



# From West to East: Tree Placement Differentially Affects Summertime Household Energy Consumption in a Semi-Arid City

By Lauren Z. Abram, MS, Joshua P. Keller, PhD,  
Elizabeth A. Tulanowski, MS, and Melissa R. McHale, PhD

**Abstract.** Background: Urban tree canopy (UTC) is often proposed as a mitigation strategy for simultaneously decreasing carbon emissions and urban heating in cities. Not only can trees reduce outdoor temperatures through shading and transpiration, but research also suggests that microclimate regulation by trees surrounding buildings can lead to cooler indoor temperatures and a subsequent decrease in summertime energy use. Methods: We analyzed summertime cooling electricity consumption for 21,048 single-family homes in a semi-arid city in northern Colorado, USA. Using Pearson's correlation coefficients and multiple linear regression models, we evaluated the potential impact of UTC on cooling electricity use in 16 different zones around each house. We hypothesized that trees closer to the home, and trees located on the west and south sides of homes, would have the greatest impact on cooling electricity use. Results: UTC in all 16 zones around residential buildings was associated with negative correlation coefficients, indicating that UTC may be having an impact on energy use. Our regression results showed that UTC on the east side of single-family homes had the greatest effect. Conclusions: Although our results indicated that trees in landscapes around residential buildings can lead to some decreases in household-level energy consumption, the reductions in electricity usage were not as substantial as previous studies have predicted. Past research has shown that tree location matters, and our results indeed show that where UTC is located in reference to a building can change how much impact trees have on energy use. However, our results also show that trees on the east side of buildings have the most impact on household energy consumption in a semi-arid city in Colorado during the summer months. These results directly contradict predictions offered by popular ecosystem service models that show trees on the west and south sides of buildings as having the most impact on energy use in the Northern Hemisphere. Furthermore, many studies have suggested that the energy benefits provided by urban trees outweigh their carbon sequestration potential, and our results indicated this assumption may not hold true in all cities.

**Keywords.** Residential Energy; Tree Benefits; Urban Ecology; Urban Forestry.

## INTRODUCTION

Climate change and the Urban Heat Island (UHI) effect are resulting in rising temperatures and prolonged, severe heat waves in our cities, threatening livability and negatively impacting the health and well-being of urban residents. As a result, more cities are attempting to create cooler spaces, both indoor and out, for their residents, especially during the summer months when high temperatures and heat waves pose the most danger to vulnerable populations. On top of putting urbanites' health at risk, cities and their utilities are struggling to keep up with energy demands during heat waves, when residents with access to air-conditioning depend heavily on this

mechanism to maintain comfortable temperatures in their homes. Even under typical, or less extreme, summertime conditions, research has shown that overall energy demand in cities can increase by 2% to 4% with every 1 °C increase in temperature (Akbari et al. 2001).

While there are many ways to address urban heating and increased energy demand in a city, one commonly cited method is to invest in urban tree canopy (UTC). Research has shown that trees in urban landscapes can mediate increased heat through shading and evapotranspiration (Middel et al. 2015; Ko 2018; Wang et al. 2018; Rahman et al. 2020; Winbourne et al. 2020). Ecosystem service models that predict the

benefits of UTC, like i-Tree (USDA; Madison, WI, USA)(Nowak 2020), have shown that trees near buildings can also reduce indoor energy use in the summertime (McPherson and Simpson 1999; Nowak 2002; Nowak et al. 2008; Nowak et al. 2017). These studies have led city managers to consider increasing UTC as one potentially valuable strategy for reducing the negative impacts of urban heating.

Although the overall phenomenon of the UHI effect and its impacts are well-known and widely recognized (Oke 1982; Tan et al. 2010; Santamouris 2014), how exactly to mitigate increased urban heating over time, at different scales, and across a variety of climates and sociocultural contexts remains a research priority and policy challenge (Myint et al. 2015; Hamstead et al. 2020). For instance, it is generally expected that increased impervious surfaces lead to increased temperatures, as these surfaces affect moisture availability and radiative energy transfer (Mojajerani et al. 2017). Contrastingly, UTC has been shown to have an impact on temperature by decreasing average near-surface air temperatures, which enhances radiative cooling and improves thermal comfort (Middel et al. 2015; Wang et al. 2018). Yet the magnitude of the negative impacts of impervious surfaces and positive impacts of vegetated landscapes varies substantially across studies, leading to research on the role of climate, latitude, season, time of day, urban density, and urban form on increased urban heating in cities (Zhou et al. 2014; Wheeler et al. 2019). A literature review by Wheeler et al. (2019) on mitigating urban heating in dryland cities delved into counter-intuitive results on how tree canopy can both reduce and increase air temperatures at different times of day and in different configurations. At the same time, there is ample evidence that UTC does impact outdoor temperature, providing an estimated \$5.3 to \$12.1 billion in various heat-reduction services across the entire US urban population, including the avoidance of heat-related morbidity and mortality (McDonald et al. 2020).

Given the temperature reductions UTC can provide outdoors, many studies have tried to quantify the indoor energy savings from UTC in summer months. Studies have found that trees planted beyond 18 m of a home do not impact energy use by creating shade (McPherson et al. 1988; McHale et al. 2007; Donovan and Butry 2009; Nelson et al. 2012) and that maximum shade benefit comes from larger trees planted

within 5 m of a home (Gómez-Muñoz et al. 2010; Hwang et al. 2015). Additionally, it is widely documented that azimuth can play a role in the impact trees have on energy use, and that trees planted on the west, east, and south sides of homes yield the most energy savings during the cooling season in the Northern Hemisphere (Simpson and McPherson 1996; McPherson and Simpson 2003; Donovan and Butry 2009; Ko and Radke 2014; Hwang et al. 2015). For example, McPherson and Simpson (2003) used a simulated model and projected that planting 50 million shade trees to the east or west side of homes would reduce cooling energy use by 1.1% over 15 years.

Despite well-documented evidence that UTC has potential to provide energy savings in the summer months, the magnitude of those savings varies largely throughout the literature. In North America alone, a recent review found substantial evidence to support the energy-saving effects of trees; however, the range of reduced cooling-energy consumption varied from 2% to 90% (Ko 2018). One reason for the differences in findings could be due to the dissimilar nature of simulation and empirical methods. Simulation studies inherently come with various assumptions depending on the models, inputs, and software used. While they do not necessarily reflect real-world cases, they are still common in the literature. Empirical approaches, unlike simulation studies, use data from real-world scenarios. The methodology used in empirical studies varies considerably, with larger energy-saving performances being found from more controlled settings, such as treatment and control (tree shade and no shade) studies (Ko 2018). Other empirical studies use real energy-consumption data, but results are heavily dependent on the resolution and quality of the data obtained (Ko 2018). Variation in results can also be attributed to differences in study locations. Many studies that have looked at the impact of UTC have taken place in warmer climates, most notably in California. However, even within the same metropolitan area of Sacramento, California, the estimated annual cooling energy savings per tree has ranged between 80 kWh and 180 kWh in simulation studies (Simpson and McPherson 1996; Ko et al. 2015). In an entirely different climate, Nelson et al. (2012) concluded that trees did not significantly impact summertime energy savings in the heavily forested Raleigh, North Carolina. Very few studies have addressed the impact of

UTC using empirical data in semi-arid, mid-sized cities, highlighting the need for such research.

