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Original Article

From canopy to comfort: The impact of residential landscape choices on thermal dynamics in a semi-arid city

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ABSTRACT

Extreme summertime heat, intensified by climate change and urbanization, is the leading weather-related cause of mortality in the USA. Cities are increasingly turning to urban forests for heat mitigation, yet the complex relationship between urban ecosystem structure and cooling remains largely uninterrogated, leaving land managers uncertain about how to optimize ecosystem services and minimize disservices. This study examined hyper-local cooling mechanisms in residential landscapes in a semi-arid Colorado, USA city, using data from thirty-two front yards varying by cardinal orientation, ground cover (grass lawns vs. xeriscapes), and canopy cover (0–100 %). Using a mobile biometeorology unit, we measured mean radiant temperature, air temperature, and actual vapor pressure. We found a linear decrease in mean radiant temperature of approximately 1 °C for every 10 % increase in canopy cover at the sub-parcel scale. Xeriscapes were approximately 1.5 °C warmer in morning air temperature than grass lawns. Cardinal orientation effects were inconclusive, questioning the common assumption that trees provide the greatest cooling benefits on the west side of buildings. Findings emphasize the need for context-specific land management recommendations and offer a foundation for further research on how urban structure shapes microclimates at human-relevant scales.

1. Introduction

Increasingly extreme summertime heat and decreasing water resources pose unprecedented challenges to cities. In 2023, for example, Phoenix, Arizona, experienced 55 summer days with temperatures exceeding 110 ℉ (43.33 ℃), compared to its average of 22 days (NOAA Online Weather Data, 2023). Meanwhile in the same year, southwestern states in the USA grappled with allocation of increasingly scarce water resources from the Colorado River, on which millions of people depend (Yachnin, 2023). To make matters worse, power grids are straining under the pressure of extreme heat events and threatening to fail, causing blackouts when they are most needed for life-saving indoor air conditioning (Stone et al., 2023).

Urban forestry is increasingly recognized as a critical strategy for mitigating the effects of extreme heat, providing cooling relief to humans, plants, and animals (Elmqvist et al., 2015), reducing building energy use (Abram et al., 2022), and even decreasing outdoor water use (Litvak et al., 2014; Rasmussen et al., 2021; Troy et al., 2024). As drought and water restrictions intensify globally, understanding trade-offs between heat and water in cities is essential. Yet key questions remain about how landscape heterogeneity—such as variations in vegetation and ground cover—affects ecosystem services under different climate regimes, particularly at fine spatial scales (Cadenasso et al., 2007; Pickett et al., 2017; McHale et al., 2018).

Although increased canopy cover is known to reduce temperatures via shading and evapotranspiration (Oke et al., 1989), common thermal metrics like air temperature (T_a) and satellite-derived land surface temperature offer limited value for land management. T_a is often homogeneous across a landscape due to air mixing, while land surface temperature is usually coarse in resolution and does not capture ground-level conditions. This creates uncertainty about the thermal experiences of urban residents.

Mean radiant temperature (T_{mrt}) —the weighted average of all incoming radiative loads in reference to an object or being—has recently gained prominence as a key metric for understanding thermal dynamics of urban systems. Unlike T_a or satellite-derived land surface temperature, T_{mrt} captures fine-scale spatial variation and offers a more accurate representation of human thermal experiences. It is a reliable physical

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proxy for human thermal comfort (Middel et al., 2019; Middel et al., 2021; Turner et al., 2022), without requiring social science data inputs.

In response to growing concerns about water scarcity and biodiversity loss, many cities are adopting xeriscaping as a one-size-fits-all approach to sustainable landscaping (Didier, 2024). Contextually, cities in the American southwest, like Phoenix, Arizona and Denver, Colorado, were historically desert landscapes that became greened through widespread planting of turf grass lawns and large trees during modern development. This transformation sometimes creates an "oasis effect," where urban areas are cooler than the surrounding desert (Oke, 1987), but the cooling benefits come with a trade-off: water use. To reduce water demand, many cities now encourage xeriscaping, which replaces turf grass with drought-tolerant plants and converts sprinkler systems to drip irrigation. These efforts are often promoted alongside biodiversity and native planting initiatives. However, this shift raises an important question: is the re-desertification of arid and semi-arid cities worsening extreme summertime temperatures? Research suggests it can—especially when xeriscaping is not paired with heat mitigation strategies such as planting shade trees with large, dense canopies (Chow and Brazel, 2012).

Sky view factor (SVF) is a common metric used to assess urban heterogeneity (Oke et al., 1980), due to its strong link to thermal outcomes. It typically involves capturing a 180° field of view upward-facing image with fisheye distortion from a single point 1.1 m above the ground, followed by a classification of sky and non-sky proportions (Miao et al., 2020). In summer, low SVF (more shade) tends to correlate with reduced daytime temperatures and improved thermal comfort, while high SVF (less shade) correlates with decreased daytime thermal comfort and reduced nighttime temperatures (Lin et al., 2010; Tan et al., 2016; Middel et al., 2019; Yan et al., 2022). These patterns reflect daytime shading from trees and buildings and nighttime heat loss. Beyond single-point measurements, SVF averaged across an area also correlates with microclimate variation (Unger, 2004; Lindberg., 2007; Chen et al., 2012). More recently, researchers have begun decomposing fisheye images sky, building, and vegetation components—known as SVF, BVF, and VVF— to better distinguish the thermal effects of built versus vegetated elements (Middel et al., 2019).

This study applies a hyper-local approach to urban ecological research, setting a foundation for planning and management strategies that prioritize on-the-ground thermal comfort. By investigating microclimates in residential landscapes—an often-overlooked segment of the urban forest—we address a critical gap in urban ecology research. Privately managed land makes up a substantial share of urban forests and is essential to achieving citywide cooling goals (Mathieu et al., 2007); in Denver, Colorado, for example, private property accounts for 85 % of the urban forest (Sachs, 2021). Here, we examine how specific front yard characteristics—canopy cover, cardinal orientation, ground cover (xeriscape vs. turf grass), sky view factor (SVF), and vegetation view factor (VVF)—affect micrometeorology, using mean radiant temperature (T_{mrt}), air temperature (T_a), and actual vapor pressure (e) as indicators of thermal conditions.

Specifically, we asked: 1) How do the strengths of effects on average front yard T_{mrt}, T_a, and e compare among canopy cover, cardinal orientation, and ground cover? 2) Is there a significant difference in T_{mrt} and T_a between front yards of different cardinal orientation? 3) Is ground cover a meaningful predictor of T_{mrt}, T_a, or e? 4) To what extent can T_{mrt} in front yards be explained by SVF, VVF, or remotely derived canopy cover (i.e., from a land cover dataset)?

