural Sciences*, *14*(1).

Arnfield, A. J. (2003). Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology*. https://doi.org/10.1002/joc.859

Bonan, G. B. (2000). The microclimates of a suburban Colorado (USA) landscape and implications for planning and design. *Landscape and Urban Planning*. https://doi.org/10.1016/S0169-2046(00)00071-2

Bowler, D. E., Buyung-Ali, L., Knight, T. M., & Pullin, A. S. (2010). Urban Greening to Cool Towns and Cities: A Systematic Review of the Empirical Evidence. *Landscape and Urban Planning*, *97*(3), 147–155.

Chen, Y., & Wong, N. H. (2006). Thermal benefits of city parks. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2005.04.003

Chen, L., Zhang, Z., Li, Z., Tang, J., Caldwell, P., & Zhang, W. (2011). Biophysical control of whole tree transpiration under an urban environment in Northern China. *Journal of Hydrology*, *402*(3–4). https://doi.org/10.1016/j.jhydrol.2011.03.034

Chesnutt, T. W. (2020). Statistical estimates of water savings from landscape transformation programs. *AWWA Water Science*. https://doi.org/10.1002/aws2.1167

Chow, W. T. L., Pope, R. L., Martin, C. A., & Brazel, A. J. (2011). Observing and modeling the nocturnal park cool island of an arid city: Horizontal and vertical impacts. *Theoretical and Applied Climatology*. https://doi.org/10.1007/s00704-010-0293-8

City of Walnut Creek. (2012). Climate Action Plan. https://www.walnut creek.org/home/showdocument?id=6479

Cohen, P., Potchter, O., & Matzarakis, A. (2012). Daily and seasonal climatic conditions of green urban open spaces in the Mediterranean climate and their impact on human comfort. *Building and Environment*. https://doi.org/10.1016/j.buildenv.2011.11.020

Coutts, A. M., Tapper, N. J., Beringer, J., Loughnan, M., & Demuzere, M. (2013). Watering our cities: The capacity for Water Sensitive Urban Design to support urban cooling and improve human thermal comfort in the Australian context. *Progress in Physical Geography*. https://doi.org/10.1177/0309133312461032

Cowles, S. (2014). *Investigations of the park cool island effect of Golden Gate Park, San*

Francisco. San Francisco State University.

DeOreo, W. B., Mayer, P. W., Martien, L., Hayden, M., Funk, A., Kramer-, M., … Heberger, M. (2011). California Single Family Water Use Efficiency Study. *Management*.

Department of Water Resources. Chapter 2.7. Model Water Efficient Landscape Ordinance (2015).

Dialesandro, J. M., Wheeler, S. M., & Abunnasr, Y. (2019). Urban heat island behaviors in dryland regions. *Environmental Research Communications*. https://doi.org/10.1088/2515-7620/ab37d0

GISTEMP. (2020). GISS Surface Temperature Analysis (GISTEMP), version 4.

Gober, P., Brazel, A., Quay, R., Myint, S., Grossman-Clarke, S., Miller, A., & Rossi, S. (2010). Using watered landscapes to manipulate urban heat island effects: How much water will it take to cool phoenix? *Journal of the American Planning Association*, *76*(1). https://doi.org/10.1080/01944360903433113

Grimmond, C. S. B., & Oke, T. R. (1999). Heat storage in urban areas: Local-scale observations and evaluation of a simple model. *Journal of Applied Meteorology*. https://doi.org/10.1175/1520-0450(1999)038<0922:HSIUAL>2.0.CO;2

Grimmond, C. S. B., Roth, M., Oke, T. R., Au, Y. C., Best, M., Betts, R., … Voogt, J. (2010). Climate and more sustainable cities: Climate information for improved planning and management of cities (Producers/Capabilities Perspective). In *Procedia Environmental Sciences*. https://doi.org/10.1016/j.proenv.2010.09.016

Grulke, N. E., Pincetl, S., Whitlow, T. H., Pataki, D. E., Carreiro, M. M., Pouyat, R. V, … Zipperer, W. C. (2011). Coupling biogeochemical cycles in urban environments: ecosystem services, green solutions, and misconceptions. *Frontiers in Ecology and the Environment*.

