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Balancing water conservation against heat mitigation: The effect of residential landscaping on thermal comfort in a semi-arid city

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Balancing water conservation against heat mitigation:
The effect of residential landscaping on thermal comfort in a semi-arid city

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ABSTRACT

Semi-arid cities must weigh the cooling effects of urban vegetation against water conservation needs. Many cities have adopted residential outdoor water use reduction policies, resulting in an increase in drought-tolerant yard landscaping. Questions remain about whether drought-tolerant landscaping affects microclimates at the scale at which residents differentially experience heat: within their own yards. I investigated the effects of landscaping choices on temperature and thermal comfort in yards across Sacramento, CA, asking, 1) Are yards landscaped for drought-tolerance hotter than those landscaped with conventional turfgrass? and 2) Does the tree canopy interact with landscaping to affect yard-scale heat? To answer these questions, I sampled drought-tolerant and conventional turfgrass yards that had a range of tree canopy cover, at both yard- and patch-scales. I measured air temperature, relative humidity, incoming solar radiation, and wind speed and direction within the yards, and estimated thermal comfort using the NOAA Heat Index (HI), Universal Thermal Comfort Index (UTCI), and Physiological Equivalent Temperature (PET).

When considered independently from the effects of tree canopy, air temperature anomalies were +0.30°C greater in drought-tolerant yards. Canopy cover within the yard offered a cooling effect across both landscaping types. The effect of high amounts of tree canopy on improving thermal comfort was more dramatic in drought-tolerant yards. In yards with low canopy cover, drought-tolerant landscaped yards exhibited an average UTCI anomaly of +3.32°C, while conventional yards were cooler at just +1.47°C. In yards with high canopy cover, however, drought-tolerant yards had an average UTCI anomaly of -3.69°C and conventional yards had an average anomaly of -2.66°C. Drought-tolerant yards were extremely heterogeneous and included a wide range of landscaping materials. Regardless of canopy cover, drought-tolerant yards with predominantly living landscaping (e.g., succulents, perennial grasses) had cooler air temperatures than those with predominantly non-living landscaping (e.g., hardscape, gravel).

This study demonstrates the importance of quantifying how changes in urban landscaping at the scale of an individual yard can affect the severity of heat experienced by residents. Advancing our understanding of localized heat and vegetation dynamics allows residents and municipal policymakers to make informed decisions at the intersection of water conservation and heat risk.

1. INTRODUCTION

Many cities are adopting nature-based solutions to adapt to the challenging intersection of water scarcity and extreme heat and to provide resilience against future climate extremes. Unfortunately, some of these solutions create trade-offs among consequent ecosystem services and disservices. Drought-tolerant landscaping has been incentivized by municipalities and adopted by homeowners as a water conservation strategy (Grant et al., 2020; Hilaire et al., 2008; Sovocool et al., 2006). Unfortunately, changing from traditional turfgrass to drought-tolerant landscaping may also create an ecosystem disservice in the form of increased localized microclimatic heat (Chow & Brazel, 2012; Vahmani & Ban-Weiss, 2016). The microclimate impacts of drought-tolerant landscaping have been modeled at neighborhood and municipal scales. However, there is a need to empirically measure the effect that drought-tolerant vegetation has at fine scales, such as individual residential yards. There is also a need to better understand how drought-tolerant landscaping may interact with other landscape features, such as the tree canopy, to influence heat. In this study, I quantify the effect of drought-tolerant landscaping, in combination with tree canopy cover, on yard-level air temperature and thermal comfort in the semi-arid city of Sacramento, CA.

1.1 Intertwining Challenges of Extreme Heat, Drought, and Water Scarcity

Extreme heat is the greatest natural disaster risk facing urban residents in the United States (Borden & Cutter, 2008). Heat in urban areas, commonly described as the urban heat island (UHI), is often exacerbated relative to surrounding rural environments due primarily to the replacement of vegetation with impervious surfaces. The largely built environment in cities alters near-surface energy budgets by increasing solar energy absorption, trapping heat in street canyons, and reducing evapotranspiration (Oke, 1982). High urban temperatures have serious implications for human morbidity and mortality (Wong et al., 2013), energy use, and associated greenhouse gas emissions (Santamouris, 2014). While urban heat islands are a distinct phenomenon from climate change induced warming, current urban heat extremes will continue to be amplified by climate change. Extreme high temperatures – where the daily maximum temperature exceeds the 99th percentile of historical heat records – are increasingly occurring in cities worldwide due to climate change (Lettenmaier et al., 2014). Climate change will continue to amplify urban heat globally, with daily averages predicted to increase by 1.5°C in most urban areas by 2052 (Masson-Delmotte et al., 2018). An increased frequency and severity of heat waves is also predicted with global climate change (Meehl & Tebaldi, 2004).

In addition to creating immediate health risks, extreme heat also exacerbates another climate challenge – drought and consequent water scarcity. Extreme drought is an increasingly common occurrence in California, as in many semi-arid regions of the world (Uejio et al., 2011). Climate models predict an increase in the co-occurrence of hot and dry conditions that result in severe droughts with anthropogenic climate change (Ault et al., 2014; Cook et al., 2015; Diffenbaugh et al., 2015). In urban areas, drought and water scarcity are codetermined by a mix of climatic and hydrological factors, as well as human activities and demand (Zhang et al., 2019).

The UHI framework focuses on the difference in temperature between the coarse scale land uses of urban compared to rural. Cities, however, are characteristically heterogeneous in land cover and land use (Cadenasso et al., 2007). This heterogeneity can result in differences in localized temperatures within the city that may be as dramatic as those differences at the urban-rural interface (Buyantuyev & Wu, 2009, 2010; G. Huang et al., 2011; Jenerette et al., 2016). Therefore, a shift in conceptualization from an urban heat island to urban heat archipelagos is needed (Buyantuyev & Wu, 2010). The heat archipelagos framework implicitly acknowledges that not all urban residents experience heat burdens equally, which allows researchers to interrogate the causes of distributional inequity in heat burden. Hoffman et al. (2020) found that historical redlining practices (racial discrimination in zoning and mortgage lending) explained increased temperatures in redlined areas relative to adjacent non-redlined areas in 94% of studied US cities. Considering this within-city heterogeneity in heat exposure, in combination with predicted increased incidence of extreme heat and drought with climate change, it is important for urban policymakers, planners, and residents to continue to develop and implement strategies to conserve water and mitigate urban heat.

1.2 Trees and Turfgrass Frequently Offer Effective Heat Mitigation

One of the most extensively studied approaches to mitigating and adapting to urban heat and improving heat-related health outcomes is the expansion of urban vegetation, particularly the tree canopy (Winbourne et al., 2020; Wolf et al., 2020). A healthy urban tree canopy can provide a suite of ecosystem services including aesthetics (Hayden et al., 2015), biodiversity (Alvey, 2006) and increased habitat availability (Le Roux et al., 2018), atmospheric carbon storage (Briber et al., 2015), air quality improvement (McPherson et al., 2016), stormwater runoff reduction (McPherson et al., 2011), and reduced pavement stress/replacement costs (McPherson & Muchnick, 2005). In addition to these benefits, trees cool air temperatures by blocking incoming solar radiation at the canopy layer (creating shade) as well as cooling the air through transpiration. Shade from trees can cool air temperatures over asphalt by up to 20°C (Bowler et al., 2010; Rahman et al., 2020), and transpiration has been shown to cool air temperatures from 1°- 8°C (Georgi & Zafiriadis, 2006; Rahman et al., 2019). Differences in cooling effects over vegetated land covers are generally less extreme than those over impervious surfaces due to their different surface thermal properties. For example, Speak et al. (2020) found that the tree canopy produced a mean temperature reduction of 16.4°C over asphalt, compared to just 8.5°C over turfgrass. Temperature effects of the tree canopy are more variable at night, and may actually result in increased air temperatures due to trapped long-wave radiation beneath the canopy (Gillner et al., 2015; L. Huang et al., 2008; Ziter et al., 2019).

Still the effect of tree canopy cover on urban heat is not easily generalized, and cooling efficiency depends on the morphological traits of the trees themselves and feedbacks between tree physiology and the built environment (Winbourne et al. 2020). The potential for the urban tree canopy to cool the air is also dependent on the amount of applied irrigation (Guhathakurta & Gober, 2010) and more research is needed to understand the differences in transpiration-based cooling among tree species with varied water-use efficiencies (Litvak et al., 2017). This relationship between water-use efficiency and air temperature is particularly important to consider amidst the continued push for drought-tolerant landscaping and outdoor water conservation which may limit water available to urban trees.

Tree canopies have been identified as important mitigation strategies for cooling neighborhoods and cities (e.g., Bowler et al. 2010). Parks and grassy residential lawns have also been found to cool urban neighborhoods, albeit at lower magnitudes (Imran et al., 2019; Lee et al., 2016; Wang et al., 2016). The cooling effect of turfgrass varies with morphological characteristics of the grassy area, the structure and configuration of the urban fabric, and irrigation patterns. Spronken-Smith and Oke (1998) found that irrigated turfgrass in a park had less than half the diurnal fluctuation of surface temperature as a park with dry, non-irrigated turfgrass. On its own irrigated turfgrass does not always create very large cooling effects, but it operates synergistically with tree shade to create greater magnitudes of cooling (Amani-Beni et al., 2018; Declet-Barreto et al., 2013; Shashua-Bar et al., 2009). The cooling capacity of grassy patches is influenced by their size with patches larger than 10 ha creating the greatest cooling effect (Aram et al., 2019). Smaller fragmented patches of turfgrass may also effectively cool landscapes (F. Kong et al., 2014), and Ossola et al. (2021) found that turfgrass at the parcel scale cooled daytime air temperatures by up to 6°C.

1.3 Models Suggest Drought-Tolerant Landscaping May Create Unintentional Microclimate Impacts

One key management strategy for cities combating drought is strategic water demand reduction (Buurman et al., 2017), including voluntary or mandated conservation as well as financial incentives for private investment in water conserving landscaping (Buurman et al., 2017; Grant et al., 2020). In many urban areas, detached single-family homes use significantly more water than multi-family homes or apartments (Ghavidelfar et al., 2018), likely due to higher demands for outdoor water use that is particularly exacerbated in summer months (Domene & Saurí, 2006). As a result, outdoor water use reduction policies, incentives, and rebate programs often specifically target single-family homeowners (Mitchell et al., 2017). Studies conducted in nine US cities suggested that about half of residential water use in single family homes is used to water outdoor lawns (Mini et al. 2014; DeOreo 2011). Consequently, recommendations and incentives for drought-tolerant landscaping have become a common approach to reducing residential outdoor water use in semi-arid cities (Grant et al., 2020; Mitchell et al., 2017).