Given the fact that urban forestry and environmental managers are relying on results from models, such as i-Tree, to inform decision-making strategies for planting and maintaining UTC in cities, residential neighborhoods, and around single-family homes, we aimed to evaluate whether or not trees in landscapes around private residences had an impact on household cooling energy consumption. Since there is evidence that impervious surfaces may increase urban heating and potentially lead to increased energy consumption in homes in the summertime, we also evaluated the role of these surfaces around single-family homes. Our focus in this study was on landscape maintenance and design around residential buildings, since a majority of any city's constructed land area is composed of this particular land use, especially in sprawling cities across the United States. Studies have also shown residential landscapes, in particular, can affect how many ecosystem services are provided to residents (Larson et al. 2016; Mao et al. 2020). Further, cities are starting to consider how different policies can influence residents to change their landscapes for increased biodiversity (Aronson et al. 2017; Jimenez et al. 2022) and reduced household water consumption (Rasmussen et al. 2021).

Specifically, our goals were to (1) evaluate whether UTC and impervious surfaces in landscapes around single-family residences can have an impact on household energy consumption, and (2) provide empirical evidence for where UTC and impervious surfaces in landscapes around homes may have the most impact. Similar to previous studies, we expected that single-family homes in the study area would experience the greatest summer cooling electricity savings with increased tree canopy on the west side of homes, but that the magnitude of this relationship would vary based on the distance from homes. Additionally, we expected that with greater impervious cover around the home, summertime cooling electricity consumption would increase, regardless of azimuth and distance from homes, due to the role impervious surfaces have in urban heating. By using a large sample of empirical data, this study provides a significant contribution to the current understanding of the role of land cover, specifically tree canopy and impervious surfaces, on energy consumption. Our results will help inform future modeling efforts regarding land

cover and energy use and can impact city planning and development by revealing where tree canopy and impervious surfaces are having the most impact on summertime cooling electricity consumption in single-family homes.

## MATERIALS AND METHODS

### Study Location

Our study area was a midsize, growing city of approximately 170,000 people (United States Census Bureau 2020) located in northern Colorado along the Front Range of the Rocky Mountains at approximately 5,000 ft (1,524 m) above sea level. The city is in a semi-arid region with average rainfall of 15 in (38.1 cm) per year, average snowfall of 50 in (127 cm) per year, and approximately 300 days of sunshine annually (National Weather Service 2018). The temperature average in the summer months is about 72 °F (22.2 °C) but can reach a maximum average of 97 °F (36.1 °C) during the day (National Weather Service 2018). While there are a limited number of naturally occurring trees, the city has prioritized the maintenance and development of an extensive UTC through various programs (Community Canopy Program 2017). The UTC in the study area includes a diversity of deciduous species that are successful in the climate, such as the littleleaf linden (*Tilia cordata*) and Kentucky coffeetree (*Gymnocladus dioica*) (Approved Street Trees 2021).

### Land-Cover Data

High-resolution land-cover data (1 m<sup>2</sup>) were derived from WorldView-2 satellite imagery and LiDAR using object-based feature extraction techniques (Zhou and Troy 2008; O'Neil-Dunne et al. 2013; Beck et al. 2016; Rasmussen et al. 2021). A hybrid-stratified random accuracy assessment with 2,400 points calculated the overall accuracy of the land-cover data set to be 95% (Congalton and Green 2019). This classification method has been conducted in other cities including New York, Baltimore, and Raleigh (Troy et al. 2007; MacFaden et al. 2012; Bigsby et al. 2014). The land-cover data set consisted of 7 classes: tree canopy, other vegetation (e.g., grasses, shrubs, etc.), bare soil, water, buildings, roads/railroads, and other impervious surfaces (e.g., driveways, sidewalks, etc.) (Figure 1, Table 1). All processing of land-cover data was completed using tools in ArcGIS Pro (Version 2.7; Esri, Redlands, CA, USA). For the purposes of this study, we reclassified land cover into 3 classes:

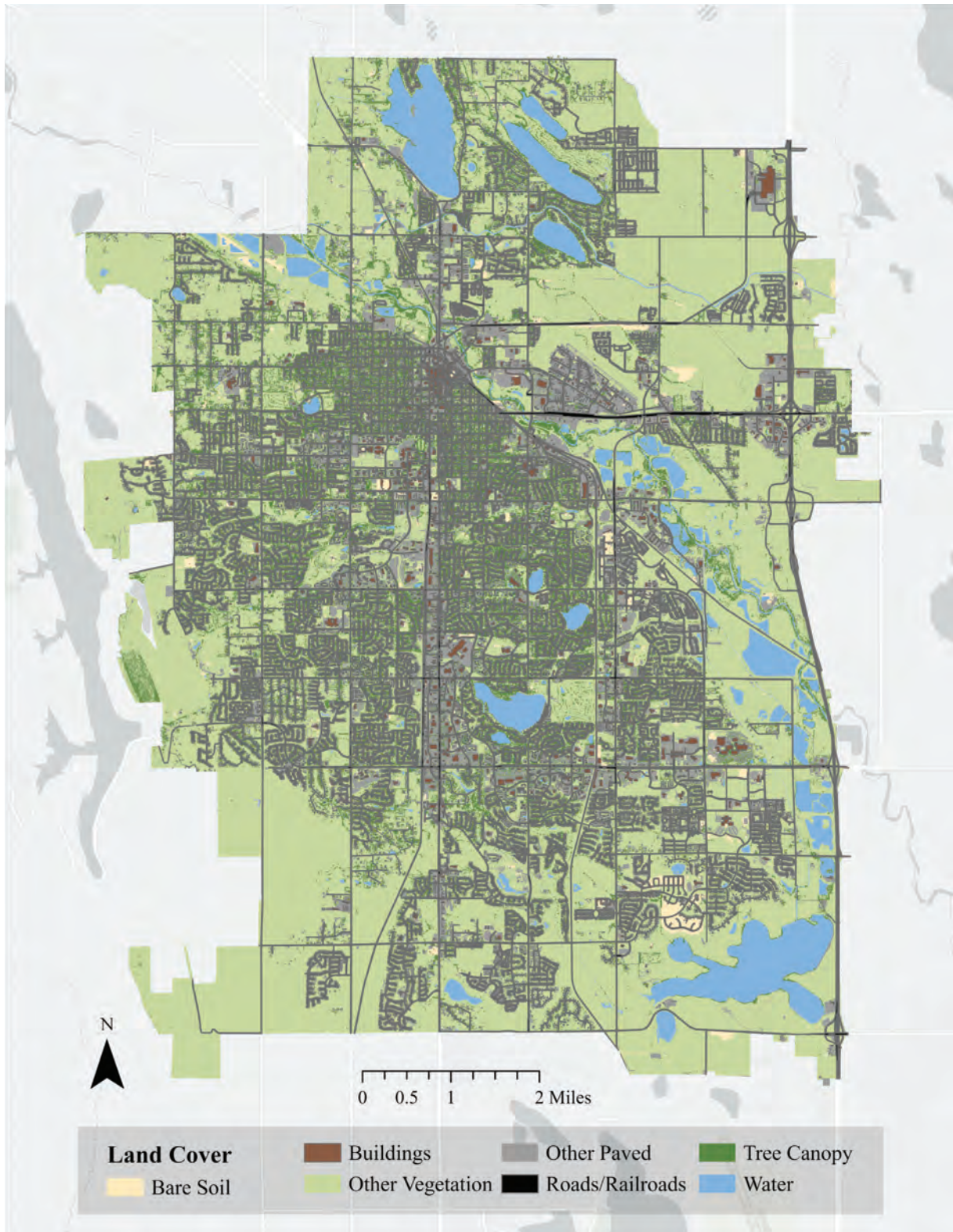


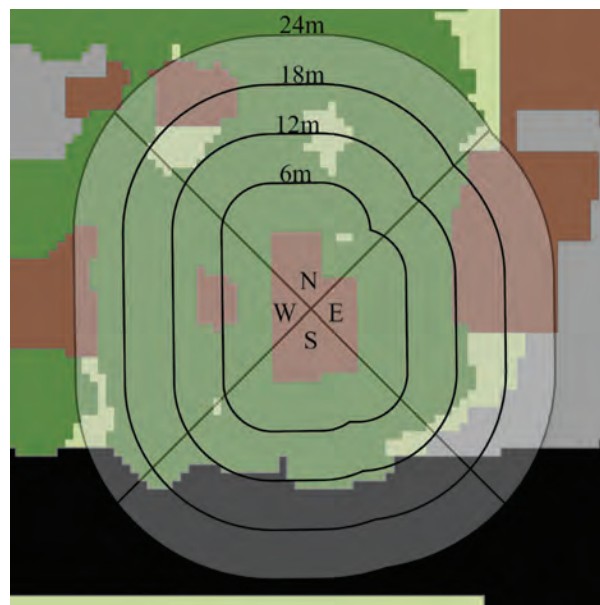
Figure 1. Land-cover classes of the study area (Rasmussen et al. 2021).