We expected front yard canopy cover to be the strongest predictor of average T_{mrt} and T_a, while also anticipating meaningful effects from yard orientation and ground cover. Specifically, we hypothesized that xeric yards would exhibit higher T_{mrt} and T_a and lower e compared to grass lawns. East facing yards, exposed to morning sun, were also expected to show elevated temperatures. Lastly, we predicted that average SVF would be a stronger predictor of T_{mrt} than VVF and canopy cover, as it has been shown as a precise indicator of hyper-local thermal conditions—though canopy cover was still expected to serve as a significant indicator of urban structure in relation to micrometeorology.

This study offers insights to inform urban planning and landscape management practices that address the realities of urban heat. By using hyper-local data, we provide a nuanced understanding of the influence of sub-parcel landscape characteristics on microclimates, revealing how everyday decisions—such as private tree planting choices—can contribute to or mitigate urban heat.

2. Methods

2.1. Study area

This study took place in Fort Collins, northern Colorado, USA, in July and August 2023. Located at the base of the Rocky Mountains' Front Range (Fig. 1) at 1500 m (5000 ft) elevation, Fort Collins has a semi-arid climate, averaging 300 days of sunshine and 37 cm (15 in) of annual precipitation.

In response to population growth and increasing strain on limited water resources in the American Southwest (Castle et al. 2014), Fort Collins has implemented measures to reduce residential water use. Outdoor irrigation accounts for up to 60 % of total residential water consumption during summer months (City of Fort Collins, 2023). To address this, the City hosts a program that encourages homeowners to replace water-intensive turf grass with xeriscaping by providing a modest rebate.

Urban forest management has also gained attention. In 2023, as the City of Fort Collins drafted its first-ever Urban Forest Strategic Plan, researchers had an opportunity to provide science-based recommendations aligned with the plan's goals of proactive tree planting, urban heat mitigation, and climate adaptation. A 2019 land cover classification (Rasmussen et al., 2021; Abram et al., 2022; Rasmussen et al., 2022) estimated city-wide canopy cover at approximately 13 %—comparable to that of Denver, Colorado (11 % in 2022) (City of Denver Parks and Recreation, 2022) and Phoenix, Arizona (12 % in 2010) (City of Phoenix, 2010).

To spatially constrain the study, we selected a single 1.64 km^2 (0.63 mi^2) neighborhood, characterized by relatively mature trees, uniform residential parcel sizes, and a gridded street layout—conditions that helped minimize the influence of parcel area and simplify analysis by cardinal orientation.

2.2. Study design

32 parcels representing a range of front yard ground cover, cardinal orientation, and tree canopy cover were selected for study. All residential parcels in the study area with publicly available address data were first filtered, then randomized. Parcels were visited in that random order and assessed for suitability based on the three front yard characteristics.

Ground cover criteria included front yards with at least 50 % manicured turf grass (Fig. 2A) and xeric yards where at least 75 % of turf had been replaced with mulch or rock-based cover (Fig. 2B). Cardinal orientation was recorded as north, east, south, or west-facing. Canopy cover percentage was visually estimated for each front yard.

Ultimately, each of the eight combinations of ground cover type and cardinal orientation had four replicates, stratified by canopy cover—low, medium-low, medium-high, and high. Despite efforts to minimize variation in yard size, the 32 front yards selected ranged from approximately 22 to 246 m^2, due to limited availability of sites meeting all selection criteria.

2.3. Thermal measurements

To characterize microclimatic conditions in each front yard, thermal measurements were recorded during two separate morning and