Despite the positive intentions, the transformation of conventional turfgrass lawns to drought-tolerant landscaping may be unintentionally increasing daytime temperatures in cities by decreasing evapotranspiration and altering surface albedo (Ruddell & Dixon, 2014; Vahmani & Ban-Weiss, 2016). Studies using microclimate modeling techniques to assess the impact of drought-tolerant vegetation on urban air temperatures have generally predicted increased average daytime temperatures. For example, Vahmani and Ban-Weiss (2016) estimated that the conversion of all turfgrass lawns in Los Angeles, CA to drought-tolerant landscaping would create an average warming of 0.7°C over the entire metropolitan area, with some areas with particularly low sea breeze levels warming by up to 1.9°C. Chow and Brazel (2012) demonstrated that the particular land cover conversion in urban yards – e.g. bare soil to xeriscape vs. turfgrass to xeriscape – strongly influences the microclimatic effects of increased xeriscaping. In Tempe, AZ, a region with residential parcels characterized by dominantly mesic land cover with turfgrass and shade trees, Chow and Brazel predicted that a scenario that changed 50% of the land cover to xeriscaping would increase local daytime temperatures by 0.8°C. The same xeriscaping scenario modeled in West Phoenix, a residential area characterized primarily by bare soil or gravel land cover, actually reduced temperatures by 0.7°C.

These two modeling studies also found an effect of landscaping change on nighttime temperatures. Vahmani and Ban-Weiss (2016) predicted a 3.2°C nighttime cooling effect of high intensity xeriscaping across the LA region, conjecturing that most of the cooling was due to reduced subsurface heat transfer in dry, non-irrigated soil. Chow and Brazel (2012) found nighttime temperatures increased by 1°C in the mesic-to-xeric conversion scenario in Tempe, while temperatures decreased by 0.75°C in the West Phoenix scenario that converted bare soil or gravel to xeric landscaping.

It is important to note that most current research on drought-tolerant vegetation and climate interactions in cities relies on urban microclimate models that use broad assumptions about land surface cover and irrigation patterns. While these models have the benefit of greater controllability, they often rely on coarse data and indices such as NDVI (Declet-Barreto et al., 2016) that may not accurately represent land cover heterogeneity in residential yards. For example, Chow and Brazel (2012) assumed that xeriscaped yards contained half “bare soil/ground” and half shade from two species of mature xeric shade trees. This xeriscaping scenario may reflect common landscaping patterns in Arizona cities, but it is unlikely that this model can be extended to capture the heterogeneity of land covers and plant functional types within all drought-tolerant yards (Pincetl et al., 2019). Oversimplified xeriscaping scenarios may result in less precise estimates of site-level evapotranspiration rates (Richards et al., 2020) and subsequent microclimate predictions. Individual land covers within a yard have different radiative and thermal properties that strongly influence surface temperatures (Carvalho et al., 2021), and thus it is important that we consider the complex suite of land covers represented in drought-tolerant yards to better understand their heat dynamics.

Models of drought-tolerant vegetation and climate dynamics also rely on assumptions about irrigation reduction that may not reflect real onsite watering patterns. For example, Vahmani and Ban-Weiss (2016) assumed that the switch to drought-tolerant landscaping was coupled with a complete stop of all yard irrigation, which is an extreme and unrealistic assumption. Multiple studies have demonstrated that the shift to drought-tolerant vegetation creates reductions in yard-level water demand (Brelsford & Abbott, 2017; Sovocool et al., 2006), but water use in residential yards is ultimately controlled by human behavior. Models that do not account for behavioral variation in watering patterns likely do not accurately represent the difference in water use and associated evapotranspiration across landscaping types. Additionally, the interaction of the tree canopy and yard-level ground vegetation can further complicate water demand. Rasmussen et al. (2021) found that parcels with a higher ratio of vegetation cover to parcel size tended toward less water consumption, most likely due to shade-driven reductions in surface evapotranspiration.

1.4 Capturing the Complex Human Experience of Heat at the Yard-Scale with Thermal Indices

In order to successfully mitigate extreme heat in cities, we need to understand the drivers and magnitude of differential residential exposure to heat. Thermal comfort indices allow us to move beyond simply considering differences in air temperature, and better understand how nature-based heat and drought adaptation strategies interact with microclimate to affect human comfort. Thermal comfort indices express the complex physiological effects of heterogeneous meteorological conditions – driven in part by changing urban landscapes – on the individual human body. The NOAA Heat Index (Rothfusz, 1990; Steadman, 1979) is one of the simplest indices and it combines the effects of air temperature and humidity on the human body. This index (hereafter “HI”) is used by many of the National Weather Service’s Weather Forecast Offices (Hawkins et al., 2017; National Weather Service, 2021) for the issuance of extreme heat warnings and advisories. More complex biometeorological indices incorporate wind speed and solar radiation or radiant temperature, and often rely on human physiological heat budget models (Höppe, 1993). These budgets consider behavioral characteristics such as physical activity and the level and amount of clothing worn in a given season. Originally these indices were developed to assess employee comfort in indoor workplaces (Fabbri, 2015), but they have evolved over time and different indices have been found to be most suitable for different settings (Ghani et al., 2021). In outdoor urban environments, two of the most commonly used thermal comfort indices include Physiological Equivalent Temperature (PET; Mayer & Höppe, 1987) and the Universal Thermal Comfort Index (UTCI; Jendritzky, 2000).

The UTCI and PET indices are both thermo-physiological indices that rely on air temperature, relative humidity, wind speed, and mean radiant temperature. The output of both indices is an equivalent temperature in degrees Celsius (°C). The UTCI is based on a multi-node thermoregulatory model that has the highest level of physiological detail of all thermal comfort indices (Staiger et al., 2019). The multi-node model includes both “passive” and “active” systems of human thermoregulation, considering physiological functions such as vasoconstriction and vasodilation of blood flow, shivering thermogenesis, and sweat (Fiala et al., 1999, 2001) and assesses thermal comfort for an “average” human that weighs 73.4 kg, with body fat content of 14%. The PET model relies on the Munich Energy-balance Model for Individuals (MEMI) which also considers the maintenance of skin and core temperatures in a given set of meteorological conditions through thermoregulatory processes like blood flow and sweat. Unlike UTCI, PET allows users to input individual human characteristics like age, gender, specific activity levels, and amount of clothing worn (Höppe 1993). The PET model often predicts more extreme thermal sensation than UTCI, possibly because it includes these dynamic human traits (Pantavou et al., 2018).

The PET and UTCI indices are both strongly predicted by mean radiant temperature and the duration of direct sun exposure (Acero & Herranz-Pascual, 2015; Ketterer & Matzarakis, 2016; Taleghani et al., 2014). As a result, they provide useful metrics for investigating the efficacy of strategies intending to block sun exposure, such as the presence of a tree canopy, to reduce urban heat. Numerous studies have shown that the tree canopy in dense urban areas successfully diffuses incoming solar radiation, reducing human-level radiant temperatures and improving thermal comfort (Colter et al., 2019; L. Kong et al., 2017; Rahman et al., 2020). While turfgrass and surface level vegetation has also been found to improve thermal comfort (Shashua-Bar et al., 2011; Sodoudi et al., 2018), the magnitude is less than that due to the tree canopy, possibly signaling that evapotranspiration and heat storage processes at the surface matter less than incoming solar radiation for thermal comfort index outcomes. In this study, HI, UTCI, and PET are all included as measures of thermal comfort due to their widespread use and familiarity in the urban climatological community, as well as their suitability for use in an outdoor urban environment (Honjo, 2009; Staiger et al., 2019).

1.5 Project Goals: Moving Beyond Turf

Beyond traditional turfgrass cover and the tree canopy, much is unknown about how land cover heterogeneity within cities and the shift towards more drought-tolerant vegetation affects variation of temperature at fine scales, particularly at the scale at which urban residents differentially experience heat – within their own yards. Additionally, there is a need to investigate how drought-tolerant landscaping may interact with the tree canopy to influence air temperatures. Since microclimate is often strongly dependent on site surface characteristics (Arnfield, 2003; Middel et al., 2012; Nichol, 1996), it is imperative for residents, landscape designers and architects, and governments to understand the role that fine-scale land cover plays in localized heat burden.

This project aims to address whether drought-tolerant landscapes affect microclimates at the individual yard scale. I quantified the effects of landscaping choices on air temperature and thermal comfort in front yards across Sacramento, CA, a semi-arid city actively participating in both drought and heat mitigation policies and practices. I asked, 1) Are yards that have been landscaped for drought-tolerance hotter than those with conventional turfgrass? and 2) Does the tree canopy at the neighborhood or yard scale interact with landscaping to affect heat? To answer these questions, I measured air temperature, relative humidity, incoming solar radiation, and wind speed and direction in drought-tolerant and conventional turfgrass residential yards nested within neighborhoods containing a range of tree canopy cover. Advancing our understanding of lands cover driven heat archipelagos within cities allows municipal policymakers to create informed legislation about outdoor water use, water conservation, and landscape-related zoning ordinances. The results of this project will also help individual residents make informed landscaping decisions at the intersection of water conservation and heat risks.

2. METHODS

2.1 Site Description

The city of Sacramento, CA, USA has an estimated population of 513,624 (Census, 2019) and total area of 258.41 km^2 for a population density of 2,030.13 people/ km^2. It is located in the Central Valley and has a drought-prone Mediterranean climate (Koppen classification Csa) with hot, dry summers and cool, wet winters. Since 1950, annual mean rainfall is 45.2cm, mean minimum temperature in January is -2.2°C, and mean maximum temperature in July is 40.6°C (National Weather Service 2020). Single family homes represent 65.4% of all housing stock in the city (BAE 2016), and approximately 19.1% of Sacramento's land is covered by a tree canopy (Davey 2018).

California has ongoing statewide efforts to develop and expand water conservation strategies according to AB 1668 and SB 606. The City of Sacramento has several local initiatives to encourage reduction in outdoor residential water use. The Sacramento Department of Utilities offers rebates for turfgrass removal, drip irrigation system upgrades, and smart sprinkler controllers (City of Sacramento, 2021a). There are also a suite of educational efforts from the University of California, Davis Arboretum on drought-tolerant plant species selection

(UC Davis Arboretum, 2021), and from the Sacramento Tree Foundation on the maintenance of canopy trees in low-water use and drought-tolerant landscaped yards (Sacramento Tree Foundation, 2021). The City is also in the process of installing residential water meters and instituting metered water rates in lieu of flat rates to incentivize residential water conservation (City of Sacramento, 2021b).

2.2 Experimental Design

A survey conducted in 2017 classified all front yards in the City of Sacramento by landscaping type. I selected a subset of these yards that were classified as either “fully conventional”, meaning that the landscaping consisted of turfgrass with or without shade trees, or “fully drought-tolerant’, meaning the yards had >66% drought-tolerant landscaping. To stratify the yards by the amount of tree canopy in the area surrounding each yard, I used a land cover layer developed in the Cadenasso lab called HERCULES (High Ecological Resolution Classification for Urban Landscapes and Environmental Systems). HERCULES is a patch-based approach to characterizing heterogeneity in urban land cover based on the relative amounts of bare soil, pavement, buildings, herbaceous vegetation, and woody vegetation (Cadenasso et al., 2007; Zhou et al., 2014).