**Table 1. Land-cover distribution within the study area. The landscape is mostly dominated by other vegetation, such as shrubs and grasses, followed by tree canopy (TC) and other paved surfaces.**

Land cover	Percentage of landscape
Other vegetation	52%
TC	13%
Other paved	13%
Roads/railroads	8%
Buildings	7%
Water	6%
Bare soil	1%

tree canopy, impervious surfaces (roads/railroads and other impervious surfaces), and other (buildings, bare soil, water, and other vegetation). Buildings were not included in the impervious surfaces category as their height can provide shade throughout the day, in addition to having sensible heat emissions, which results in a more complex relationship with urban heating. In addition, a recent study has suggested that the impact of building shade on sensible heat flux from the ground is relatively small, even from buildings as tall as 6 stories (Alhazmi et al. 2022). Our analysis was conducted in residential areas that only have 2-story homes or smaller; therefore, impervious surfaces were isolated to those surfaces that lie flat on the ground. In order to determine whether or not we were missing potentially large impacts associated with buildings, we completed a preliminary analysis including buildings in our models. These results suggested that adding buildings to the analyses did not change the effects associated with trees and impervious surfaces in residential landscapes.

To determine the maximum cooling benefit UTC had on summer electricity consumption, as well as the impact that impervious surfaces had on summer electricity consumption, we generated 4 buffers at 6-m, 12-m, 18-m, and 24-m distances around single-family homes by using the Buffer tool with a building polygon layer provided by the city as our input. This resulted in 4 polygonal buffers for each building in our sample. The 6-m distance buffers consisted of the area over the home up to 6 m away; the 12-m distance buffers were the area 6 m to 12 m from the home; the 18-m distance buffers were the area 12 m to 18 m from the home; and the 24-m distance buffers were the area 18 m to 24 m from the home. Each buffer was



**Figure 2. Buffers broken into quadrants: 6-m, 12-m, 18-m, and 24-m distance buffers were broken down by azimuth (North, South, East, and West) resulting in 16 separate zones.**

then broken into quadrants to account for azimuth (North, South, East, and West) using the Subdivide Polygon tool, resulting in 16 separate zones. We created our zones in size increments of 6 m in the 4 cardinal directions due to their usage in previously published studies that examined the impact of tree canopy on electricity consumption (McPherson and Simpson 1999; McHale et al. 2007; Donovan and Butry 2009; Nelson et al. 2012). Creating these zones was an important step to isolate locations of tree canopy and impervious surfaces according to their distance and direction from single-family homes in our study (Figure 2, Table 2).

We summarized the area of tree canopy and impervious surfaces within each zone using the Intersect tool and converted area to percent cover for every household in our sample. This process was completed for the 16 separate zones, resulting in 32 explanatory variables (Table 3). The distribution of all land-cover variables was positively skewed but included a spread across all percentage values, negating the need for any type of transformation.

## Electricity Data

Unlike many other localities, the city owns their electricity utility, allowing us to obtain parcel-level electricity consumption data for the year 2016. We restricted analysis to single-family detached houses

**Table 2. Descriptive statistics of zone areas (m<sup>2</sup>). Note that the 6-m distance buffer contains the area over the home up to 6 m away, while the 12-m distance buffer is the area 6 m to 12 m, the 18-m distance buffer is the area 12 m to 18 m, and the 24-m distance buffer is the area 18 m to 24 m.**

	6 m				12 m				18 m				24 m			
	Min	Median	Mean	Max	Min	Median	Mean	Max	Min	Median	Mean	Max	Min	Median	Mean	Max
<b>North</b>	60	168	174	768	115	172	174	370	171	228	230	420	228	285	287	473
<b>East</b>	63	167	172	648	116	172	174	359	173	228	230	397	229	285	286	446
<b>South</b>	60	168	174	768	115	172	174	370	171	228	230	420	228	285	287	473
<b>West</b>	63	167	172	648	116	172	174	359	173	228	230	397	229	285	286	446

**Table 3. Descriptive statistics of tree canopy (TC) and impervious surfaces (IS) in zones (%).**

	6 m				12 m				18 m				24 m			
	Min	Median	Mean <sup>a</sup>	Max	Min	Median	Mean <sup>a</sup>	Max	Min	Median	Mean <sup>a</sup>	Max	Min	Median	Mean <sup>a</sup>	Max
<b>TC</b>																
<b>North</b>	0	15	22/27	100	0	23	29/33	100	0	14	23/27	100	0	15	22/25	100
<b>East</b>	0	15	21/26	100	0	21	28/32	100	0	14	22/26	100	0	16	22/25	100
<b>South</b>	0	18	25/31	100	0	22	28/32	100	0	14	22/26	100	0	15	22/25	100
<b>West</b>	0	18	27/33	100	0	21	27/32	100	0	13	22/25	100	0	16	22/24	100
<b>IS</b>																
<b>North</b>	0	18	20/24	85	0	16	26/29	100	0	26	38/42	100	0	32	39/42	100
<b>East</b>	0	20	22/25	85	0	16	24/27	100	0	25	36/39	100	0	32	38/41	100
<b>South</b>	0	16	19/23	87	0	16	26/30	100	0	26	38/42	100	0	32	39/42	100
<b>West</b>	0	17	20/24	89	0	17	24/28	100	0	27	36/40	100	0	33	39/41	100

<sup>a</sup>Where 2 values appear in a cell, the first includes all households, and the second includes only households where that variable > 0.