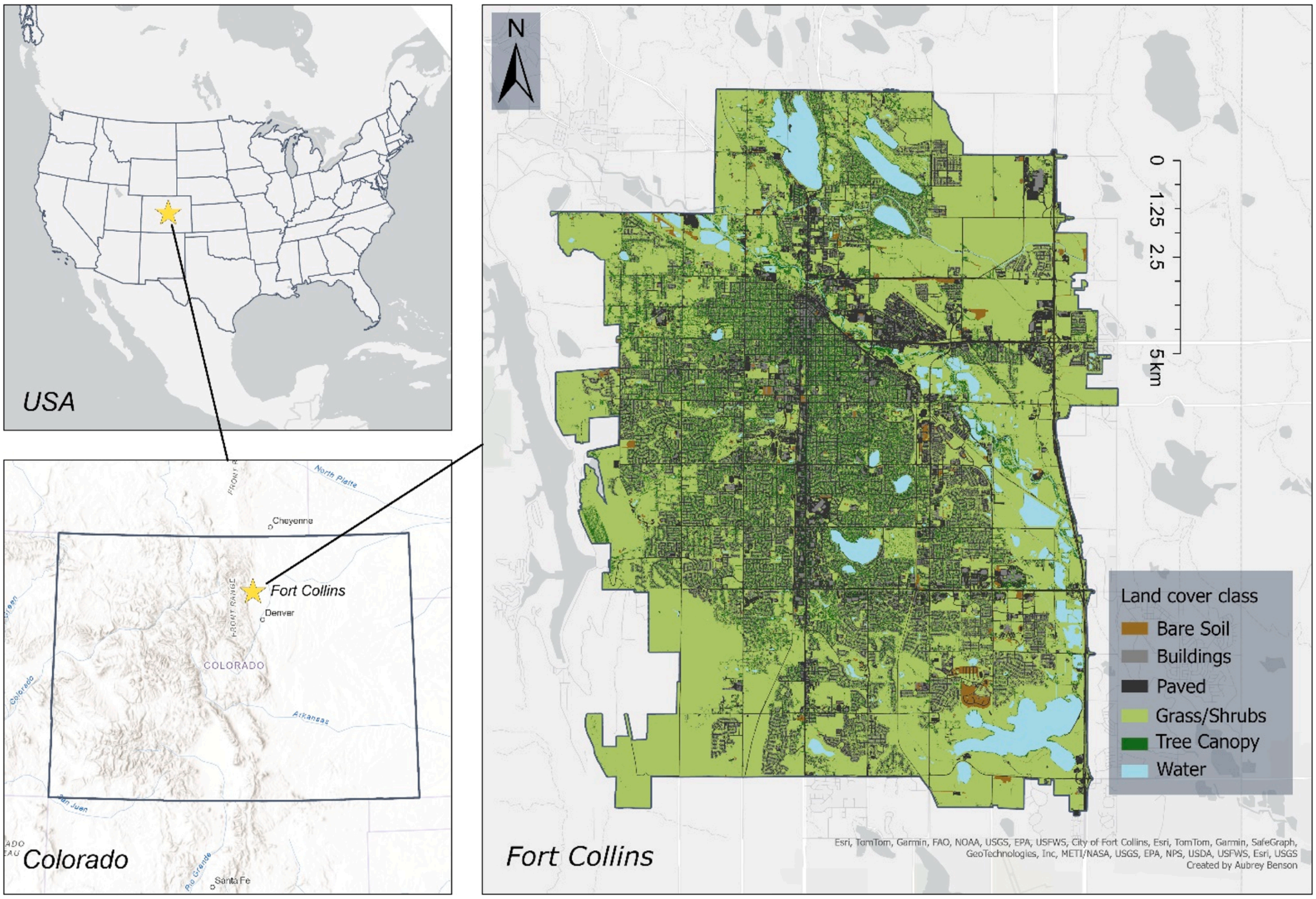

Fig. 1. Fort Collins is a city in northern Colorado, USA, at the base of the Rocky Mountains.

Fig. 2. Example of a typical turf grass front yard (A). Example of a typical xeric front yard (B). Houses are blocked out with gray color for privacy.

afternoon visits to each site between July 17 and August 16, 2023 (Table 1). Morning measurements were collected at three different houses at 08:30, 09:30, and 10:30, with the same houses revisited in the same order in the afternoon at 14:30, 15:30, and 16:30. Time slots were selected based on preliminary field data and hourly weather records from the Western Regional Climate Center (2023) (WRCC) station in Buckeye, Colorado, both of which showed relatively stable temperatures between 08:00–11:00 and 14:00–17:00. Properties were visited in random order during the first round of data collection. Once all yards had been visited, a second round was conducted using a new randomized order.

Five measurement points were systematically identified in each yard by dividing the space into four quadrants and selecting the center of each quadrant plus the entire site's center. Occasionally, a designated point was not feasible due to fragile plants, steep slopes, or dense ground cover. In such cases, the sample point was relocated to the nearest

Table 1
Summary of explanatory and response variables: ground cover, cardinal direction, canopy cover, view factors, area, air temperature (T_a), mean radiant temperature (T_{mrt}), and actual vapor pressure (e).

		Data source	Data type	Scale/ resolution
EXPLANATORY VARIABLES	**Ground cover**	Field	Categorical	Front yard
	Cardinal direction	Field	Categorical	Front yard
	Canopy cover	GIS layer	Numeric continuous (0−1)	1 m^2
	View factors	Field	Numeric continuous (0−1)	Average of 5 points from front yard
	Area (m^2)	Field	Numeric continuous	Front yard
RESPONSE VARIABLES	**T_a (°C)**	Field	Numeric continuous	Average of 5 points from front yard
	T_{mrt} (°C)	Field	Numeric continuous	Average of 5 points from front yard
	e (kPa)	Field	Numeric continuous	Average of 5 points from front yard

accessible area within the immediate vicinity.

We avoided taking measurements during rain events—defined as times in which rain was actively showering from the sky—to prevent data from being highly skewed. Due to the record-breaking rainy conditions of the summer, measurements were occasionally taken while it was lightly drizzling.

Micrometeorological measurements were recorded at five sample points per yard using the mobile biometeorology system, "MaRTa," a custom-built device based on the MaRTy platform developed by Middel and Krayenhoff (2019). At each point, MaRTa was positioned over the marked location and recorded data for one minute. The system measures shortwave and longwave radiation in six directions each, air temperature (T_a), surface temperature (T_s), wind velocity, and relative humidity (Fig. 3).

Mean radiant temperature (T_{mrt}) was calculated from the 12 shortwave and longwave measurements captured by MaRTa using the following equation:

$$T_{mrt} = \sqrt[4]{\frac{\sum_{i=1}^{6} W_i(a_k K_i + a_l L_i)}{a_l * \sigma}} - 273.15 \quad K$$

Where K_i = incoming shortwave radiation, L_i = incoming longwave radiation, a_k = human emissivity for shortwave radiation (0.7), a_l = human emissivity for longwave radiation (0.97), σ = the Stefan-Boltzmann constant, and W_i = weighting parameters for the angles of a standing human (0.06 for upward and downward radiation; 0.22 for lateral radiation) (Middel et al., 2019).

2.4. Explanatory variables

2.4.1. Field measurements: ground cover, cardinal orientation, and area

Ground cover (grass or xeric), cardinal orientation (north, east, south, or west), and area (m^2) were recorded for each of the 32 front yards during site visits (Table 1). Ground cover and orientation levels were assessed visually, while area was measured by hand.

2.4.2. Canopy cover

Front yard percent canopy cover was derived from a high-resolution (1 m^2) 2019 land cover raster (Rasmussen et al., 2021; Abram et al., 2022; Rasmussen et al., 2022), using a method adapted from Ossola et al. (2019). For each parcel, the largest building footprint was identified, and the front-facing edge—based on the yard's cardinal orientation—was manually determined. The parcel was then split at this edge to isolate the front yard, and canopy cover for that area was extracted.

2.4.3. View factors

Sky, vegetation, and building view factors (SVF, VVF, and BVF) were obtained from fisheye photos taken at each of the five measurement points in each front yard using a Nikon Coolpix 4500 camera with a 180° FC-E8 fisheye lens (Middel et al., 2019; Miao et al., 2020). The camera was mounted on a tripod and positioned 1.5 m above ground. Photos were segmented and classified using a supervised pixel classification

Fig. 3. The MaRTa machine, equipped with shortwave and longwave radiation sensors in six directions, along with sensors for other metrics including air temperature, relative humidity, and wind velocity.

method, and resulting classes were quantified into proportions of sky, vegetation, and building view factors (Fig. 4). View factors were averaged across the five points, yielding a single areal mean for each yard.

To reduce post-processing time, view factor photographs were taken only during the first of the four site visits and applied to all subsequent visits. At one site, a tree was removed between sampling days, though this appeared to be an isolated case.

2.4.4. City-wide daily air temperature

City-wide daily T_a data was obtained from an external weather station to account for regional weather conditions on each sampling day. MesoWest data (University of Utah, Department of Atmospheric Sciences, 2024) were sourced from the Fort Collins/Loveland–Northern Colorado Regional Airport station, located approximately 20 km (12 mi) southeast of the study area.