While individual HERCULES patches are determined by all six land covers, the land covers vary independently of each other which allowed me to select patches according to the amount of tree canopy, regardless of the prevalence of other land cover types (see Cadenasso et al., 2007; Zhou et al., 2014 for more details). HERCULES was applied to 2016 NAIP (National Agriculture Imagery Program) aerial images for Sacramento. Patches were included in the sampling process if they were within the interior 90% of patch size distribution and contained at least 5 drought-tolerant yards identified in the initial 2017 survey. HERCULES patches that met these criteria were then identified as containing <10%, 10-20%, 20-30%, 30-40%, or >40%

canopy cover. From this pool, I randomly selected six HERCULES patches in each canopy cover category, for a total of 30 initial patches (Fig 1).

I mailed an access request form with return postage to the residents of 2000 randomly selected homes (1000 conventional yards, 1000 drought-tolerant) within the 30 HERCULES patches, requesting one-time access to the front yard. Permission was granted by 491 homeowners. Due to possible changes in residential landscaping since the initial yard classification was completed in 2017, I reviewed each positive response on Google Earth and removed any yards if recent imagery revealed that the land cover was no longer consistent with the conventional or drought-tolerant categories. Yards were also removed if the yard area was less than 30 m^2 to ensure adequate spacing for multiple meteorological measurements within the yard. There was an exceptionally high response rate in two patches in the highest canopy category, so I randomly selected a subset of positive respondents for measurement in those patches. In addition to the mail-based yard enrollment, another 6 drought-tolerant yards were sourced through the Sacramento Perennial Plant Club (scattered across 4 new HERCULES patches). Due to low/no response in patches with <10% tree canopy, additional outreach was conducted to yards in 5 additional HERCULES patches in this category. The final sample for measurement included 149 drought-tolerant and 105 conventional yards, for a total of 254 yards distributed across the 5 canopy cover classes in 29 HERCULES patches (Table 1).

2.3 Yard Data Collection

I collected data on clear-sky afternoons from 1:00 – 6:00 PM PDT during the summer months of July – September 2020. Although a narrower summer timeframe would have been preferable to avoid shifts in background weather conditions and angle of solar incidence, I had to make considerable adjustments to data collection due to safety concerns from the COVID-19 pandemic. Additional delays in data collection occurred in late August due to smoke from summer wildfires which presented a health risk and may have potentially impacted meteorological readings.

Within each front yard, I classified all surface land cover (Table 2) using a Braun-Blanquet-like land cover assessment (adaptation from Braun-Blanquet, 1932), with each land cover type being classified as 0-1%, 1-5%, 6-25%, 26-50%, 51-75%, 75-95%, or 96-100% of the yard's total land surface cover. I performed a Braun-Blanquet assessment for the canopy layer over the yard as well, recording the proportion of the canopy layer contributed by broadleaf and conifererous trees and palms. I estimated yard-scale canopy cover as the sum of midpoints of the Braun-Blanquet canopy cover ranges for each tree type (broadleaf, conifer, palm). To better understand differences among drought-tolerant yards, I calculated a ratio of living:nonliving covers for each yard using the midpoints from the ground-level Braun-Blanquet survey.

I collected meteorological measurements with a portable, custom-built weather station (see Supplementary Fig S1), including sensors for air temperature, relative humidity, wind speed and direction, and solar radiation (specifications in Table 3). To ensure the averaged yard-level temperature data was representative of the whole yard, I selected multiple locations for measurement within each yard. For yards under 45 m^2, I set up the station in 3 locations within the yard (Fig 2). For yards 45 m^2 or larger, I added 1 additional location for each 15 m^2 up to a maximum of 9 total locations for any single yard. Sample location within a yard had to occasionally be adjusted in yards that were irregularly shaped or were otherwise irregular due to resident property or landscaping.

The total time spent on each yard was approximately 10-15 minutes, with the collection period for meteorological data averaging 7.2 minutes. To minimize variation in background conditions, no yard was sampled for longer than 30 minutes. At each individual location within the yard, I positioned the station 1.8 m above the land surface and collected meteorological data for one minute. I averaged all meteorological measurements to the level of the yard.

On three separate days during the field season, the metal attachment securing the pyranometer to the meteorological station separated, preventing the pyranometer from leveling and rendering the radiation data unusable for the yards visited on those days (n=30 yards). As a result, I conducted all analyses which required radiation data only on the 224 yards with complete radiation data.

2.4 Quantifying Heat and Thermal Comfort

I calculated the NOAA Heat Index (HI) for each yard using the Rothfusz polynomial regression which has associated error ± 1.3° F (eq. 1; NOAA 2014). This regression requires temperature to be input in degrees Fahrenheit, but final HI temperatures were converted back to Celsius.

Eq 1) $HI = -42.379 + 2.04901523*T + 10.14333127*RH - .22475541*T*RH - .00683783*T^2 - .05481717*RH^2 + .00122874*T^2*RH + .00085282*T*RH^2 - .00000199*T^2*RH^2$

where T= air temperature °F and RH = % relative humidity, both averaged over sample period within a yard

To assess the effects of the tree canopy on thermal comfort, I estimated UTCI and PET using the RayMan Pro software (Krüger et al., 2014; Matzarakis et al., 2006). In addition to air temperature, wind speed, and relative humidity, these indices require mean radiant temperature (Gagge et al., 1972; Jendritzky et al., 2012; Mayer & Höppe, 1987), or a combination of radiation data and building morphology or sky view factor (SVF) data (Matzarakis et al., 2006). No building morphology or SVF data for our 254 yards were available, so I estimated mean radiant temperature (T_{mrt}) in Rayman Pro using only air temperature and incoming solar radiation. To estimate T_{mrt}, PET, and UTCI using the RayMan Pro model, I input the measured yard air temperature, relative humidity, incoming solar radiation, wind speed, geographical location, and date and time. The Rayman Pro model estimates T_{mrt} by dividing the three-dimensional site into hemispheres above and below human height (approximately 1.1m; Matzarakis et al., 2010). In addition to the incoming solar radiation directly input to the model from my pyranometer data, long-wave radiation from below human-height was estimated by the model using the Stefan-Boltzmann law. The Rayman Pro model is closed-source, and therefore no more specific detail on the model's use and calculation of radiation fluxes is provided beyond that detailed in Gál and Kántor (2020). Default model settings were kept for the amount of clothing worn by a model human, the activity level, height, weight, age, and sex. For a list of meteorological variables input to the RayMan model, see Supplementary Table 1.

For comparison of measurements taken at different times and days throughout the summer, I gathered data from two permanent reference weather stations. Air temperature, wind speed, and relative humidity data were collected from the Sacramento International Airport (KSMF) which had the highest temporal resolution of data of the three Sacramento airports. KSMF is located at 38.70071°N, 121.59479°W, at elevation of 6.0 m, and approximately 16.5 km northwest of the centroid of all sampled yards. Global incoming solar radiation data is not measured at the KSMF station, so these data were acquired separately from the California Irrigation Management Information System (CIMIS) station #155 BRYTE. CIMIS #155 is located at 38º35'57°N, 121º32'25°W, at an elevation of 12.2 m, and approximately 7.0 km northwest of the centroid of all sampled yards. The CIMIS #155 site was approximately 11.2 km distance southeast from the KSMF station, which is a 0.1 decimal degrees difference in latitude. To estimate background conditions for the study, I averaged data from KSMF and CIMIS over the same dates and time frames as when measurements were taken in the yards. Reference HI estimates were calculated using Eq. 1, and the reference data was also input to the RayMan Pro model to calculate a reference UTCI and PET, following the methods for yard-level analyses.

All temperature and thermal comfort data are reported as anomalies, comparing the individual yards to the data from the two reference stations. Air temperature, HI, UTCI, and PET were converted from raw temperature equivalents to temperature anomalies using eq. 2. A positive anomaly indicates that a yard was hotter than the reference temperature, and a negative anomaly indicates a yard was cooler than the reference temperature.

Eq. 2) $T_{anom,t} = T_{yard,t} - T_{ref,t}$

where $T_{,t}$ = temperature equivalent °C (T) averaged over time (t) within a yard

2.6 Statistical Analysis

I used linear mixed models, LMMs, (using the "lmer" function in R package "lme4" version 1.1-23; Bates et al. 2015), to test the effects of yard type, and HERCULES patch and yard scale canopy cover, and the ratio of living:nonliving land covers within drought-tolerant yards on air temperature, HI, PET, and UTCI. All statistical analyses were conducted in R Statistical Programming Software (R Core Team 2020). I derived p-values using the "lmerTest" package (Kuznetsova et al. 2017) and created graphs and confidence intervals for our regression models using the "effects" package (Fox & Weisberg 2018). All models used HERCULES patch ID as a random effect to account for spatial autocorrelation in our study design. Fixed effects terms for all models included: yard type ("conventional" or "drought-tolerant"), day of year to account for temporal autocorrelation due to study delays, yard area (m^2) to account for variation in yard size, Braun-Blanquet described yard-scale canopy (%), and HERCULES patch-scale canopy (%).

To determine whether the tree canopy exerted a stronger effect on microclimate in drought-tolerant yards compared to conventional yards, I evaluated the interaction between yard type and tree canopy cover on localized heat. No significant interaction was found between yard type and HERCULES patch-scale tree canopy for any heat outcomes, Therefore, none of the final models included an interaction between HERCULES patch-scale canopy and yard type. Interactions between yard type and yard-scale canopy cover were also tested and model comparison (Akaike's information criterion) revealed no significant differences between interaction and non-interaction models for air temperature anomaly and HI. The final models for these two outcomes did not include interactions. There was a significant effect of the interaction between yard type and yard-scale canopy on PET and UTCI, however, so the interaction term is included in the final models for these outcomes.

3. RESULTS

All sampled yards were similar in size, with an average yard size of 72 m^2 (Table 4). Approximately 85% of yards included at least one tree within the yard boundaries, and some of the most commonly found trees within yards included *Lagerstroemia indica* (Crape myrtle), *Acer palmatum* (Japanese maple), *Platanus x acerifolia* (London Planetree), and various kinds of palms, such as *Washingtonia robusta* (Mexican fan palm). The most common irrigation method in conventional yards was overhead spray sprinkler systems (68.6%), while most drought-tolerant yards had drip irrigation systems (69.8%; Table 4). In the three instances where a yard was actively being spray irrigated upon arrival, a revisit was scheduled for a time when the irrigation system was turned off. We were not able to survey homeowners to get more information about irrigation timing, patterns, or volumetric water use.