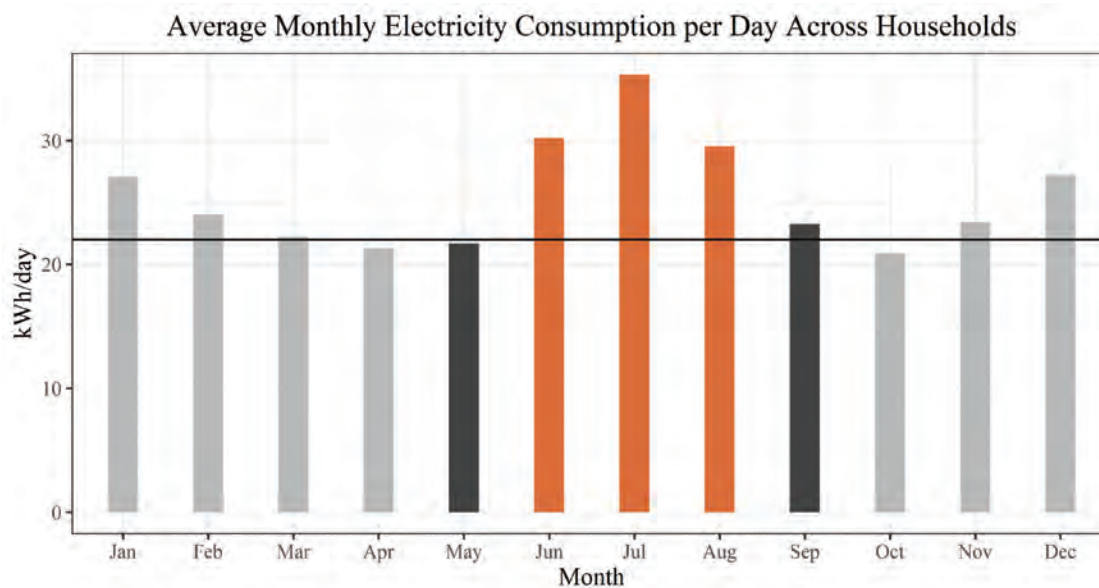
in an effort to reduce the variability in consumption patterns that might arise by including commercial and multi-unit properties. Due to limitations on electric heating information as well as seasonal variation, we focused on summer (defined as June 1st to August 31st) cooling electricity consumption. Annual electricity consumption is known for having an *M*-type distribution curve, with peaks occurring in summer and winter, making it important to analyze the data seasonally to prevent any trends or patterns from being averaged out (Figure 3).

To prepare the data for analysis, we isolated single-family residential households using parcel information from the city as well as the county assessor's office (Larimer County Assessor's Office, unpublished data). We joined unique premise codes of household electricity consumption data to single-family residential parcel polygons and removed parcels that had duplicate information (i.e., multiple premise codes per parcel or multiple parcel numbers per premise), incomplete consumption readings, or a change in residency

during the year, resulting in 24,346 singlefamily residential parcels.

To determine average consumption for each household, we used billing information to prorate electricity consumption based on read dates and days of service to calculate the average use for each calendar month. We then averaged each household's use for the months of June through August and divided by the number of days from June 1st to August 31st (92) to get the average summer kWh per day (kWh/day) for each household.

To get cooling electricity use, we used information from the shoulder months of May and September when electricity is less likely to be used for cooling or heating due to milder temperatures. We averaged the kWh/day for May and September together and subtracted that from the summer kWh/day to get cooling kWh/day (Figure 3). We normalized the electricity consumption data by the square footage of the home, documented by the assessor's office, to calculate our response variable as kWh/day per 1,000 ft<sup>2</sup> (kWh/day/1,000 ft<sup>2</sup>) (Table 4). Our analysis response variable was performed using



**Figure 3.** Average monthly consumption (kWh/day) across single-family households in the study area. Two peaks are observable in the winter and summer months. Months in dark gray are shoulder months, and months in orange are peak summer months. The horizontal line represents the average consumption in shoulder months. Averages above the line during the months of June, July, and August represent cooling electricity consumption.

**Table 4.** Descriptive statistics of house size and electricity consumption in our study sample. Values in parentheses represent metric conversions ( $m^2$ ).

Variable	Min	Median	Mean	Max
House size ( $ft^2$ )	381 (35.4)	1,836 (170.6)	1,918 (178.2)	7,241 (672.7)
Cooling electricity use (kWh/day)	0.0006	8.26	9.21	63.71
Cooling electricity use (kWh/day/1,000 $ft^2$ )	0.0005 (0.005)	4.5 (48)	5 (50)	13 (150)

English units due to the preferences of the local utility, however metric conversions are documented in parentheses ( $m^2$ ).

From our initial 24,346 households, we removed 2,866 households that had negative consumption patterns, meaning they used more electricity in the shoulder months than in the summer months. This could be due to a variety of reasons, such as summer being a common time for vacationing in the city. Additionally, we identified 432 households as outliers with consumption values 1.5 times the interquartile range beyond the third quartile or less than the first quartile. Upon investigation, outliers were primarily due to individual circumstances of extremely high average cooling electricity consumption, small household square footage, or a combination of both. Once outliers were removed, the final sample size was 21,048, and the distribution for the response variable was approximately normal.

## Correlations

We calculated Pearson's correlation coefficients using R (Version 3.6.2) for both tree canopy variables ( $n = 16$ ) and impervious surface variables ( $n = 16$ ), as well as between all land-cover variables and summer cooling electricity consumption (The R Foundation 2019). Correlations between land-cover variables and electricity consumption were used to identify the direction and magnitude of unadjusted, marginal relationships. Positive correlations indicated that with higher amounts of land cover, there was greater cooling electricity consumption, while the opposite was true for negative correlations.

## Linear Regression Models

To quantify the relationship land-cover variables had with summer cooling electricity consumption and further isolate the most impactful location for UTC and impervious surfaces, we fit 3 multiple linear

regression models: one with tree canopy variables, one with impervious surface variables, and a combined model with tree canopy and impervious surface variables. Since our goal was to estimate associations, not predict energy consumption amount, we did not apply a variable selection process or introduce additional variables in this analysis. Similar to correlations, positive coefficients in these models indicated that with higher amounts of land cover there was greater cooling electricity consumption, while the opposite was true for negative coefficients. Models were fit in R (Version 3.6.2)(The R Foundation 2019).

## RESULTS

### Correlations

The correlation analysis among tree canopy variables showed relatively strong, positive relationships among all zones in the same cardinal orientation (Figure 4). We found a similar pattern in impervious surface variables in the 12-m, 18-m, and 24-m zones (Figure 5).

The correlations between our tree canopy variables and cooling electricity consumption showed small, statistically significant negative correlations for most zones (Figure 6a). The 6-m and 12-m east and west zones had relatively stronger, negative correlations than all other zones. Contrastingly, the correlations between our impervious surface variables and cooling electricity consumption displayed small, but

nonsignificant positive correlations across all zones (Figure 6b). Correlations were relatively strongest within the 6-m zones at all orientations for impervious surfaces.

### Linear Regression Models

In the tree model, many variables had a significant negative relationship with cooling electricity consumption, including tree canopy in the 6-m and 24-m zones at all orientations and in the 12-m east and west zones (Table 5). Variables in the tree model that had the largest impact on cooling electricity use were tree canopy in the 6-m, 12-m, and 24-m east zones (Table 5). The negative coefficients indicated cooling energy consumption was lower in homes with a higher percentage of tree canopy in the corresponding zones, when accounting for tree canopy in all other zones. In context, the average-sized single-family home (1,918 ft<sup>2</sup> [178.2 m<sup>2</sup>])(Table 4) with the average percent of tree canopy within 6 m east of the home (21%)(Table 3) would be expected to have 26 kWh less electricity consumption over the course of peak summer, compared to a home with no tree cover within 6 m east of the home, holding all other tree canopy variables constant.

Results from the impervious surfaces model showed a consistent pattern where impervious surfaces in the 6-m zones at all orientations around the home had the most impactful, positive coefficients of all our

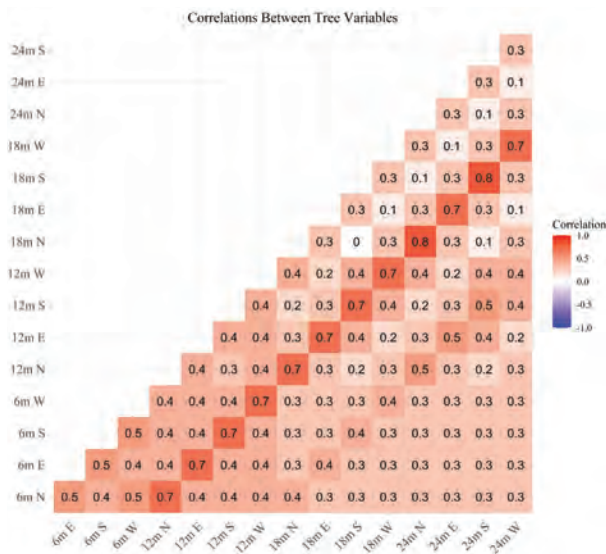


Figure 4. Pearson's correlation coefficients among tree canopy variables (%). The strongest correlations occurred in zones located in the same cardinal direction: for example, 6 m north and 12 m north.