Gunawardena, K. R., Wells, M. J., & Kershaw, T. (2017). Science of the Total Environment Utilising green and bluespace to mitigate urban heat island intensity. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2017.01.158

Guo, Y., Gasparrini, A., Li, S., Sera, F., Vicedo-Cabrera, A. M., de Sousa Zanotti Stagliorio Coelho, M., … Tong, S. (2018). Quantifying excess deaths related to heatwaves under climate change scenarios: A multicountry time series modelling study. *PLoS Medicine*. https://doi.org/10.1371/journal.pmed.1002629

Hall, S. J., Learned, J., Ruddell, B., Larson, K. L., Cavender-Bares, J., Bettez, N., … Trammell, T. L. E. (2016). Convergence of microclimate in residential landscapes across diverse cities in the United States. *Landscape Ecology*. https://doi.org/10.1007/s10980-015-0297-y

Hann, R. (San F. S. U. (2020). *Impact of the Built Environment on Microclimate in San José, California*. San Francisco State University.

Hayden, L., Cadenasso, M. L., Haver, D., & Oki, L. R. (2015). Residential landscape aesthetics and water conservation best management practices: Homeowner perceptions and preferences. *Landscape and Urban Planning*. https://doi.org/10.1016/j.landurbplan.2015.08.003

Leconte, F., Bouyer, J., Claverie, R., & Pétrissans, M. (2015). Using Local Climate Zone scheme for UHI assessment: Evaluation of the method using mobile measurements. *Building and Environment*. https://doi.org/10.1016/j.buildenv.2014.05.005

Li, H., Meng, H., He, R., Lei, Y., Guo, Y., Ernest, A. atta, … Tian, G. (2020). Analysis of cooling and humidification effects of different coverage types in small green spaces (SGS) in the context of urban homogenization: A case of HAU campus green spaces in summer in Zhengzhou, China. *Atmosphere*. https://doi.org/10.3390/ATMOS11080862

Marchionni, V., Revelli, R., & Daly, E. (2019). Ecohydrology of Urban Ecosystems. In *Dryland Ecohydrology*. https://doi.org/10.1007/978-3-030-23269-6_20

Milesi, C., Running, S. W., Elvidge, C. D., Dietz, J. B., Tuttle, B. T., & Nemani, R. R. (2005). Mapping and modeling the biogeochemical cycling of turf grasses in the United States. *Environmental Management*. https://doi.org/10.1007/s00267-004-0316-2

Millennium Ecosystem Assessment. (2003). Ecosystems and their services. In *Ecosystems and Human Well-being: A Framework for Assessment*. https://doi.org/10.1007/s13398-014-0173-7.2

Offerle, B., Grimmond, C. S. B., Fortuniak, K., Kłysik, K., & Oke, T. R. (2006). Temporal variations in heat fluxes over a central European city centre. *Theoretical and Applied Climatology*. https://doi.org/10.1007/s00704-005-0148-x

Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*. https://doi.org/10.1002/qj.49710845502

Oke, T. R. (1989). The micrometeorology of the urban forest. *Philosophical Transactions - Royal Society of London, B*, *324*(1223). https://doi.org/10.1098/rstb.1989.0051

Ossola, A., Staas, L., & Leishman, M. (2020). *Urban trees and people's yards mitigate extreme heat in western Adelaide: final summary report*.

Peng, S., Piao, S., Ciais, P., Friedlingstein, P., Ottle, C., Bréon, F. M., … Myneni, R. B. (2012). Surface urban heat island across 419 global big cities. *Environmental Science and Technology*. https://doi.org/10.1021/es2030438

Pincetl, S. (2007). Accounting for environmental services in cities: The new frontier for sustainability. *Social and Environmental Accountability Journal*. https://doi.org/10.1080/0969160X.2007.9651768

Pincetl, S. (2010). From the sanitary city to the sustainable city: Challenges to institutionalising biogenic (nature's services) infrastructure. *Local Environment*. https://doi.org/10.1080/13549830903406065

Potchter, O., Cohen, P., & Bitan, A. (2006). Climatic behavior of various urban parks during hot and humid summer in the Mediterranean city of Tel Aviv, Israel. *International Journal of Climatology*, *26*(12). https://doi.org/10.1002/joc.1330

Robinson, P. J. (2001). On the definition of a heat wave. *Journal of Applied Meteorology*. https://doi.org/10.1175/1520-0450(2001)040<0762:OTDOAH>2.0.CO;2

Seapy, B. (2015). *Turf removal & replacement: lessons learned*.