3.1 Effects of Yard Type Without Considering Tree Canopy

Drought-tolerant yards had warmer air temperature anomalies on average compared to conventional yards. Air temperature anomalies in conventional yards ranged from -2.2°C to 1.58°C with a mean anomaly of -0.214°C, indicating that on average conventional yards were cooler than the reference station. In drought-tolerant yards, anomalies ranged more widely, from -3.23°C to 2.16°C with a mean anomaly of 0.33°C, indicating that drought-tolerant yards were warmer on average than the reference station. Regardless of tree canopy, air temperatures in drought-tolerant yards were estimated by the model to be 0.34°C warmer ($p = 0.027$) than those in conventional yards (Fig 3A). Heat Index values showed an opposite pattern, with conventional yards exhibiting 0.91°C warmer HI anomalies on average compared to drought-tolerant yards (Fig 3B, $p=0.023$).

3.2 Tree Canopy at HERCULES Patch and Yard Scales Affect Microclimate

The tree canopy at the HERCULES patch-scale did not significantly affect the air temperature or HI anomalies within yards. It did however have a significant effect on PET and UTCI ($p=0.025$ and $p=0.011$). Yards in HERCULES patches with <5% tree canopy had an average UTCI anomaly of 3.08°C and PET anomaly of 5.60°C, while yards in patches with >50% tree canopy had an average UTCI anomaly of -5.33°C and PET value of -8.16°C, indicating a large cooling effect due to coarser scale canopy differences across the city.

At the yard-scale, tree canopy cooled air temperature anomalies ($p=0.011$) and warmed HI anomalies ($p=0.008$) in both yard types (Fig 4A, B). The difference in air temperature anomaly between the least and most canopied yards was approximately 0.5°C. Yard type and amount of yard-scale tree canopy did not significantly interact to influence air temperature or HI anomalies. This interaction was significant however for the UTCI and PET models ($p=0.007$, $p=0.028$), suggesting that the tree canopy had a stronger effect in drought-tolerant yards. In the least shady yards (<5% yard-scale canopy), yards with drought-tolerant landscaping had an average UTCI anomaly of 3.32°C, while the average anomaly in conventionally landscaped yards was just 1.47°C. At the highest levels of tree canopy (>50% yard-scale canopy), drought-tolerant yards had an average UTCI anomaly of -3.69°C and conventional yards had an average anomaly of -2.66°C. The significant interaction (Fig 5) may indicate that at low amounts of tree canopy within the yard, drought-tolerant yards had higher equivalent temperatures than conventional yards, but at very high amounts of tree canopy that pattern reversed, and drought-tolerant yards became cooler than conventional yards

3.3 Drought-Tolerant Yards Are Cooler When Landscaped with Majority Living Materials

Conventional yards, by definition, were dominated by turfgrass (Fig 6A, C), but drought-tolerant yards contained a suite of heterogeneous land covers. There was a mix of living and nonliving land covers found with varying frequency (Table 5) and abundance in drought-tolerant yards. Some of the most common land covers in drought-tolerant yards included light and dark color wood mulch, light and dark color gravel, dark color impervious hardscape, bare soil, and succulents and cacti.

The ratio of living:nonliving land covers within drought-tolerant yards significantly affected air temperatures with a greater proportion of living material resulting in cooler air temperature anomalies ($p=0.036$; Fig 7A). Air temperature anomalies in drought-tolerant yards with no living land cover were 0.80°C on average, while yards with the greatest proportion of living materials had a temperature anomaly of -0.63°C on average. The UTCI was the only thermal comfort index statistically significantly affected by the living:nonliving ratio ($p=0.040$; Fig 7D), despite all three thermal comfort indices indicating a slight increase in temperature anomaly with increasing amounts of living land cover. In yards with a living:nonliving ratio of less than 1.0, the average UTCI anomaly was -0.95°C, while yards with a ratio of greater than 1.0 had an average UTCI anomaly of 0.94°C. Neither HI nor PET showed a statistically significant relationship with the ratio ($p=0.324$ and 0.10 respectively; Fig 7B, C).

4. DISCUSSION

Despite the challenges of working in an extremely heterogeneous environment, I found that landscaping choices influence the microclimate in residential front yards during the summer in a semi-arid city. As hypothesized, drought-tolerant yards created warmer yard-level air temperatures when considered separate from tree canopy over the yard. Yard type interacted with yard-scale tree canopy to create a more nuanced story for the PET and UTCI indices, however. For these two indices, the high amounts of tree canopy within the yard resulted in greater cooling in drought-tolerant yards compared to conventional yards. In addition, drought-tolerant yards with a greater proportion of living land covers had cooler temperatures than those dominated by hardscape, rock, and mulch, revealing that decision-making about individual land covers significantly influences the microclimate and comfort of urban residents.

It is challenging to find clear and significant differences in microclimate within a system containing tremendous heterogeneity of materials and their spatial arrangement. When working in real yards, outside of a tightly controlled modeling framework, there is a mix of land covers and tree canopy affecting climate at multiple scales, unknown information about residential irrigation practices, and other variables such as building density and impervious surface area, all of which create noise in microclimate measurements. These challenges and limitations associated with biometeorological sampling in residential yards are more fully discussed at the end of this section.

4.1 Tree Canopy at Multiple Scales Cools Yards

The presence of a tree canopy at both yard- and HERCULES patch-scales resulted in improved thermal comfort. This finding is well-aligned with decades of literature exploring canopy cooling in urban areas (see Winbourne et al., 2020 and Bowler et al., 2010 for reviews). I found that the amount of tree canopy within a HERCULES patch did not significantly affect air temperature or HI anomalies but as patch-scale tree canopy increased, the PET and UTCI anomalies became significantly cooler. The cooling effect of the tree canopy at coarser spatial scales is influenced by the size and spatial configuration of the trees, the arrangement and orientation of surrounding buildings, as well as the prevailing wind patterns in the area (Xiao et al., 2018), all of which were beyond the scope of this study. Despite these complicated weather dynamics and the landscape heterogeneity contained in coarser scales, UTCI and PET were still able to detect the influence of patch-scale tree canopy on yard-scale temperatures.

At the yard-scale, air temperature, PET, and UTCI anomalies all demonstrated cooling effects of the tree canopy, with greater cooling estimated by PET and UTCI. This is likely due to the high sensitivity of these two indices to radiation (Figs S4, S5) which was blocked by the tree canopy. The HI showed an opposite pattern – growing warmer with increasing amounts of tree canopy. This result is likely because HI is a function of air temperature and relative humidity, and relative humidity has been shown to be higher underneath dense tree canopies due to evapotranspiration (Z. Huang et al., 2020).

The interaction between yard type and yard-scale tree canopy on UTCI and PET suggests that drought-tolerant yards that are extremely well-shaded may actually be cooler than well-shaded conventional yards. This aligns with Chow and Brazel's (2012) finding that xeriscaping in combination with shade trees in particularly dry areas might lower temperatures rather than exacerbate heat. Understanding why UTCI and PET displayed this interaction, while air temperature and HI did not, may offer further insights as to the driving mechanisms of heat disparity across landscaping types. As noted before, UTCI and PET are the two indices which capture the strong effect of radiative blocking by the tree canopy in the afternoon. This may suggest that heat related to incoming solar radiation influences the difference seen between yard types as much as shifts in ground-level vegetation. The interaction between yard-scale tree canopy and yard type may also reflect some key differences in plant physiology and transpiration among different kinds of vegetated landscaping. Drought-tolerant yards include many Crassulacean Acid Metabolism (CAM) plants, in contrast to the shrubbery and turfgrass (C3 or C4 plants) that dominate conventional yards. Drought-tolerant CAM plants typically keep their stomates closed during the day, and often utilize morphological features, such as light-colored foliage, hair leaf surfaces, sunken stomata, and thickened, waxy leaves, to reduce transpiration rates. Regardless of the amount of tree canopy, there is essentially no transpirational cooling from the CAM plants in daytime. The physical effect of reduced radiation load under high amounts of tree canopy would then lower the localized air temperatures near CAM plants. For C3 and C4 plants, stomatal control is strongly influenced by radiation. It is possible that when the tree canopy reduces radiation levels sufficiently to reduce C3 and C4 plants' stomatal conductance, it results in reduced transpirational cooling and therefore results in an increase in heat despite the tree canopy shade. In essence, while the tree canopy may not shift the transpiration of CAM plants in drought-tolerant yards, it may reduce transpiration from grass surfaces in conventional yards, resulting in warmer highly shaded conventional yards.

Further exploration of in situ plant physiology could lend tremendous insights to the varied cooling efficiency of different photosynthetic plant types under a tree canopy. Regardless of the specific mechanisms driving the interactive effect between yard type and yard-scale canopy, this is an important finding because it suggests that drought-tolerant yards may not create the unintentional warming effect modeled in the literature if they are appropriately coupled with high amounts of tree canopy.

4.2 Drought-Tolerant Yards Decrease Thermal Comfort but Land Cover Variation May Hold the Key to Keeping Cool

Yard type significantly affects the heat that residents experience within their yards. Considering air temperature alone, the difference found between yard types is relatively small, but when the UTCI and PET indices are considered, drought-tolerant yards are 2-3°C warmer on average than conventional yards. Vahmani and Ban Weiss (2016) and Chow and Brazel (2012) also found relatively small increases in air temperature from drought-tolerant landscaping (<1°C). By including thermal comfort indices, I inferred that the full suite of biometeorological impacts of yard type may result in greater differences in thermal comfort than that captured by air temperature alone.

Variation in thermal comfort among drought-tolerant yards was larger than variation among conventional yards – indicating that the category “drought-tolerant landscaping”, per se, may not sufficiently describe the effect that individual land covers can have on localized microclimate. The ratio of living:nonliving land covers within drought-tolerant yards significantly affected air temperature and UTCI anomalies. Air temperatures significantly decreased with greater proportions of living land cover, while UTCI anomalies increased with greater living cover. The difference between signal direction for these two measures likely reflects the different meteorological variables considered. Air temperature alone may be cooler from greater latent heat flux in yards containing more living land covers, whereas UTCI accounts for the increase in relative humidity and also deals with variable radiative loads across yards. A coincidence of study design resulted in lower levels of yard-scale tree canopy in the drought-tolerant yards with the greatest living:nonliving ratios. As a result, the cooling effect of the ground surface may have been outweighed by the incoming radiation that wasn’t blocked by a tree canopy.

The considerable variation among air temperature effects of drought-tolerant yards necessitates a reimagining of the generalized categories used to describe urban landscaping regimes (drought-tolerant, water wise, xeriscaping, etc.) and again consider the photosynthetic and water use properties of individual plants within drought-tolerant landscaping and in combination with the tree canopy. My results suggest an opportunity for landscape planners and homeowners to avoid the heat implications of drought-tolerant yards all together by designing with the appropriate mix of landscaping materials. As a category, “drought-tolerant landscaping,” may not reveal as much about yard-scale energy budgets as the unique composition of landscaping materials and their related irrigation patterns.