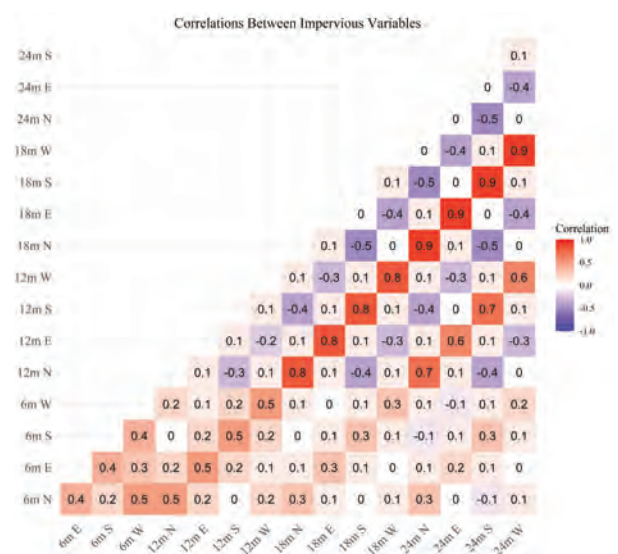


Figure 5. Pearson's correlation coefficients among impervious surface variables (%). The strongest correlations occurred in zones located in the same cardinal direction beyond 6 m: for example, 12 m north and 18 m north.

impervious surface variables (Table 6). Positive coefficients for impervious surface variables indicated that as the percentage of impervious surface increased, cooling kWh/day/1,000 ft<sup>2</sup> consumption increased as

well. In context, the average-sized single-family home (1,918 ft<sup>2</sup> [178.2 m<sup>2</sup>])(Table 4) with the average percent impervious surface within 6 m west of the home (20%)(Table 3), would increase electricity

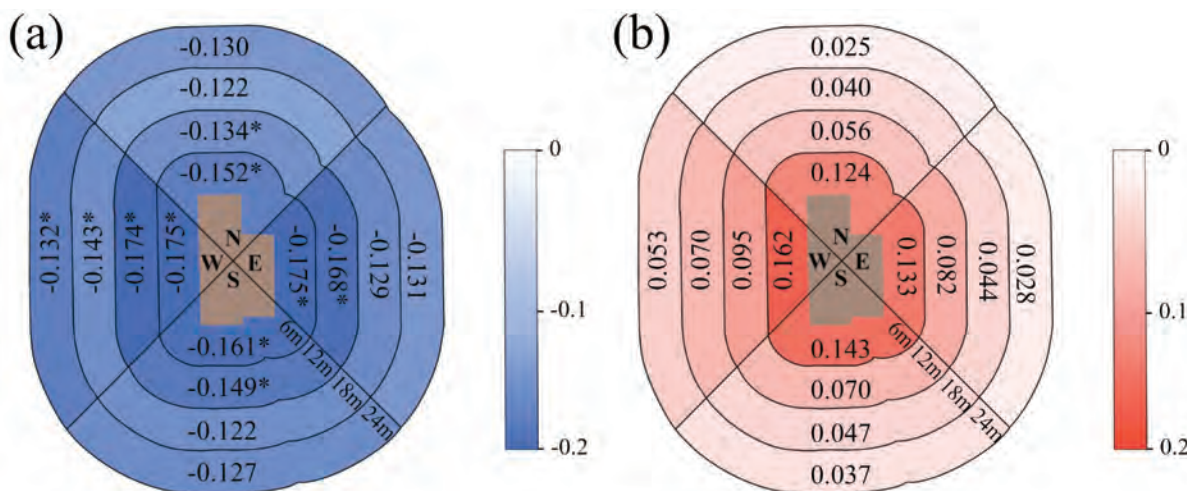


Figure 6. Pearson's correlation coefficients between tree canopy (a) and impervious surface variables (b) and cooling electricity consumption (kWh/day/1,000 ft<sup>2</sup>). All tree canopy variables had a negative relationship with cooling electricity consumption, and all impervious surface variables had a positive relationship with cooling electricity consumption. Values with \* notes statistical significance  $P < 0.05$ .

Table 5. Regression-model results using tree canopy (TC) variables. Variables are sorted by the magnitude of the coefficient and statistical significance.

Model 1 – TC		
Predictors	Estimates	CI
(Intercept)	5.86384 ***	5.78747 to 5.94021
6 m E	-0.00702 ***	-0.00980 to -0.00424
24 m E	-0.00684 ***	-0.00976 to -0.00391
12 m E	-0.00529 ***	-0.00810 to -0.00247
12 m W	-0.00466 **	-0.00747 to -0.00185
6 m W	-0.00455 ***	-0.00686 to -0.00224
24 m W	-0.00414 **	-0.00710 to -0.00117
24 m N	-0.00360 *	-0.00654 to -0.00066
24 m S	-0.00328 *	-0.00624 to -0.00032
6 m S	-0.00325 **	-0.00566 to -0.00085
6 m N	-0.00324 *	-0.00596 to -0.00052
12 m N	0.00251	-0.00030 to 0.00532
18 m E	0.00225	-0.00103 to 0.00553
18 m S	0.00165	-0.00167 to 0.00498
18 m N	-0.00151	-0.00475 to 0.00173
18 m W	-0.00225	-0.00561 to 0.00110
12 m S	-0.00259	-0.00537 to 0.00019
Observations		21048
R <sup>2</sup> /R <sup>2</sup> adjusted		0.056/0.055

\*  $P < 0.05$  \*\*  $P < 0.01$  \*\*\*  $P < 0.001$

Table 6. Regression-model results using impervious surface (IS) variables. Variables are sorted by the magnitude of the coefficient and statistical significance.

Model 2 – IS		
Predictors	Estimates	CI
(Intercept)	3.53010 ***	3.39263 to 3.66757
6 m W	0.01529 ***	0.01231 to 0.01826
6 m S	0.01175 ***	0.00864 to 0.01486
6 m E	0.01028 ***	0.00731 to 0.01324
6 m N	0.00791 ***	0.00480 to 0.01102
18 m N	0.00653 ***	0.00312 to 0.00994
12 m N	-0.00544 ***	-0.00863 to -0.00224
18 m W	0.00516 **	0.00179 to 0.00852
18 m S	0.00356 *	0.00011 to 0.00700
12 m S	-0.00325 *	-0.00641 to -0.00009
24 m N	-0.00320 *	-0.00605 to -0.00035
18 m E	0.00337	-0.00000 to 0.00674
12 m E	0.00287	-0.00027 to 0.00601
12 m W	-0.00012	-0.00318 to 0.00294
24 m W	-0.00022	-0.00304 to 0.00260
24 m E	-0.00065	-0.00343 to 0.00213
24 m S	-0.00104	-0.00392 to 0.00183
Observations		21048
R <sup>2</sup> /R <sup>2</sup> adjusted		0.044/0.043

\*  $P < 0.05$  \*\*  $P < 0.01$  \*\*\*  $P < 0.001$

consumption over the course of peak summer by about 54 kWh, compared to a home with no impervious surfaces within 6 m west of the home, holding all other impervious surface variables constant.