2.5. Statistical analysis

2.5.1. Question 1: How do the Strengths of Effects on Average Front Yard T_{mrt}, T_a, and e Compare Among Canopy Cover, Cardinal Orientation, and Ground Cover?

We used multiple linear models in R Studio Team (2020) with the "tidyverse" package (Wickham et al., 2019) to assess the effects of canopy cover, cardinal orientation, and ground cover on T_{mrt}, T_a, and e. To allow for varying diurnal dynamics, separate models were developed for morning and afternoon periods, resulting in six models total. Each model varied in thermal response variable and included all explanatory variables.

MesoWest T_a data were used as a fixed-effect covariate to account for general weather conditions during each sample period. Average T_a between 08:00–11:00 was used for morning and 14:00–17:00 for afternoon.

Yard area was excluded in the final models due to collinearity with canopy and ground cover—our primary variables of interest. Yard size is often strongly associated with vegetation structure, as larger parcels provide more space for planting but also require more resources to maintain (Bigsby et al., 2014; Ossola et al., 2019; Rasmussen et al., 2021).

For each model, we tested a random effect and interactions. The random effect incorporated front yard site ID (1−32), accounting for temporal variation across site visits. We used the "nlme" R package (Pinherio et al., 2023) to perform a likelihood ratio test; non-significant ($\alpha = 0.1$) random effects were removed. We also tested two-way interactions between ground cover, cardinal orientation, and canopy cover, but none were significant ($\alpha = 0.05$).

We assessed the significance of explanatory variables using the "car" package (Fox and Weisberg, 2019), applying F-tests or likelihood ratio tests based on model structure.

2.5.2. Questions 2 and 3 Is There a Significant Difference in T_{mrt} and T_a Between Front Yards of Different Cardinal Orientation? Is Ground Cover a Meaningful Predictor of T_{mrt}, T_a, or e?

To compare the impact of cardinal orientation and ground cover levels on thermal responses, we used estimated marginal means and standard errors from each model and its levels via the "emmeans" R package (Lenth, 2024). Pairwise comparisons for orientation were conducted using the Tukey method ($\alpha = 0.1$), and a likelihood ratio test was used to assess differences between ground cover types.

2.5.3. Question 4 To what Extent Can T_{mrt} in Front Yards be Explained by SVF, VVF, or Canopy Cover?

To compare indicators of urban vegetation, we evaluated areal means SVF and VVF (difficult to obtain and niche in applicability but detailed in measurement) against canopy cover (more accessible and applicable to urban forestry). We compared model performance for each indicator to assess trade-offs between accuracy, efficiency, and applicability.

We used the afternoon T_{mrt} model—selected for its sensitivity to structural variation—as the basis for this analysis. After reducing the model to include only significant terms (canopy cover and city-wide T_a, $\alpha = 0.05$), we added SVF, VVF, and canopy cover individually to compare their predictive power via model summaries and coefficients.

3. Results

3.1. Study period weather conditions

The data collection period turned out to be Fort Collins' wettest summer on record (NOAA Online Weather Data, 2023). Between June and August of 2023, the city received a monthly average of 129 mm (5.06 in) of precipitation, which is nearly 3 times the average monthly summertime precipitation between 1990 and 2022 of 44 mm (1.73 in) (NOAA Online Weather Data, 2023).

3.2. Question 1 How do the Strengths of Effects on Average Front Yard T_{mrt}, T_a, and e Compare Among Canopy Cover, Cardinal Orientation, and Ground Cover?

To understand the role of landscape elements in determining thermal responses at the sub-parcel scale, we examined relationships between

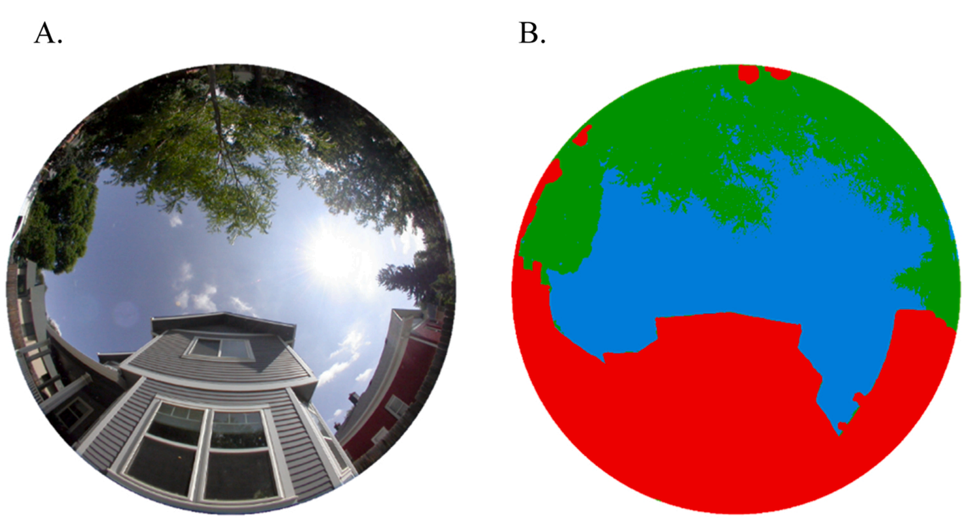

Fig. 4. Example of a raw fisheye image (A) and its associated sky (blue), vegetation (green), and building (red) view factors (B).

explanatory variables (canopy cover, cardinal orientation, and ground cover) and front yard thermal responses. For each model developed, a random location effect was tested. The only random effect that was significant was for the morning T_{mrt} model. As expected, canopy cover was the most significant explanatory variable in the mean radiant temperature (T_{mrt}) models (Table 2; morning $p = 0.03$; afternoon $p = 0.04$), showing significant reductions in T_{mrt} with increasing percent cover (Fig. 5). Yet, canopy cover did not appear as a significant predictor in the air temperature (T_a) models (morning $p = 0.34$; afternoon $p = 0.65$), which is likely related to the fact that T_a did not vary much across the front yards we studied in the first place. Although we also hypothesized that cardinal orientation and ground cover type (xeric vs. grass landscapes) would have an impact on T_{mrt}, these variables were not significant in our models, with one exception: cardinal orientation was significant in the morning T_{mrt} model ($p = 0.08$). The T_a models mostly lacked statistical significance with all explanatory variables ($\alpha = 0.1$), yet there was a significant relationship with ground cover in the morning ($p = 0.02$).

3.3. Question 2 Is There a Significant Difference in T_{mrt} and T_a Between Front Yards of Different Cardinal Orientation?