There is some preliminary work addressing the thermal properties of individual urban land covers. Soudoudi et al. (2018) noted that there was no significant difference between the thermal comfort effect of 10cm vs 50cm tall grasses. Cahvalo et al. (2021) recently found that hardwood mulch poorly diffused thermal energy into the surface, resulting in higher surface temperatures than those associated with decomposed granite or turfgrass. More work like this is needed to assess differences in the cooling effects of different kinds of vegetation and surface covers in actual yards in the urban environments. Diurnal patterns of radiation retention also need to be considered, particularly since human heat stress and vulnerability is predicted to be exacerbated at night (Laaidi et al. 2012). Human decision-making in urban areas creates highly heterogenous landscapes, irrigation patterns, and subsequent microclimatic impacts. By better capturing this heterogeneity in on the ground measurements, we can move forward to improve our models of urban heat archipelagos within cities and better predict future climate scenarios.

4.4 Disentangling the Variation Among Thermal Comfort Indices

There is appreciable variation among the results from the different thermal comfort indices, which is expected since each index uses and weighs meteorological variables differently. The primary mechanisms through which drought-tolerant yards alter the surface energy budget include a decrease in evapotranspiration and differences in soil/surface heat flux, which depends on soil/surface albedo and associated radiation, air temperature, and soil moisture. It is challenging to assess from the results of this study, whether these yard-scale impacts on localized climate are better captured by some thermal comfort indices than others. Currently, it is unclear whether PET and UTCI can answer questions of the specific biometeorological effect of surface-level vegetation heterogeneity. Human comfort and heat stress morbidity should theoretically be better measured with PET and UTCI, but these indices are more difficult to calculate due to required measurement and estimation of additional variables. See Supplementary Fig S2 for a comparison of indices against each other, and see Figs S3, S4, and S5 for a comparison of each input meteorological variable against mean radiant temperature, UTCI, and PET respectively.

Further research in urban landscape-driven thermal comfort will need to explore the role that different structural layers of vegetation have within the same yard to better understand the relative magnitude of effect that each element of the landscaping has on the thermal comfort of residents. Rather than treating the urban landscape as one composite “surface layer”, it is likely worth partitioning the surface into canopy, human-experienced air space, and surface land cover layers, paying attention to photosynthetic activity, to better investigate their individual and synergistic effects on experienced heat. More sophisticated sensor arrays, coupled with increased sampling resolutions, and potentially measuring additional variables such as surface temperature could assist in increasing an understanding of how individual nature-based heat mitigation efforts differentially affect HI, PET, and UTCI.

4.5 Limitations & Future Research Needs

In addition to the challenges of measuring microclimate in a highly heterogeneous environment, there were several limitations of the study due to timing and design. Wildfire smoke and pandemic conditions extended the timeline for yard measurement to several months. Background variation in weather conditions may have muted the signal found between yard types and among different amounts of tree canopy. Similarly, I was only able to take measurements during the afternoon, and there may be important differences in outcomes measured during the evening.

Additional challenges to interpreting my results include the field methodology which involved relatively rapid changes in sampling locations. This movement in combination with wind speed variation may not have consistently allowed for sufficient equilibration time of the unaspirated temperature and relative humidity sensors. Since the unaspirated sensor response time varies with wind speed, the variable equilibration may have interacted with some of the measurements in unpredictable ways for the different yard types and canopy cover. Improved weather station equipment, perhaps allowing multiple simultaneous measurements at different locations, could enhance the ability to discern differences in indices between the different landscaping types.

Overall, the study reveals the significant opportunity to further examine the effects of residential landscaping conversions at multiple spatial scales. Future research should explore the microclimatic impacts of individual land covers commonly used in drought-tolerant yards, and consider actual residential irrigation behavior. More generally, there is a need to explicitly investigate changes in water use across landscaping types in urban areas, and measure 1) whether use of drought-tolerant landscaping materials is truly coupled with reductions in residential water use across a range of canopy covers and 2) whether reductions in water use alter evapotranspirative cooling from the land surface and from urban trees.

4.6 Implications for Management

Key management implications from this project include 1) the need to emphasize living land covers within drought-tolerant yards, and 2) the need for continued expansion of the urban tree canopy. As arid and semi-arid cities continue to restrict residential water use and more yards shift to drought-tolerant landscaping, it is important to consider the potential microclimatic effects these changes will create for homeowners. This is particularly important to consider in yards and neighborhoods with low tree canopy cover that already experience more heat or are at greater risk of the negative impacts of heat (Wolf et al., 2020). Increasing the urban canopy faces a suite of challenges, from water demand (Pataki et al., 2011), financial and labor costs (Widney et al., 2016), and poor tree survival (Smith et al. 2019), but overcoming these challenges may allow cities to not only avoid additional heat burden from water conservation, but actually improve thermal comfort and improve resilience against heat.

An emphasis on living land covers can also mitigate some of the warming associated with water-conserving landscaping, although it should be noted that complex garden-like yards require greater time and energy from the resident to maintain, and still require more water use, compared to hardscape or gravel covered yards. Since the primary intention of installing drought-tolerant yards is water conservation, it should also be considered how much water use within the yard and across the city is required to maintain a healthy tree canopy and living land covers, and how that water use compares to the water required to generate electricity for comparable indoor temperature reductions.

5. CONCLUSION

My results suggest that intentionally designed drought-tolerant yards that emphasize living materials in combination with a tree canopy may actually cool yard-scale air temperatures and increase residential thermal comfort. This is a hopeful message as municipalities continue to develop and implement outdoor residential water use conservation policies. It is of particular importance in areas with lower tree canopy coverage that may already be heat archipelagos within cities and need to have particular care taken to avoid exacerbating land surface-driven temperature increases. An emphasis on within-yard land cover heterogeneity in combination with a tree canopy will facilitate smart landscaping design at the heat-water nexus. Through further investigations of the thermal properties of drought-tolerant land covers, homeowners, planners, and landscapers can create residential yards that help mitigate urban heat while also conserving water.

TABLES

Table 1. Distribution of the 254 sampled yards. Number (n) of HERCULES patches in each category. Number (n) and percent (%) of yards of each yard type by HERCULES patch-scale canopy category and the total number of sampled yards in each yard type (total n).

	Patches	**Yard Type**			
		Conventional		**Drought-tolerant**	
HERCULES Tree Canopy Category	**n**	**n**	**%**	**n**	**%**
<10% canopy	4	8	7.6	16	10.7
10-20%	4	9	8.6	24	16.1
20-30%	9	11	10.5	23	15.4
30-40%	8	28	26.7	38	25.5
>40%	4	49	46.7	48	32.2
Total (n)	29	105		149	

Table 2. Land cover categories used in Braun-Blanquet assessment of yard land cover

Living Land Covers		
Annual Grasses	Bamboo	Broadleaf Trunk
Perennial Ornamental Grasses	Succulents/Cacti	Evergreen Trunk
Conventional Lawn	Leafy Herbaceous Vegetation	Palm Trunk
	Shrubs	
Non-Living Land Covers		
Artificial Turf	Light Color Mulch	Light Color Hardtop
Bare Soil	Dark Color Mulch	Dark Color Hardtop
Sand/Decomposed Granite	Light Color Gravel	Decking/Built Material
	Dark Color Gravel	Other

Table 3. Components of mobile meteorological station. Sensor used to measure each variable and reported accuracies within the specified range and response time. Response time given for 63% threshold. Air temperature and relative humidity sensor was placed within the naturally ventilated solar radiation shield. Approximate response time within naturally ventilated shield was 258s. Datalogger identified.

Meteorological Variable	Sensor	Accuracy	Sensor Range	Response Time
Air Temperature & Relative Humidity	Campbell Scientific HygroVUE 5	±0.3 °C ±1.8%	-40 to 70°C 0 to 100%	130s 8s
Wind Speed and Direction	Campbell Scientific 03002 R.M. Young Wind Sentry Set, including the 03101 R.M. Young Wind Sentry Anemometer & 03301 R.M. Young Wind Sentry Vane	±0.5 m s^{-1} Vane threshold 0.8 m s^{-1}	0 to 50 m s^{-1} 352°	Settling time 20ms
Global Solar Radiation	LI-COR LI200 Pyranometer	90 μA per 1000 W m^{-2}	400 to 1100 nm	< 1μs
GPS Coordinates	Garmin GPS16X-HVS GPS Receiver	<15 m	NA	< 2s
Data Storage	Campbell Scientific CR1000X Datalogger			

Table 4. Characteristics of sampled yards, including average yard size, number of yards of each type with at least one tree within the yard, number of yards with at least one street tree directly adjacent to the yard, and the number and percent of each yard type by irrigation method.

	Yard Type			
	Conventional		**Drought-Tolerant**	
Average Yard size (m^2)	79.0		68.5	
Yards with Tree Within Yard (n)	89		126	
Yards with Adjacent Street Tree (n)	26		50	
	n	**%**	**n**	**%**
Irrigation Method on Yard				
Drip	3	2.9	104	69.8
Spray	72	68.6	26	17.4
Both	16	15.2	2	1.3
Other	3	2.9	1	0.7
None	11	10.5	16	10.7

Table 5. Frequency of land cover occurrence among all yards of each type, grouped as living or nonliving covers.

		Drought-Tolerant (%)	Conventional (%)
Living	Leafy Herbaceous Vegetation	94.0	76.2
	Shrubs	86.6	81.0
	Broadleaf Stem	74.5	82.9
	Perennial Ornamental Grasses	54.4	13.3
	Succulents/Cacti	32.2	12.4
	Evergreen Stem	13.4	9.5
	Palm Stem	9.4	8.6
	Annual Grasses	6.7	4.8
	Conventional Lawn	2.0	100.0
	Bamboo	0.7	0.0
Nonliving	Light Color Hardtop	91.3	98.1
	Bare Soil	47.7	48.6
	Light Color Mulch	47.0	10.5
	Dark Color Mulch	44.3	21.9
	Light Color Gravel	44.3	19.1
	Dark Color Hardtop	32.2	23.8
	Dark Color Gravel	26.2	7.6
	Sand/Decomposed Granite	9.4	1.9
	Built Material	4.7	1.9
	Artificial Turf	4.0	0.0
	Other	2.0	1.9