Shashua-Bar, L., & Hoffman, M. E. (2000). Vegetation as a climatic component in the design of an urban street. An empirical model for predicting the cooling effect of urban green areas with trees. *Energy and Buildings*, *31*(3). https://doi.org/10.1016/S0378-7788(99)00018-3

Shashua-Bar, Limor, Pearlmutter, D., & Erell, E. (2011). The influence of trees and grass on outdoor thermal comfort in a hot-arid environment. *International Journal of Climatology*. https://doi.org/10.1002/joc.2177

Singer, C. K., & Martin, C. A. (2008). Effect of landscape mulches on desert landscape microclimates. *Arboriculture and Urban Forestry*, *34*(4).

Song, J., & Wang, Z. H. (2015). Impacts of mesic and xeric urban vegetation on outdoor thermal comfort and microclimate in Phoenix, AZ. *Building and Environment*. https://doi.org/10.1016/j.buildenv.2015.10.016

Souch, C., & Grimmond, S. (2006). Applied climatology: Urban climate. *Progress in Physical Geography*. https://doi.org/10.1191/0309133306pp484pr

Sovocool, K. A., Morgan, M., & Bennett, D. (2006). An in-depth investigation of Xeriscape: As a water conservation measure. *Journal / American Water Works Association*. https://doi.org/10.1002/j.1551-8833.2006.tb07590.x

Spronken-Smith, R. A., & Oke, T. R. (1998). The thermal regime of urban parks in two cities with different summer climates. *International Journal of Remote Sensing*, *19*(11). https://doi.org/10.1080/014311698214884

Szegedi, S., & László, E. (2012). Park Cool Island Examinations in Debrecen, Hungary. In *8th International Conference on Urban Climates and 10th Symposium on the Urban*

Environment.

State of California, Department of Finance, *E-1 Population Estimates for Cities, Counties and the State with Annual Percent Change.* Sacramento, California, 2019

United States Environmental Protection Agency Office of Water. (2002). *Water-efficient landscaping: preventing pollution & using resources wisely*.

Vahmani, P., & Ban-Weiss, G. (2016). Climatic consequences of adopting drought-tolerant vegetation over Los Angeles as a response to California drought. *Geophysical Research Letters*, *43*(15). https://doi.org/10.1002/2016GL069658

Wheeler, S. M., Abunnasr, Y., Dialesandro, J., Assaf, E., Agopian, S., & Gamberini, V. C. (2019). Mitigating Urban Heating in Dryland Cities: A Literature Review. *Journal of Planning Literature*. https://doi.org/10.1177/0885412219855779

Xiong, Y., Zhang, J., Xu, X., Yan, Y., Sun, S., & Liu, S. (2020). Strategies for improving the microclimate and thermal comfort of a classical Chinese garden in the hot-summer and cold-winter zone. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2020.109914

Zhang, Z., Lv, Y., & Pan, H. (2013). Cooling and humidifying effect of plant communities in subtropical urban parks. *Urban Forestry and Urban Greening*. https://doi.org/10.1016/j.ufug.2013.03.010

Zhao, L., Lee, X., Smith, R. B., & Oleson, K. (2014). Strong contributions of local background climate to urban heat islands. *Nature*. https://doi.org/10.1038/nature13462

Zoulia, I., Santamouris, M., & Dimoudi, A. (2009). Monitoring the effect of urban green areas on the heat island in Athens. *Environmental Monitoring and Assessment*. https://doi.org/10.1007/s10661-008-0483-3