Pairwise comparisons were conducted between front yards of different cardinal orientations to determine where trees matter the most for heat mitigation; the warmest directions should be prioritized for heat interventions. Overall, our findings were largely inconclusive, with minor differences in micrometeorology indicators between cardinal orientation levels (Fig. 6). This may be a result of our limited sample size and/or the unusually wet and cool conditions of the summer. Significant temperature differences between orientation were found only between north and east-facing properties for T_{mrt} in the morning ($p = 0.06$). Our model indicated that north-facing yards were, on average, 13.1 ℃ higher in morning T_{mrt} than east-facing yards (± ∼4 ℃), and that east orientations were coolest in the morning. We also saw T_{mrt} increase by 12.92 ℃ from morning (± 3.43 ℃) to afternoon (± 2.54 ℃) on east-facing yards.

3.4. Question 3 Is Ground Cover a Meaningful Predictor of T_{mrt}, T_a, or e?

Thermal differences between ground cover types were examined to better understand the impact of xeriscaping on heat in a semi-arid environment. Our models indicated that morning T_a around grass sites were generally 1.5 ℃ cooler than xeric landscapes ($p = 0.02$) (Fig. 7). We also saw that grass sites tended to be 0.15 kPa higher in e ($p = 0.03$), indicating higher atmospheric water vapor content than xeriscapes. In the afternoon, our models showed that temperatures and atmospheric water vapor content equilibrated between grass and xeric landscapes; the afternoon T_{mrt}, T_a, and e models all predicted grass and xeric front yards to have very similar means.

3.5. Question 4 To what Extent Can T_{mrt} be Explained by SVF, VVF, or Canopy Cover?

Sky view factor (SVF), vegetation view factor (VVF), and canopy cover were analyzed to explore trade-offs between accuracy and ease of acquisition across different metrics of ecosystem structure in relation to urban micrometeorology. SVF is known to be highly related to T_{mrt} and involves field measurements and intensive post-processing, while canopy cover is a variable commonly mapped across cities using remote sensing data. VVF was obtained to better inform our comparison between SVF and canopy cover.

By swapping out SVF, VVF, and canopy cover in the afternoon T_{mrt} model, SVF showed the most significant relationship with T_{mrt} ($p < 0.0001$; Table 3), though canopy cover also showed a meaningful association with T_{mrt} ($p = 0.02$). VVF, in contrast, exhibited a weak, non-significant relationship with afternoon T_{mrt}. The SVF model explained the most variation in average front yard T_{mrt} ($R^2 = 0.42$), compared to both the canopy cover and VVF models. This higher R^2 value is likely because SVF accounts for shading potential from both vegetation and buildings, whereas canopy cover and VVF only reflect overhead vegetation coverage. Interestingly, canopy cover performed better than VVF as a descriptor, despite both metrics being vegetation-based. This is notable given the four-year mismatch between the canopy cover dataset (2019) and the micrometeorology measurements (2023).

4. Discussion

4.1. Cool canopies: a 10 % increase in tree cover reduces temperature by ∼1 °C

Although mean radiant temperature (T_{mrt}) is inherently variable due to its sensitivity to fine-scale thermal differences, we observed a statistically significant ($p = 0.05$) linear relationship between it and canopy cover, highlighting the importance of more ambitious canopy cover targets for heat reduction. We expect this effect would be more pronounced during a typical hot, dry summer—unlike the unusually wet and cloudy summer of our study period—as trees are thought to play a greater role in regulating thermal dynamics under arid conditions (Ibsen et al., 2024). Similarly, we suspect tree cover to have a bigger temperature impact in a neighborhood with lower overall vegetation cover.

This finding aligns with other studies using surface and air temperatures. At 10 m buffers, Ziter et al. (2019) in Madison, Wisconsin, USA, found a linear, negative relationship between canopy cover and air temperature (T_a), while analyses at larger buffer sizes of 60 and 90 m showed a non-linear relationship, with greatest heat reductions occurring at > 40 % tree cover and totaling ∼2.5 ℃ in heat reduction from zero to 100 % cover. At a 60 m buffer, Ibsen et al. (2022) established a linear ∼2.5 ℃ reduction in T_a across 0–100 % tree cover in Denver, Colorado, while Coutts and Harris (2013) identified a linear correlation between land surface temperature and canopy cover at 30 m in Melbourne, Australia, totaling in a reduction of ∼8 ℃ from 0–100 % tree

Table 2
Summary of multiple linear regression model results. Column 2 represents the response variable of the model: air temperature (T_a), mean radiant temperature (T_{mrt}), or actual vapor pressure (e). Columns 3, 4, 5, and 6 show p-values for each explanatory variable with estimated coefficients in brackets and standard errors in parentheses for continuous variables. Ta refers to a variable accounting for city-wide conditions. Asterisks indicate p-values of: 0 < *** < 0.001 **<** ** < 0.01 < * < 0.05 < **.** < 0.1. The last column depicts R^2 values for each model; For all linear models, R^2 is the coefficient of determination, while the marginal/conditional R^2 values are listed for the morning T_{mrt} model, which was a linear mixed effects model.

		T_a covariate	Canopy cover	Cardinal direction	Ground cover	R^2
MORNING	T_a (℃)	< 0.0001***	0.34 [−1.14] (1.17)	0.16	0.02*	0.65
	T_{mrt} (℃)	< 0.0001***	0.03* [−13.26] (6.12)	0.08.	0.18	0.26/0.70
	e (kPa)	0.93	0.20 [−0.15] (0.12)	0.70	0.02*	0.12
AFTERNOON	T_a (℃)	< 0.0001***	0.65 [−0.33] (0.73)	0.67	0.97	0.86
	T_{mrt} (℃)	< 0.0001***	0.04* [−9.55] (4.53)	0.50	0.90	0.34
	e (kPa)	0.45	0.74 [−0.05] (0.14)	0.40	0.51	0.07