FIGURES

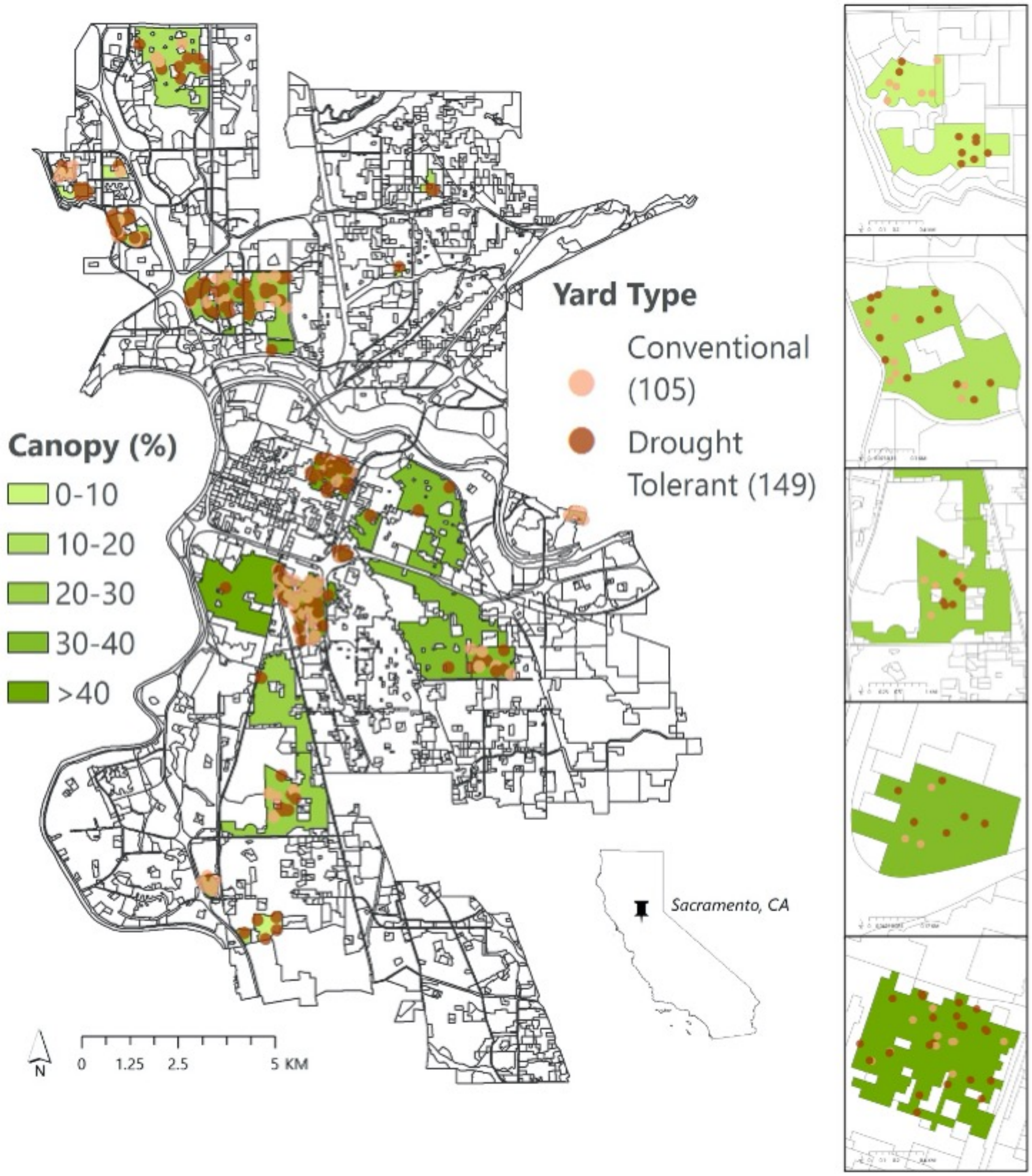

Figure 1. Map of the 29 final HERCULES patches in Sacramento, CA, classified by percent canopy cover and the final selection of sampled yards indicated. Side panel shows example patches in each canopy cover category.

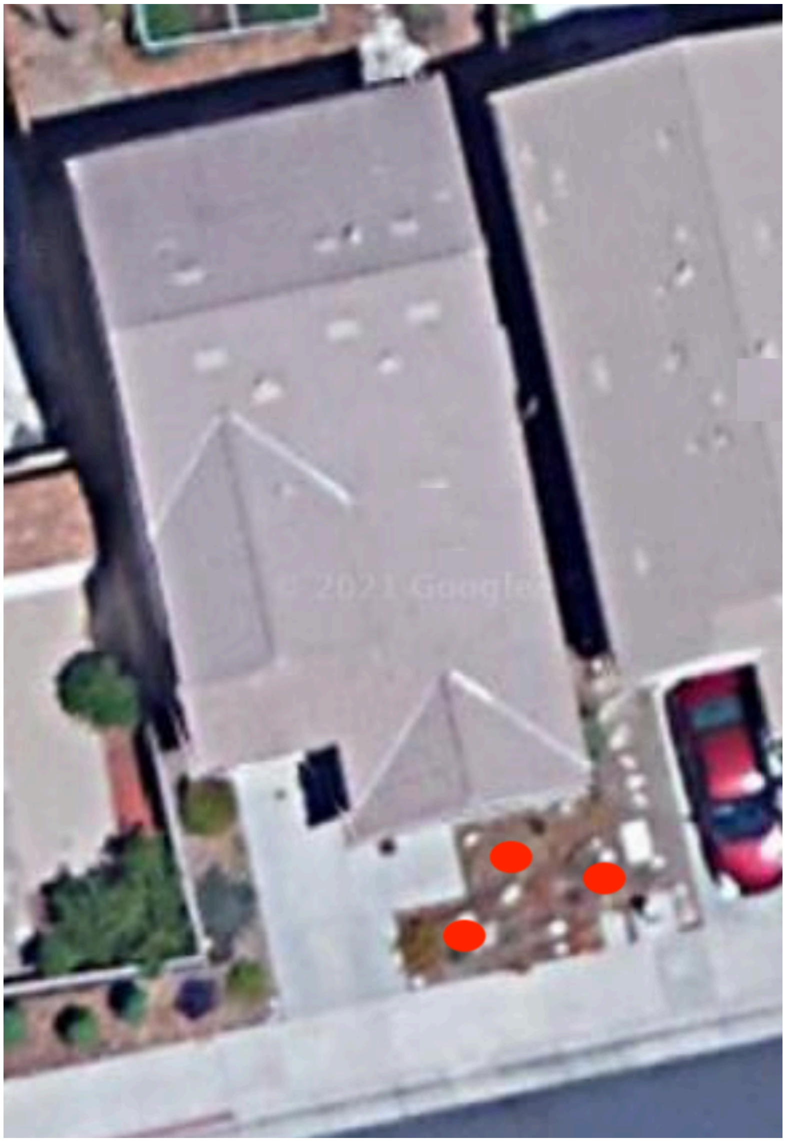

Figure 2. Top-down view of sampled drought-tolerant front yard, with red dots marking three meteorological sample locations within the yard (area = 39.44 m^2).

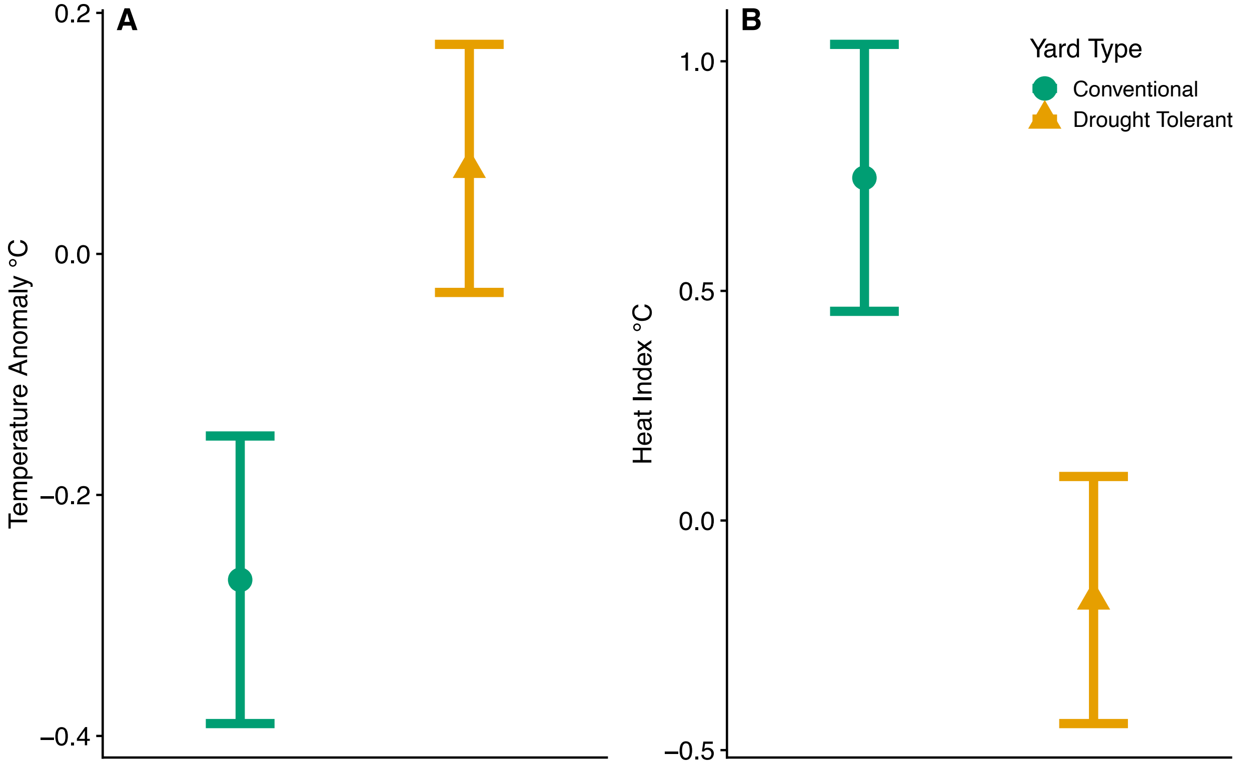

Figure 3. Estimated effect of yard type on A) air temperature anomaly and B) HI anomaly relative to the reference station. Each bar is the mean with 95% confidence intervals.

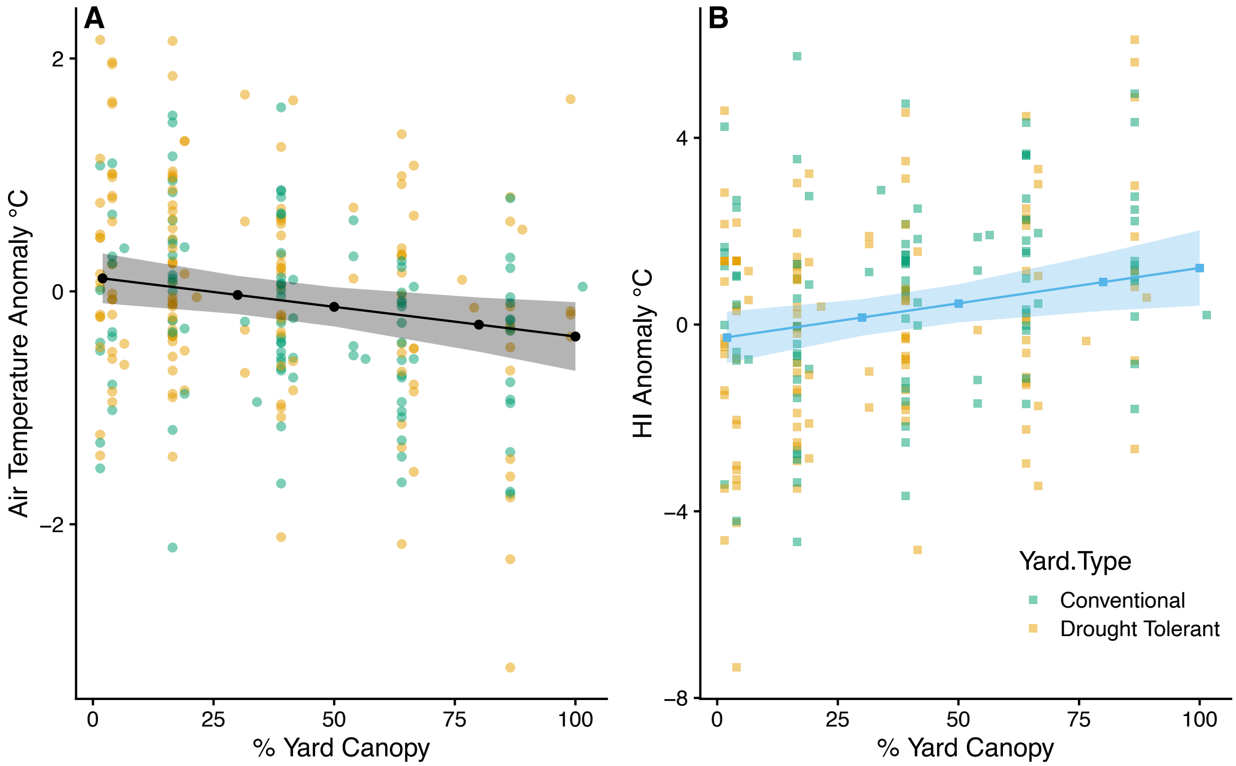

Figure 4. A) Effect of yard-scale tree canopy on temperature anomaly relative to the reference station with 95% confidence intervals. B) Effect of yard-scale tree canopy on equivalent temperature from HI with 95% confidence intervals.