Our third model, which included both tree canopy and impervious surface variables, showed similar results to both our tree canopy model and our impervious surfaces model (Table 7). Again, tree canopy located on the east side in either the 6-m, 12-m, or 24-m zones, as well as the 12-m west zone and the 24-m north zone, had the largest significant negative coefficients. Impervious surfaces in the 6-m west and south zones were statistically significant and showed a strong positive relationship with cooling consumption. Impervious surfaces in the 18-m west zone and 6-m north zone also had a statistically significant positive relationship. In context, the average-sized single-family home (1,918 ft<sup>2</sup> [178.2 m<sup>2</sup>])(Table 4) with the average percent tree canopy in the 24-m east zone (22%)(Table 3) and average percent impervious surfaces in the 6-m west zone (20%)(Table 3) would result in the same magnitude of impact—a 27 kWh decrease and 27 kWh increase in cooling consumption over the course of peak summer, respectively, compared to a home with no impervious surfaces or tree cover in these zones, when all other variables are held constant. Our combined model also showed a slightly higher *R*-squared (0.061) when compared to the separate tree canopy and impervious surface models (0.056 and 0.044, respectively).

## DISCUSSION

### Impact of Tree Canopy and Impervious Surfaces

Our correlation and regression results indicated that both tree canopy and impervious surfaces had an impact on summer cooling electricity consumption in single-family homes in the city. Pearson correlation coefficients between land-cover variables and cooling electricity consumption, as well as results from all 3 regression models, showed that increased UTC was generally associated with less energy consumption, in contrast to increased impervious surfaces which were associated with more energy consumption. This is in line with previous studies that suggest tree canopy can mitigate energy consumption through shading and evapotranspiration (Ko 2018; Wang et al. 2018; Rahman et al. 2020; Winbourne et al. 2020). Our results also support previous research that shows

**Table 7. Regression-model results using tree canopy (TC) and impervious surface (IS) variables. For clarity, IS variables are shaded in gray in the table. Variables are sorted by the magnitude of the coefficient and statistical significance.**

Model 3 – TC & IS		
Predictors	Estimates	CI
(Intercept)	5.41441 ***	5.16648 to 5.66233
IS 6 m W	0.00763 ***	0.00437 to 0.01090
TC 24 m E	-0.00703 ***	-0.01032 to -0.00374
TC 24 m N	-0.00609 ***	-0.00940 to -0.00278
IS 6 m S	0.00600 ***	0.00260 to 0.00940
TC 6 m E	-0.00559 ***	-0.00859 to -0.00258
IS 12 m N	-0.00499 **	-0.00835 to -0.00162
IS 24 m N	-0.00498 **	-0.00813 to -0.00183
IS 12 m S	-0.00494 **	-0.00828 to -0.00161
TC 12 m W	-0.00491 **	-0.00792 to -0.00191
TC 12 m E	-0.00477 **	-0.00774 to -0.00181
IS 18 m W	0.00412 *	0.00051 to 0.00773
TC 24 m S	-0.00401 *	-0.00734 to -0.00068
IS 6 m N	0.00387 *	0.00051 to 0.00723
TC 6 m W	-0.00276 *	-0.00523 to -0.00029
IS 18 m N	0.00363	-0.00008 to 0.00733
IS 18 m E	0.00357	-0.00003 to 0.00717
IS 6 m E	0.00313	-0.00011 to 0.00638
TC 12 m N	0.00255	-0.00045 to 0.00555
TC 18 m S	0.00214	-0.00152 to 0.00580
IS 18 m S	0.00201	-0.00171 to 0.00573
TC 18 m E	0.00160	-0.00199 to 0.00520
IS 24 m W	0.00063	-0.00247 to 0.00373
IS 12 m E	0.00010	-0.00318 to 0.00337
TC 18 m W	-0.00050	-0.00418 to 0.00318
TC 18 m N	-0.00082	-0.00445 to 0.00280
TC 24 m W	-0.00151	-0.00484 to 0.00182
TC 6 m S	-0.00183	-0.00442 to 0.00076
TC 6 m N	-0.00188	-0.00477 to 0.00102
IS 24 m S	-0.00200	-0.00518 to 0.00118
IS 12 m W	-0.00209	-0.00530 to 0.00112
TC 12 m S	-0.00230	-0.00527 to 0.00068
IS 24 m E	-0.00251	-0.00558 to 0.00056
Observations		21048
<i>R</i> <sup>2</sup> / <i>R</i> <sup>2</sup> adjusted		0.061/0.059

\* *P* < 0.05 \*\* *P* < 0.01 \*\*\* *P* < 0.001

impervious surface can increase electricity consumption, possibly due to its role in increasing land surface temperatures in urban environments (Chithra et al. 2015).

## Most Impactful Orientations

The most impactful orientations for both tree canopy and impervious surfaces did not align with our hypotheses and showed different patterns when compared to previous studies. A well-established body of literature on the impact of tree canopy on cooling electricity savings has consistently shown that tree canopy on the west side of homes produces the largest savings, followed by the east and south sides (Simpson and McPherson 1996; Donovan and Butry 2009; Ko and Radke 2014; Hwang et al. 2015). Additionally, it has been assumed that trees planted beyond 18 m of a home do not impact electricity use directly through shading (McPherson et al. 1988; McHale et al. 2007; Donovan and Butry 2009; Nelson et al. 2012). In our analysis, both the tree canopy model and the combined tree canopy/impervious surface model challenge these assumptions. Our results showed that the most impactful variables in order of magnitude were the 6-m east zone, followed by the 24-m east and 12-m east zones in our tree model, and the 24-m east zone, followed by the 24-m north and 6-m east zones in our combined model.

The impact of impervious surfaces around homes on cooling electricity consumption is not well-documented in the literature, but the role of impervious surfaces in urban heating is well-researched, specifically in research on the UHI effect (Chithra et al. 2015; Estoque et al. 2017). Our results showed a clear pattern that impervious surfaces within 6 m of the home at all orientations were the most impactful in our impervious surfaces model. The combined model showed slightly more variation, but impervious surfaces within 6 m west and south of the home still showed high impact and significance. All significant impervious surface variables with a positive relationship were within 18 m of the home in both the impervious surfaces model and combined model. Since increases in impervious surfaces in cities can result in higher ambient temperatures (Weng 2001), it is possible that impervious surfaces closer to the home would have a more-pronounced impact on the microclimate than those located at a further distance.

## Comparison to Other Studies

While previous studies on the orientation of impervious surfaces around homes and the resulting impact on cooling electricity are scarce, there is ample evidence that UHI is associated with increased cooling

energy consumption in warmer months (Li et al. 2019; Su et al. 2021). However, there is high variation in this impact, with the increase in electricity demand per increase in degree of temperature falling between 0.5% and 8.5% (Santamouris et al. 2015). More specifically, in Colorado, data showed that daily electricity demand in the Colorado Springs utility district increased 4,000 kW, or about 1%, for every 1 °F increase in temperature (Akbari et al. 1992). Because our analysis did not have access to ambient air temperature around homes, we cannot directly compare our results to those that have studied urban heating and electricity demand. However, our results do support the notion that impervious surfaces around homes can contribute to increased cooling electricity consumption and are influencing microclimate around buildings.