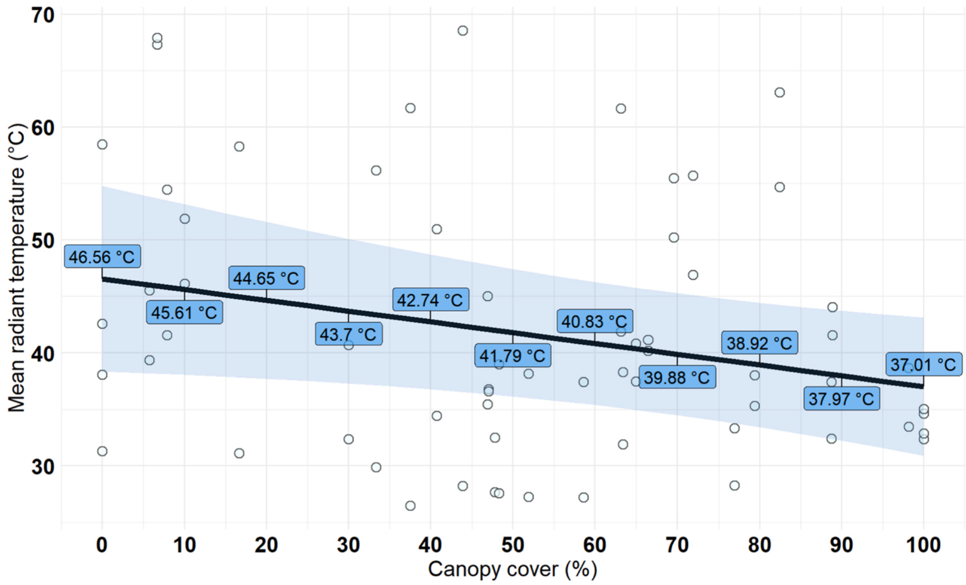

Fig. 5. Front yard canopy cover (%) and afternoon mean radiant temperature (*Tmrt*), based on a multiple linear regression with canopy cover, cardinal orientation, ground cover class, and city-wide air temperature as explanatory variables, and afternoon *Tmrt* as the response. To visualize the link between canopy cover and *Tmrt*, ground cover was set to the class xeric, cardinal orientation was set to north, and air temperature (a continuous covariate accounting for city-wide conditions) was set to its mean value. Shaded areas indicate 95 % confidence intervals. Points represent average front yard afternoon *Tmrt* by percent canopy cover (n = 64), with *Tmrt* labels at every 10 % increment. From 0 % to 100 % canopy cover, *Tmrt* decreases by 9.55 ℃ (p = 0.04).

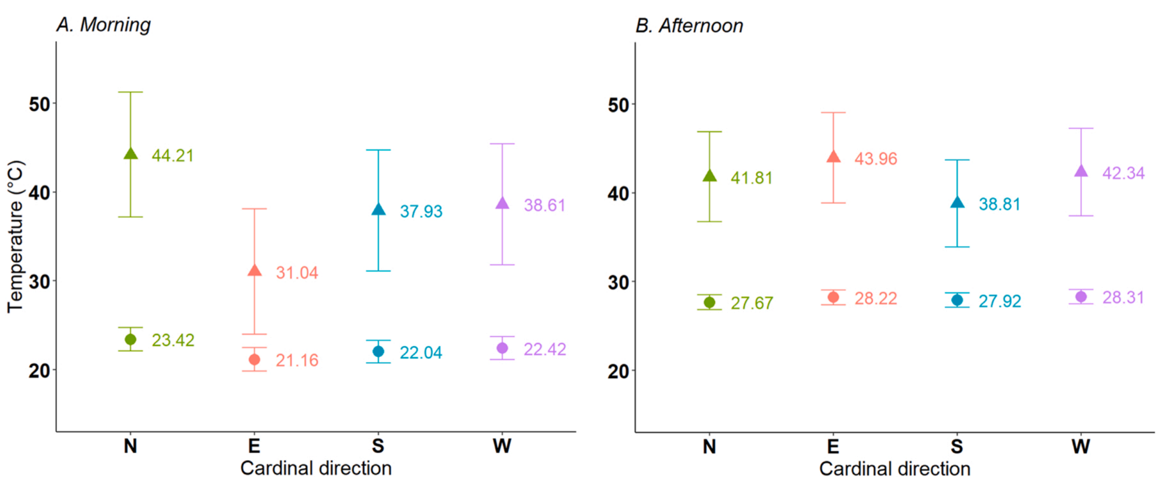

Fig. 6. Estimated marginal means for morning (panel A) and afternoon (panel B) temperatures by front yard cardinal direction (north, east, south, or west), based on linear models. Triangles represent mean radiant temperature (*Tmrt*) and circles represent air temperature (*Ta*). Error bars denote upper and lower values for a 95 % confidence level. The only significant difference in temperature between cardinal direction levels was for *Tmrt* in north and east-facing front yards in the morning (p = 0.06), with north-facing properties 13.17 ℃ warmer in *Tmrt* compared to east yards. From morning to afternoon, our analysis shows a 12.92 ℃ increase in *Tmrt*.

cover.

To our knowledge, no other urban heat studies have examined the full range of percent canopy cover (0–100 %) using on-the-ground T_{mrt} data. Our findings suggest that the right tree(s) in the right place can create critically cooler microclimates at ground level, significantly influencing thermal experiences for humans and other organisms below the canopy. While our analysis was conducted at the sub-parcel scale, the results raise questions about broad benchmarks, such as a 30 % canopy cover target, as stand-alone goals for urban forest management. Rather than uniformly applying the same ruleset across diverse neighborhoods, cities could prioritize context-specific planning that responds to what actually improves people's thermal experiences. This includes tailoring strategies to local conditions and lived experiences, while pushing cities toward more ambitious and equitable urban forestry practices—such as prioritizing tree planting in heat-vulnerable communities, targeting high-foot-traffic areas like bus stops, integrating trees along active transportation routes to support alternative forms of mobility, and updating tree requirements for new developments based on site-specific conditions.

4.2. *Cardinal orientation: trouble in (western) paradise?*

This study aimed to identify cardinal orientations that should be prioritized for heat mitigation interventions via greening. The prevailing literature to date predicts that west-facing landscapes are hottest (Simpson and McPherson, 1996; McHale et al., 2007; Donovan and Butry 2009; Ko and Radke, 2014; Hwang et al., 2015), leading to widespread recommendations to prioritize planting shade trees on the west side of buildings. However, our findings did not support this assumption. We observed only minor, non-significant differences in