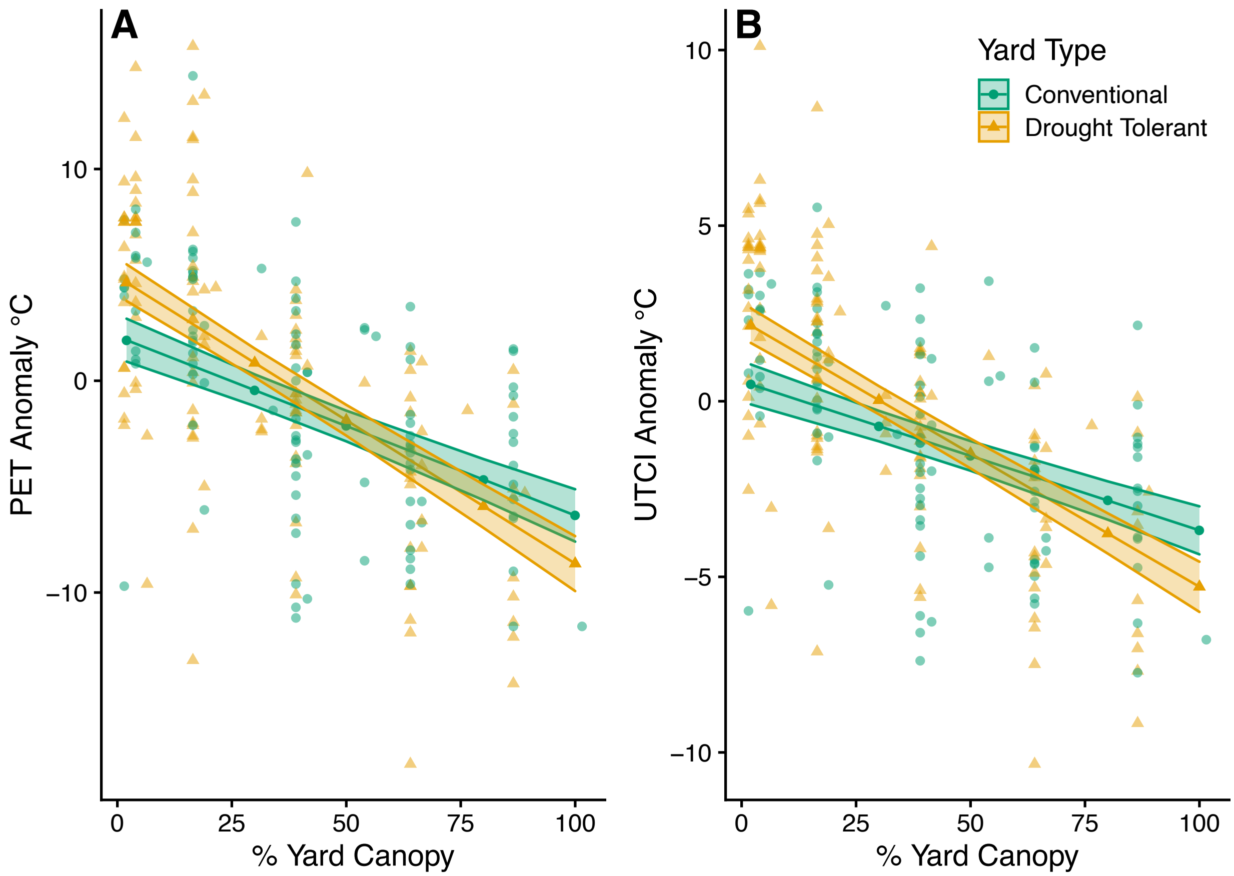

Figure 5. Estimated effect of interaction between yard type and yard-scale tree canopy on A) PET temperature equivalent and B) UTCI temperature equivalent, with 95% confidence intervals.

Figure 6. Images of typical yard conditions A) conventional yard with low amount of yard-scale tree canopy, B) drought-tolerant yard with low amount of yard-scale tree canopy, C) conventional yard with high yard-scale tree canopy, and D) drought-tolerant yard with high yard-scale tree canopy.

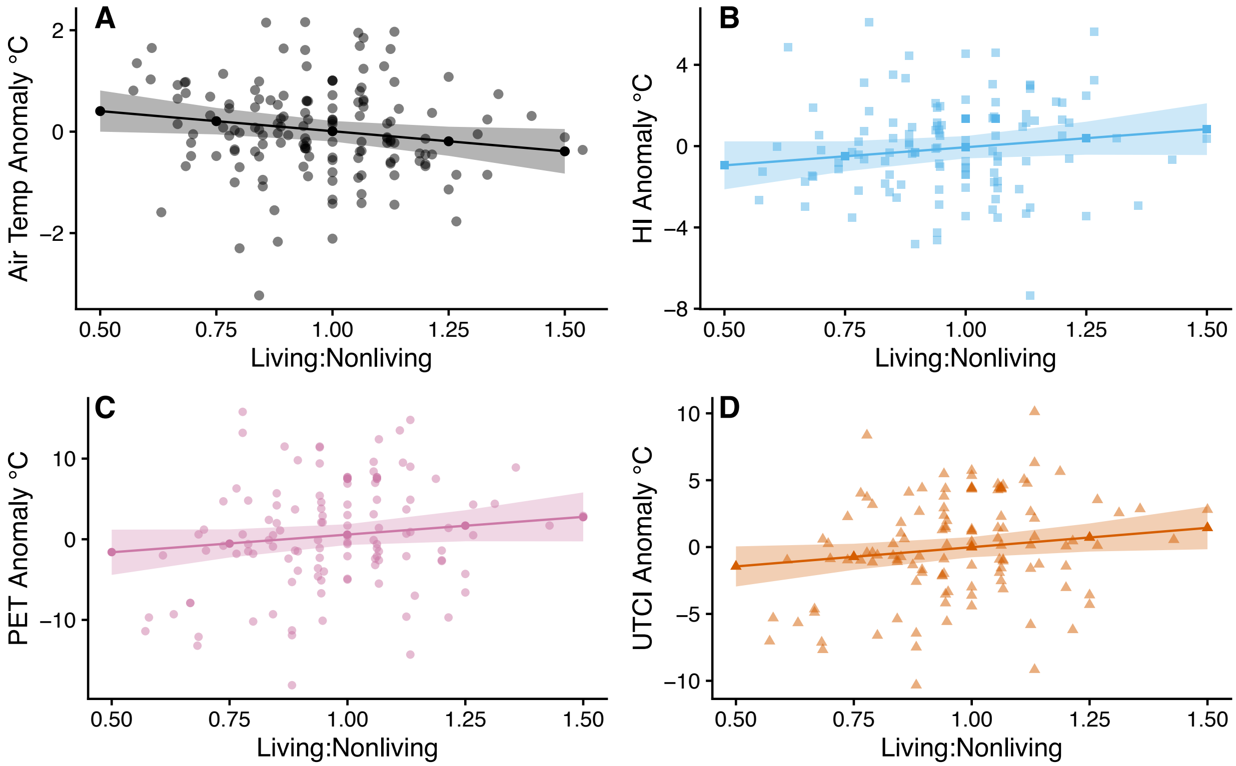

Figure 7. Effect of the ratio of living:nonliving land covers in drought-tolerant yards on A) air temperature anomaly B) HI anomaly, C) PET anomaly, and D) UTCI anomaly, with predicted regression lines and 95% confidence intervals.

SUPPLEMENTARY TABLES & FIGURES

Table S1. List of thermal comfort models, including the predicted outcome, the yard-level and reference meteorological data (from KSMF and CIMIS station #155) included to account for variation in background conditions.

Outcome Variable	Yard-Level Meteorological Data	Reference Meteorological Data
Air temperature anomaly	air temperature	air temperature
NOAA Heat Index	air temperature, relative humidity	air temperature, relative humidity
Universal Thermal Comfort Index (UTCI)	air temperature, relative humidity, wind speed, incoming solar radiation, geographic location, date and time	air temperature, relative humidity, wind speed, incoming solar radiation, geographic location, date and time
Physiological Equivalent Temperature (PET)	air temperature, relative humidity, wind speed, incoming solar radiation, geographic location, date and time	air temperature, relative humidity, wind speed, incoming solar radiation, geographic location, date and time

Figure S1. Custom-built micrometeorological station. A) Station at human-height in a sampled yard. Image shows the station on an adjustable tripod, with the aspirated temperature and relative humidity sensor, wind vane, and three cup anemometer all visible. Note, the pyranometer is present, but not visible on the other side of the station. B) Interior of the datalogger box, including signal converter and the CR1000X datalogger. C) Hand-made and self-levelling pyranometer mount with a gimbal.