The study of the impact of tree canopy on energy use has taken many forms in the literature with variations among sample size, residential building type, location, explanatory and response variables, and the method of analysis. For example, in simulation studies, annual cooling has been found to be as high as 180 kWh/tree (Simpson and McPherson 1996) and as low as 80 kWh/tree (Ko et al. 2015). The conservative prediction of 80 kWh/tree is comparable to other empirical results found by Donovan and Butry (2009). On the other hand, there are also empirical studies that have found little-to-no impact of tree canopy on summertime energy savings (Clark and Berry 1995; Abbott and Meentemeyer 2005; Nelson et al. 2012). This variation and subsequent spread in the magnitude of results, as well as how results were reported, makes it difficult to draw direct comparisons between our results and other studies. However, our results seem to show a much smaller impact than is typically predicted, even compared to more conservative estimates of savings found in both simulation and empirical studies. Our most impactful tree canopy variable common to our tree model and combined model was positioned in the 24-m east zone. The average tree canopy in this zone was 22%, which would be equivalent to about 63 m<sup>2</sup>, based on the average 24-m east zone size. This area roughly translates to a tree with a 30-ft (9.14-m) crown, which would be a common size for a large, deciduous tree in the city, such as a green ash (*Fraxinus pennsylvanica*). Using these calculations, we estimated savings of 27 kWh/tree in our combined model and 26 kWh/tree in our tree canopy model over the course of peak summer

while holding all other variables constant, which is considerably less than the low end of savings previously reported (80 kWh/tree annually) (Donovan and Butry 2009; Ko et al. 2015).

It is likely that the study location and methodology employed are playing a role in how different our findings are compared to previous studies. For example, the i-Tree model has been commonly applied in simulation studies to determine energy savings of trees in a variety of urban settings (McPherson and Simpson 1999; Nowak 2002; Nowak et al. 2008; Nowak et al. 2017). In contrast, our methodology included a large sample size at 21,048 single-family households, giving us an extensive pool of data to work with. Additionally, our explanatory variables were calculated using high-resolution spatial data which did not discriminate between individual trees, their heights, or their species. These differences in methodology and assumptions are important to consider, as they could be contributing to differences in results.

Our study area is a semi-arid city where most trees are not naturally occurring. Central air conditioning in the city has historically been less common due to cooler temperatures and low humidity, which is distinct from other study locations in warmer climates, like Sacramento. In addition to being semi-arid, the study area is located close to the Rocky Mountains, which could have climatic impacts altering the relative importance of UTC on summer cooling electricity. In contrast to somewhat older, larger, and more established cities, our study area is a relatively young, midsize city. This age and size difference could be reflected in the age of homes, how they were developed, or the overall design of homes in the study area, ultimately impacting the overall role UTC plays on cooling electricity consumption.

Based on our study, which used a large amount of high-resolution data for both the explanatory and response variables, the impact of tree canopy on summer cooling electricity is comparatively less than models and studies that are often referenced for energy savings provided by trees and highly utilized by city managers (McPherson and Simpson 1999; Donovan and Butry 2009; Nowak et al. 2017; Ko 2018). For context, running a 10 W LED lightbulb instead of a 60 W incandescent lightbulb for 5 hours/day over the course of the summer would save you about 23 kWh, just shy of the 26 kWh/tree savings in our study area. Despite low cooling energy savings, it is important to

note that UTC provides other ecosystem services such as removing particulate matter from the air, sequestering carbon, reducing noise, improving water quality, and reducing outdoor water use, enhancing its overall value to urban ecosystems (Herrington 1974; Dwyer et al. 1992; Scholz et al. 2018; Rasmussen et al. 2021).

## Limitations and Future Research

A component that our analysis omits is tree species, which can impact the cooling effectiveness of trees through differences in tree characteristics. Tree growth rates, Leaf Area Index (LAI), and crown size have all been found to impact cooling effects in urban areas (Armson et al. 2013; Rahman et al. 2015; Speak et al. 2020). This type of analysis would be especially helpful in the study area, where most trees are not naturally occurring and good planning and care are required to ensure the health and sustainability of the UTC. Additionally, tree height was not included in our analysis, which results in the omission of a dimension that could further account for the impact of shading throughout the day. Tree height has been used minimally in studies looking at the impact of UTC on energy savings, but when included it has shown significant results where a greater sum of tree heights in east, south, and west configurations around homes was associated with lower summer cooling electricity use (Ko and Radke 2014).

Looking at electricity data seasonally is important to prevent averaging out of trends; however, it leaves out the impact that trees or impervious surfaces have on winter energy use. Our data set is solely for electricity use, so applying a similar analysis to winter would not account for homes that may use natural gas for heating. There is evidence that trees, especially those planted on the south side, can hinder passive solar warming during the heating season and increase energy use (Heisler 1986; Hwang et al. 2015). In addition, climate, latitude, time of day, urban density, and urban form have also been found to impact urban heating and energy savings of trees (Zhou et al. 2014; Myint et al. 2015; Wheeler et al. 2019), and we did not capture these variables in our analysis. These are important considerations for future analysis to fully understand the role that land cover, especially UTC, plays in energy use in single-family homes.

Our goals for this study were to evaluate whether UTC and impervious surfaces surrounding single-family homes have an impact on summertime energy

consumption and provide empirical evidence for where UTC and impervious surfaces in landscapes around homes have the most impact. Our hypotheses followed results from previous studies, expecting the greatest summer cooling electricity savings from UTC to be on the west side of homes with a varying relationship with distance. We also expected that greater impervious cover around homes would increase summertime cooling electricity consumption regardless of azimuth and distance from homes, due to the role impervious surfaces have in urban heating. While our research focused on evaluating if UTC and impervious surfaces were impacting summer cooling electricity use in the city, the lack of explanation of variance in our models, as indicated by low *R*-squared values, suggests that there is much more to investigate. Our future work will expand on drivers of summer cooling electricity consumption in the city by bringing in more explanatory variables such as urban form, building, sociodemographic, and behavioral characteristics. This could help identify major contributors to cooling electricity use which could be targets for policy or program intervention.

## CONCLUSIONS

Although there is an ever-growing number of studies on the ecosystem services provided by trees, we still lack the necessary data and analyses needed to effectively develop management strategies to maximize the benefits provided by UTC, and in particular the impacts of UTC on increased urban heating. Previous studies and ecosystem service models suggest that trees around buildings can have a significant impact on summertime energy use, yet the magnitude of energy savings varies largely throughout the literature, highlighting the need for ongoing research on the topic in diverse landscapes.

Using a large sample of empirical data, our study aimed to evaluate the effect of UTC and impervious surfaces on energy consumption in a residential landscape. Although our results indicated that UTC around single-family homes can lead to some reduction in household-level energy consumption, the impacts were not as substantial as suggested by previous literature. Furthermore, the location of trees in landscapes does matter, but our results demonstrated that trees on the west and south sides of buildings may not always be the most effective at cooling homes.

Our results have implications for how cities develop UTC management strategies, as the reliance on

previously published findings or models regarding energy savings and optimal planting locations may not represent reality in all cities and urban environments. More empirical research is needed in cities of different sizes, located in various biomes, and across a variety of neighborhoods with different designs to understand the real impact trees may have on energy use associated with cooling buildings in the summertime, as well as other times of the year.