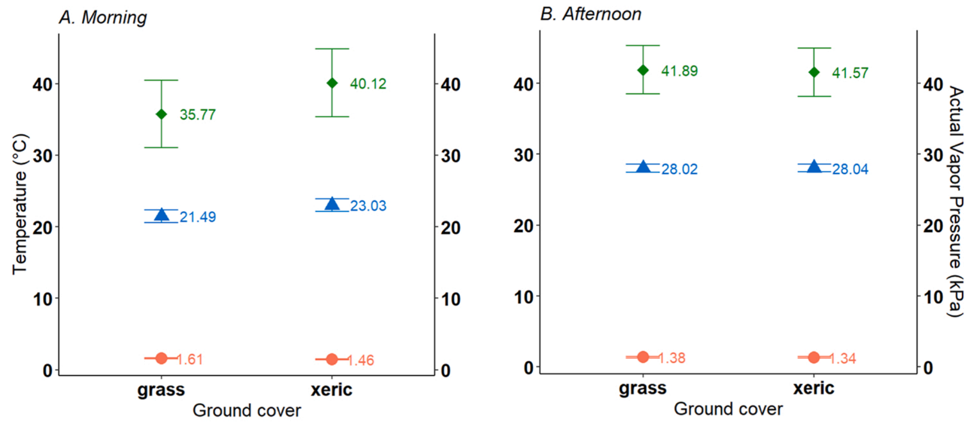

Fig. 7. Estimated marginal means for morning (panel A) and afternoon (panel B) temperatures and actual vapor pressure by front yard ground cover type (grass or xeric), based on linear models. Green diamonds represent mean radiant temperature (*Tmrt*), blue triangles represent air temperature (*Ta*), and orange circles represent actual vapor pressure (*e*). Error bars denote upper and lower values for a 95 % confidence level. The 16 xeric front yards tended to have 1.5 °C cooler *Ta* and 0.15 kPa lower *e* in the morning, compared to the 16 grass landscapes. Differences between xeric and grass groups were not significant in the afternoon. Morning pairwise comparison results: *Tmrt* p = 0.19; *Ta* p = 0.02; *e* p = 0.03. Afternoon pairwise comparison results: *Tmrt* p = 0.90; *Ta* p = 0.97; *e* p = 0.52.

Table 3
Results of afternoon T_{mrt} multiple linear models with either sky view factor (SVF), vegetation view factor (VVF), or canopy cover as the key explanatory variable, along with a city temperature covariate. Asterisks indicate p-values of: 0 < *** < 0.001 < ** < 0.01 < * < 0.05 < . < 0.1. R^2 is the coefficient of determination. SVF was the strongest predictor of T_{mrt}, although canopy cover was still significant. SVF explained the most variation in T_{mrt}, followed by canopy cover and then VVF.

	SVF	VVF	Canopy cover
p-value	< 0.0001***	0.29	0.02*
R^2	0.42	0.26	0.31

peak temperatures across yard orientations.

The "west is best" guidance largely originates from urban forest models such as STRATUM (Street Tree Resource Analysis Tool for Urban Forest Managers) (Mcpherson et al., 2005), UFORE (Urban FORest Effects) (Nowak et al., 2000), and i-Tree (Nowak, 2020), which simulate tree benefits and predict that trees on the west side offer the greatest cooling in the Northern Hemisphere. However, ground-based studies increasingly challenge these model-based assumptions. For example, Nelson et al. (2012) found that trees in the northeast and northwest provided modest energy savings in Raleigh, North Carolina, USA, while Abram et al. (2022) observed greater cooling benefits from east-side trees.

While we expect that a larger sample size and more typical summertime conditions would detect any thermal differences among yard orientations, our findings support growing calls to revisit simplified planting guidelines and emphasize the need for site-specific strategies grounded in empirical evidence. Land managers should consider a wide range of contextual factors—such as neighbourhood layout, latitude, climate, vegetation type, and seasonal tradeoffs (McHale et al., 2007; Nelson et al., 2012)—when making planting decisions.

4.3. *Xeriscapes: amplifying morning heat—even during a record-breaking rainy summer*

Although thermal differences between grass and xeric sites were more modest than anticipated, our models revealed that xeriscapes had slightly lower morning atmospheric moisture and warmer morning temperatures. These findings are particularly notable given that the study took place during the wettest summer on record—characterized by cooler temperatures, frequent cloud cover, and sustained rainfall.

While we did not directly measure soil moisture or household irrigation, widespread precipitation suggests that soil moisture was elevated across sites, regardless of ground cover. This unusual context provided a unique opportunity to examine landscape thermal dynamics under conditions likely approaching soil moisture saturation. Field observations and conversations with homeowners indicated that some grass sites were actively irrigated, especially in sunnier areas, while xeric yards generally did not appear to be.

We expect that, even under uniformly high soil moisture from rainfall, turf grass provided greater cooling than xeriscapes due to its higher evapotranspirative potential—especially at sites where irrigation was also applied. These patterns align with prior research demonstrating that irrigated turf grass can provide localized cooling once soil moisture is sufficient for evapotranspiration (Cheung et al., 2023; Cheung et al., 2024).

In more typical hot, dry, and cloud-free summers, we expect the contrast between grass and xeric yards to be greater. Increased irrigation in grass yards and reduced soil moisture in xeric ones would likely amplify evapotranspiration differences and intensify variation in T_{mrt}, T_a and *e*. However, it should be noted that xeriscapes are not inherently water-conserving—previous studies show they may not always reduce outdoor water use as intended (Martin, 2001; Wentz and Gober, 2007). This underscores the need for data on household irrigation and soil moisture data to evaluate the true water and thermal performance of landscape types.

Incentives such as xeriscape rebate programs offer a promising path toward more resilient social and ecological systems, but their effectiveness could be improved through greater specificity. Not all xeriscapes function the same—indeed, differences in vegetation cover, ground material (e.g., mulch vs. rock), and time since establishment likely shape both hydrological and thermal outcomes. Future research should move beyond binary "grass vs. xeriscape" categories and instead assess xeric yards based on distinct traits. Incorporating soil moisture and irrigation data into micrometeorological models would enhance our understanding of how different landscaping choices affect local heat and water dynamics, helping cities fine-tune programs without unintentionally promoting particularly hot or high-water-use designs.

4.4. *Urban Ecosystem Structure: Sky View Factor Is More Precise, but Percent Canopy Cover May Be More Useful*

In line with previous studies, our research shows a clear relationship between sky view factor (SVF) and T_{mrt}. Although our analyses show that average yard SVF (i.e., areal means across five points) holds strong predictive power for afternoon T_{mrt}, we propose that canopy cover is a more useful metric for management purposes. Our results show that remotely derived percent canopy cover maintains a significant relationship with on-the-ground T_{mrt} measurements, even with a four-year mismatch between the land cover classification (2019) and micrometeorology measurements (2023). This is compelling because canopy cover can be efficiently extracted at large scales using remote sensing methods and aligns with the data typically used by cities worldwide to set and assess urban forestry goals (Blood et al., unpublished results).

Notably, vegetation view factor (VVF) alone did not have strong predictive power for T_{mrt}. SVF represents the inverse of vegetation pixels (VVF) combined with building pixels (BVF), demonstrating how the built environment also plays an important role in shaping ground-level micrometeorology. Furthermore, canopy cover outperformed VVF—possibly because it provides more complete spatial coverage across each yard, whereas our VVF values were based on the average of five point-based measurements.