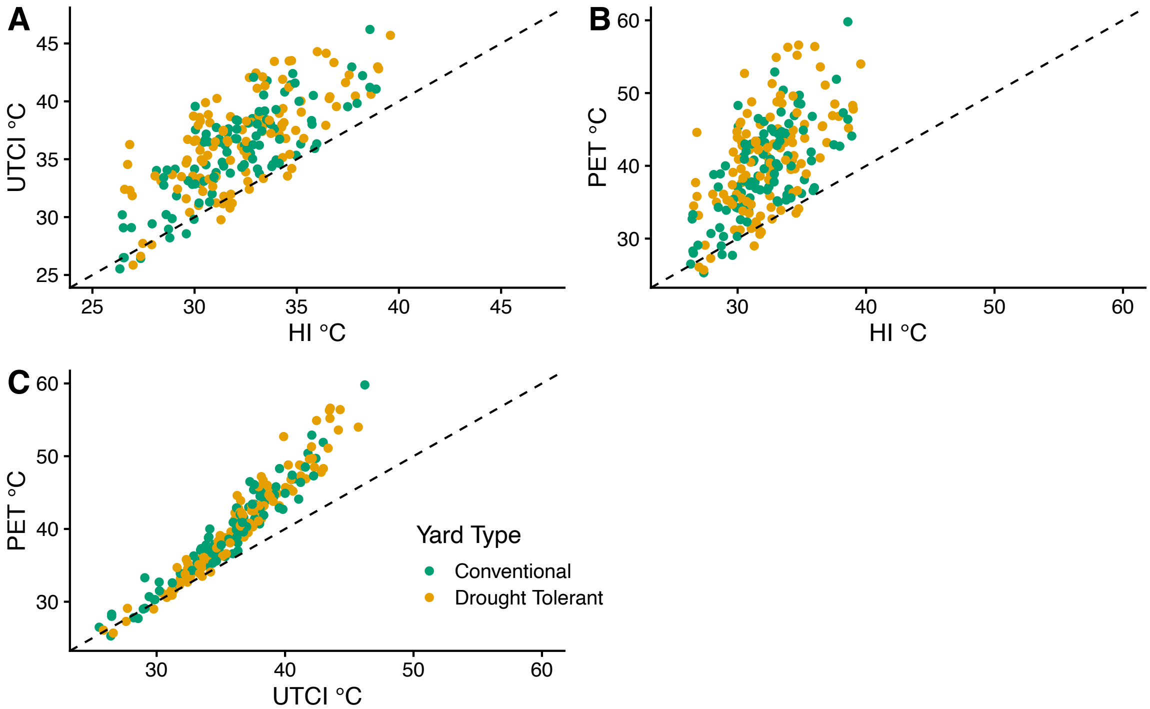

Figure S2. Scatterplots comparing raw equivalent yard temperatures for each thermal comfort index, with A) HI and UTCI, B) HI and PET, and C) UTCI and PET.

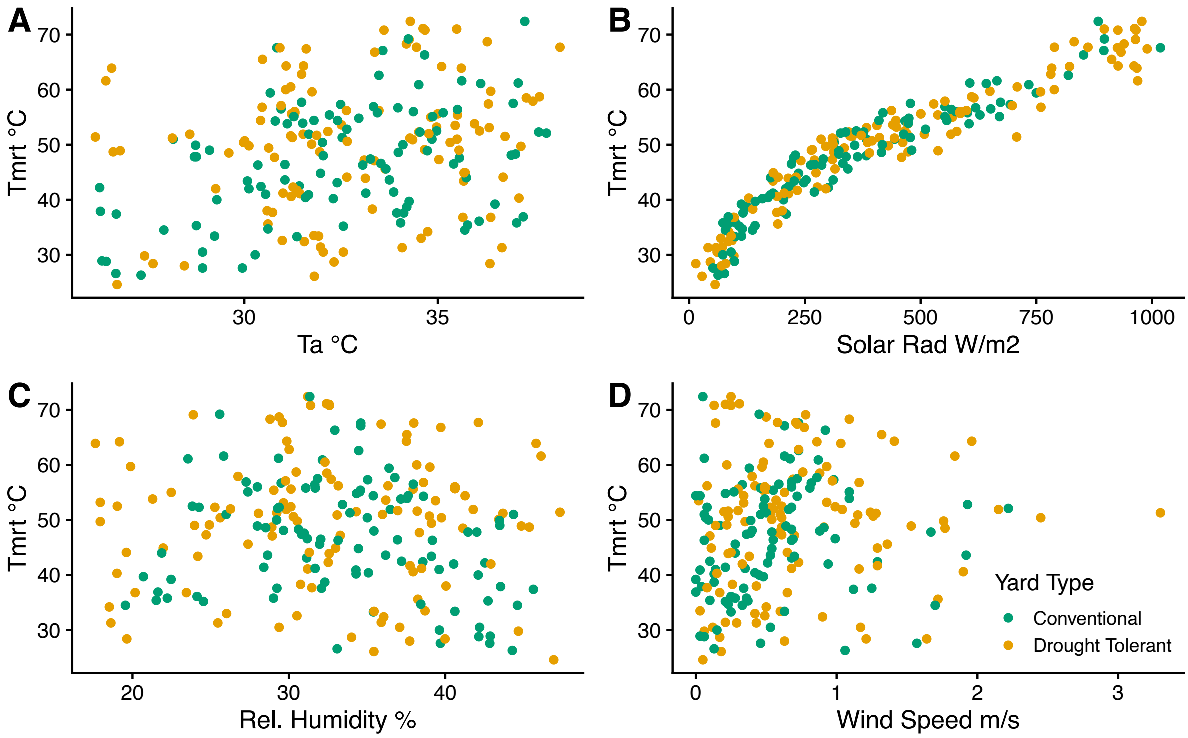

Figure S3. Scatterplots of the input meteorological variables A) air temperature, B) incoming solar radiation, C) relative humidity, and D) wind speed, against the mean radiant temperature modeled by RayMan Pro.

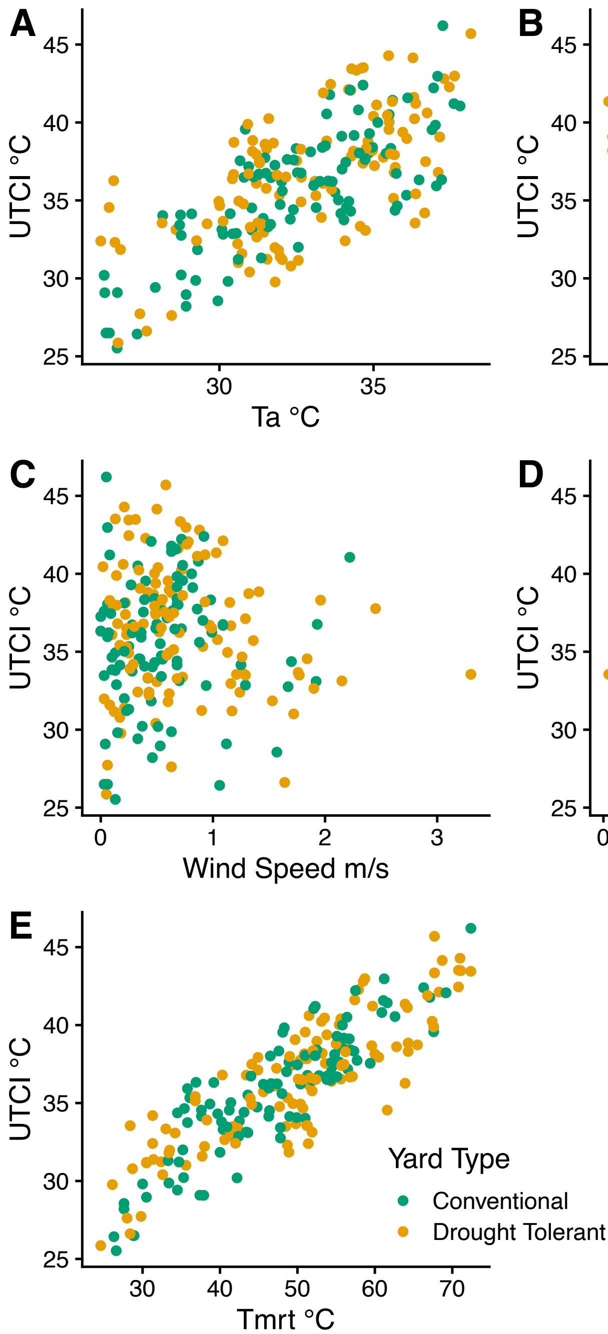

Figure S4. Scatterplots of the input meteorological variables A) air temperature, B) relative humidity, C) wind speed, D) incoming solar radiation, and E) modeled mean radiant temperature, compared against the UTCI equivalent temperature modeled in RayMan Pro.

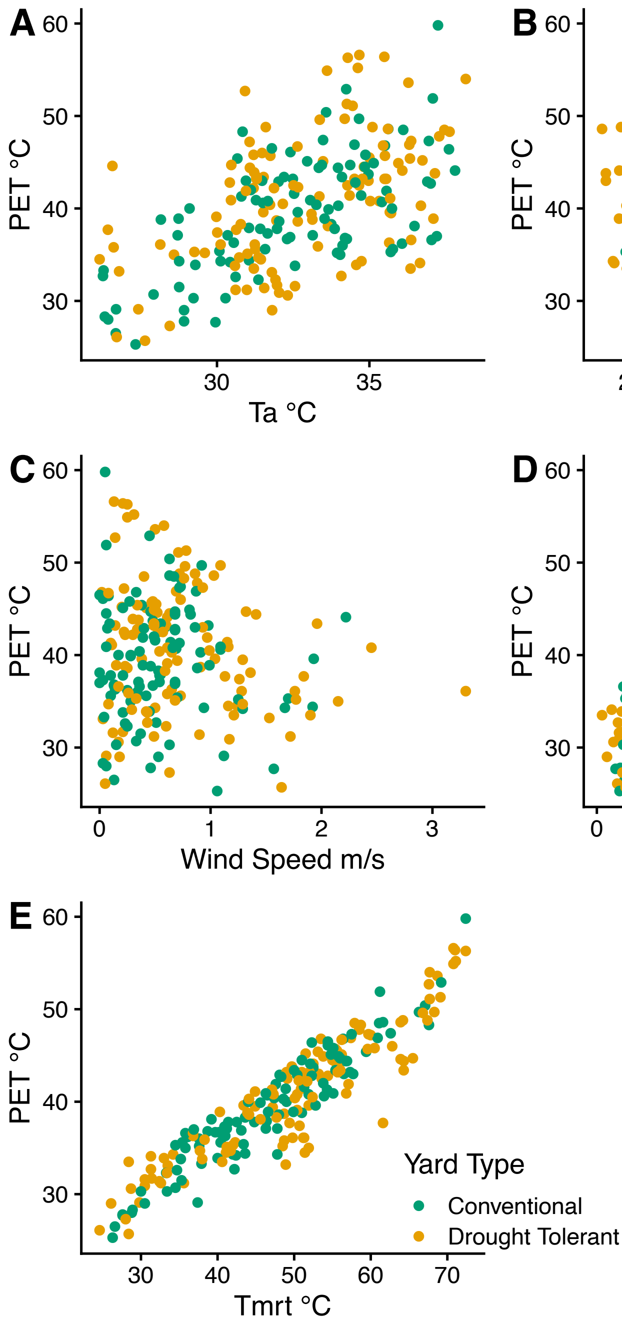

Figure S5. Scatterplots of the input meteorological variables A) air temperature, B) relative humidity, C) wind speed, D) incoming solar radiation, and E) modeled mean radiant temperature, compared against the PET equivalent temperature modeled in RayMan Pro.

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