Our findings suggest that, while the view factor approach offers precision in linking urban structure to micrometeorology, it does not offer sufficient additional value from an ecological or urban forestry management perspective to justify its resource intensity. In contrast, canopy cover is not only easier to obtain at large scales using remote sensing methods, but it also supports a broader range of ecological and planning applications beyond urban climatology. For example, existing canopy cover can be directly tied to common urban forest strategies such as tree planting initiatives and canopy cover targets (e.g., 40 % canopy cover by 2050). Given its significant relationship with afternoon T_{mrt} —even across a multi-year data gap—we posit that percent canopy cover derived from land cover classification offers a practical and ecologically meaningful alternative to more cumbersome metrics like SVF and VVF.

4.5. Yard area: another key factor shaping residential landscapes

Although not a focal variable in the original study design, front yard area emerged as a meaningful contextual factor. Despite efforts to limit variation in yard size, it ultimately varied enough (22–246 m^2) to be correlated with front yard canopy cover, ground cover, and thermal outcomes. To avoid multicollinearity and preserve interpretability of key explanatory variables, yard area was excluded from final models, allowing us to isolate the effects of canopy cover, ground cover, and cardinal orientation without introducing redundancy to the models. However, post hoc investigations suggested that parcel size contributed to unexplained variation in T_{mrt} with our model tending to overpredict T_{mrt} for smaller yards and underpredict for larger yards; residuals from the full afternoon T_{mrt} model were significantly related to yard area ($p = 0.007$),

In our sample, larger yards tended to exhibit lower canopy cover (as per a 2019 land cover classification) and higher afternoon T_{mrt}—contradicting studies from other regions. For instance, research in the eastern USA found positive relationships between front yard area/parcel size and canopy cover (Bigsby et al., 2014; Ossola et al., 2019). These discrepancies may reflect underlying ecological differences: unlike areas with higher precipitation, Colorado's arid climate limits spontaneous tree growth, making vegetation more dependent on active planting and irrigation. Local research by Rasmussen et al. (2021) similarly found that smaller parcels in Fort Collins had higher canopy cover and lower water use during summer months, reinforcing the distinct dynamics of urban landscaping in semi-arid regions.

Yard area also differed across ground cover types. Grass yards were larger on average (mean = 105 m^2, range = 22–246 m^2) than xeric yards (mean = 71 m^2, range = 35–134 m^2). This may reflect our selection criteria, as we excluded partially converted yards from the xeric category. We suspect small parcels are more likely to undergo full xeriscape conversion, while larger yards may implement only partial conversions–though our data cannot confirm this.

We also acknowledge that our use of a fixed number of five measurement points per yard—regardless of yard size—may have affected the representativeness of our thermal measurements. In smaller yards, this approach captured more of the variation present than in larger yards, where the same number of points may have under sampled heterogeneity. We note the importance of adapting sampling intensity to parcel size in future research.

As scientists and practitioners work to refine land management strategies, parcel size should be considered. Yard area can shape microclimates both directly—for example, smaller yards may heat up more quickly due to closer proximity to buildings and pavement—and indirectly, by enabling or limiting available space for plants to grow. This implies that uniform greening strategies such as minimum tree counts per parcel may require re-evaluation, as a fixed number of trees has different implications depending on area. Future research should continue exploring how parcel size interacts with private landscaping decisions, water use, and thermal dynamics—particularly across different biogeographic regions.

5. Conclusion

As communities worldwide face intensifying summer heat and water scarcity, there is a growing need for localized strategies that reflect how people and other organisms within the urban ecosystem actually experience heat on the ground. This study applied a fine-scale ecological sampling approach using hyper-local micrometeorology data to assess thermal differences between residential landscaping types. We found some significant patterns—particularly related to canopy cover—but not others, which we suspect was due to the unusually wet summer during data collection. Our findings provide a foundation for further research that aims to leverage similarly localized methods.

Using micrometeorology data from 32 front yards across a 0–100 % canopy gradient, our research highlights the reality that tree canopy doesn't just cool cities—it shapes distinct microclimates across urban landscapes. Rather than treating the city as a uniform space with a single "urban heat island" effect, we show that differences in canopy cover at the sub-parcel scale can produce fine-scale variation in thermal experience. Although past studies have linked canopy cover with reductions in air and surface temperature, this is the first study to evaluate mean radiant temperature (T_{mrt}) –a key metric for understanding how people experience heat–across the full 0–100 % canopy spectrum. Our results show a strong, linear relationship between canopy cover and T_{mrt}, reinforcing the idea that even modest increases in canopy can translate to meaningful changes in thermal exposure—even when air temperatures remain relatively stable.

We also compared the performance of sky view factor (SVF) and canopy cover in explaining T_{mrt}, and, while SVF proved to be a precise predictor of radiant heating, canopy cover was significant in our models as well. This has important implications for urban forest researchers and practitioners: canopy cover is not only more practical for cities to work with but also has broader ecological and urban forestry relevance beyond micrometeorology.

We examined ground cover (grass lawns versus xeriscapes) and cardinal orientation (north, east, south, and west-facing yards) but did not find the significant relationships with T_{mrt} or T_a that we expected. We anticipate these effects would be more pronounced in the hotter, drier conditions typical of Colorado Front Range cities.

To realize the potential of their urban forests, cities must engage with private property owners—who collectively manage a large proportion of urban land. While development requirements and incentive programs can help, many current approaches rely on city-wide canopy targets or other broad planting recommendations that overlook the heterogeneity in how heat is distributed at the human-relevant scales. By quantifying how front yard characteristics influence variation in T_{mrt}, this study helps bridge that gap between coarse-scale management strategies and fine-scale thermal realities.

T_{mrt} reductions observed here demonstrate that small changes in landscape structure can shift the microclimate in perceptible and impactful ways. Measuring urban heat at this scale, using accessible data like canopy cover, empowers cities to identify priority areas, refine planting programs, and develop interventions that respond to the lived experiences of residents. By embracing heterogeneity and planning with hyper-local conditions in mind, cities can move beyond one-size-fits-all solutions and build more resilient, equitable, and livable urban environments.

CRediT authorship contribution statement

Melissa R. McHale: Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Travis Warziniack:** Writing – review & editing, Resources, Project administration. **Bianca N.I. Eskelson:** Writing – review & editing, Methodology, Formal analysis. **Aubrey Benson:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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