## LITERATURE CITED

- Abbott JA, Meentemeyer V. 2005. Research note—Vegetation effects on suburban air conditioning. *Urban Geography*. 26(6):558-564. <https://doi.org/10.2747/0272-3638.26.6.558>
- Akbari H, Davis S, Dorsano S, Huang J, Winnett S, editors. 1992. *Cooling our communities: A guidebook on tree planting and light-colored surfacing*. Berkeley (CA, USA): Lawrence Berkeley Laboratory; Washington (DC, USA): Environmental Protection Agency. 244 p. <https://doi.org/10.2172/5032229>
- Akbari H, Pomerantz M, Taha H. 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy*. 70(3):295-310. [https://doi.org/10.1016/S0038-092X\(00\)00089-X](https://doi.org/10.1016/S0038-092X(00)00089-X)
- Alhazmi M, Sailor DJ, Anand J. 2022. A new perspective for understanding actual anthropogenic heat emissions from buildings. *Energy and Buildings*. 258:111860. <https://doi.org/10.1016/j.enbuild.2022.111860>
- Approved Street Trees. 2021. Forestry. Fort Collins (CO, USA): City of Fort Collins, Forestry Division. [Accessed 2021 April 10]. <https://www.fcgov.com/forestry/approved-street-trees>
- Armson D, Rahman MA, Ennos AR. 2013. A comparison of the shading effectiveness of five different street tree species in Manchester, UK. *Arboriculture & Urban Forestry*. 39(4):157-164. <https://doi.org/10.48044/jauf.2013.021>
- Aronson MFJ, Lepczyk CA, Evans KL, Goddard MA, Lerman SB, MacIvor JS, Nilon CH, Vargo T. 2017. Biodiversity in the city: Key challenges for urban green space management. *Frontiers in Ecology and the Environment*. 15(4):189-196. <https://doi.org/10.1002/fee.1480>
- Beck SM, McHale MR, Hess GR. 2016. Beyond impervious: Urban land-cover pattern variation and implications for watershed management. *Environmental Management*. 58:15-30. <https://doi.org/10.1007/s00267-016-0700-8>
- Bigsby KM, McHale MR, Hess GR. 2014. Urban morphology drives the homogenization of tree cover in Baltimore, MD, and Raleigh, NC. *Ecosystems*. 17:212-227. <https://doi.org/10.1007/s10021-013-9718-4>
- Chithra SV, Nair MVH, Amarnath A, Anjana NS. 2015. Impacts of impervious surfaces on the environment. *International Journal of Engineering Science Invention*. 4(5): 27-31. <https://www.ijesi.org/papers/Vol%284%295/E045027031.pdf>
- Clark KE, Berry D. 1995. House characteristics and the effectiveness of energy conservation measures. *Journal of the American Planning Association*. 61(3):386-395. <https://doi.org/10.1080/01944369508975649>
- Community Canopy Program. 2017. Fort Collins (CO, USA): City of Fort Collins, Forestry Division. [Accessed 2021 April

- 10]. <https://www.fcgov.com/forestry/treecanopy.php>
- Congalton RG, Green K. 2019. *Assessing the accuracy of remotely sensed data: Principles and practices*. 3rd Ed. Boca Raton (FL, USA): CRC Press. 346 p. <https://doi.org/10.1201/9780429052729>
- Donovan GH, Butry DT. 2009. The value of shade: Estimating the effect of urban trees on summertime electricity use. *Energy and Buildings*. 41(6):662-668. <https://doi.org/10.1016/j.enbuild.2009.01.002>
- Dwyer JF, McPherson EG, Schroeder HW, Rowntree RA. 1992. Assessing the benefits and costs of the urban forest. *Journal of Arboriculture*. 18(5):227-234. <https://doi.org/10.48044/jauf.1992.045>
- Estoque RC, Murayama Y, Myint SW. 2017. Effects of landscape composition and pattern on land surface temperature: An urban heat island study in the megacities of Southeast Asia. *Science of the Total Environment*. 577:349-359. <https://doi.org/10.1016/j.scitotenv.2016.10.195>
- Gómez-Muñoz VM, Porta-Gándara MA, Fernández JL. 2010. Effect of tree shades in urban planning in hot-arid climatic regions. *Landscape and Urban Planning*. 94(3-4):149-157. <https://doi.org/10.1016/j.landurbplan.2009.09.002>
- Hamstead Z, Coseo P, AlKhaled S, Boamah EF, Hondula DM, Middel A, Rajkovich N. 2020. Thermally resilient communities: Creating a socio-technical collaborative response to extreme temperatures. *Buildings and Cities*. 1(1):218-232. <http://doi.org/10.5334/bc.15>
- Heisler GM. 1986. Energy savings with trees. *Journal of Arboriculture*. 12(5):113-125. <https://joa.isa-arbor.com>
- Herrington LP. 1974. Trees and acoustics in urban areas. *Journal of Forestry*. 72(8):462-465. <https://doi.org/10.1093/jof/72.8.462>
- Hwang WH, Wiseman EP, Thomas VA. 2015. Tree planting configuration influences shade on residential structures in four U.S. cities. *Arboriculture & Urban Forestry*. 41(4):208-222. <https://doi.org/10.48044/jauf.2015.020>
- Jimenez MF, Pejchar L, Reed SE, McHale MR. 2022. The efficacy of urban habitat enhancement programs for conserving native plants and human-sensitive animals. *Landscape and Urban Planning*. 220:104356. <https://doi.org/10.1016/j.landurbplan.2022.104356>
- Ko Y. 2018. Trees and vegetation for residential energy conservation: A critical review for evidence-based urban greening in North America. *Urban Forestry & Urban Greening*. 34:318-335. <https://doi.org/10.1016/j.ufug.2018.07.021>
- Ko Y, Lee J-H, McPherson EG, Roman LA. 2015. Long-term monitoring of Sacramento Shade program trees: Tree survival, growth and energy-saving performance. *Landscape and Urban Planning*. 143:183-191. <https://doi.org/10.1016/j.landurbplan.2015.07.017>
- Ko Y, Radke JD. 2014. The effect of urban form and residential cooling energy use in Sacramento, California. *Environment and Planning B: Planning and Design*. 41(4):573-593. <https://doi.org/10.1068/b12038p>
- Larson KL, Nelson KC, Samples SR, Hall SJ, Bettez N, Cavender-Bares J, Groffman PM, Grove M, Heffernan JB, Hobbie SE, Learned J, Morse JL, Neill C, Ogden LA, O'Neil-Dunne J, Pataki DE, Polsky C, Roy Chowdhury R, Steele M, Trammell TLE. 2016. Ecosystem services in managing residential landscapes: Priorities, value dimensions, and cross-regional patterns. *Urban Ecosystems*. 19:95-113. <https://doi.org/10.1007/s11252-015-0477-1>
- Li X, Zhou Y, Yu S, Jia G, Li H, Li W. 2019. Urban heat island impacts on building energy consumption: A review of approaches and findings. *Energy*. 174:407-419. <https://doi.org/10.1016/j.energy.2019.02.183>
- MacFaden SW, O'Neil-Dunne JPM, Royar AR, Lu JWT, Rundle AG. 2012. High-resolution tree canopy mapping for New York City using LIDAR and object-based image analysis. *Journal of Applied Remote Sensing*. 6(1):063567. <https://doi.org/10.1117/1.JRS.6.063567>
- Mao Q, Wang L, Guo Q, Li Y, Liu M, Xu G. 2020. Evaluating cultural ecosystem services of urban residential green spaces from the perspective of residents' satisfaction with green space. *Frontiers in Public Health*. 8:226. <https://doi.org/10.3389/fpubh.2020.00226>
- McDonald RI, Kroeger T, Zhang P, Hamel P. 2020. The value of US urban tree cover for reducing heat-related health impacts and electricity consumption. *Ecosystems*. 23:137-150. <https://doi.org/10.1007/s10021-019-00395-5>
- McHale MR, McPherson EG, Burke IC. 2007. The potential of urban tree plantings to be cost effective in carbon credit markets. *Urban Forestry & Urban Greening*. 6(1):49-60. <https://doi.org/10.1016/j.ufug.2007.01.001>
- McPherson EG, Herrington LP, Heisler GM. 1988. Impacts of vegetation on residential heating and cooling. *Energy and Buildings*. 12(1):41-51. [https://doi.org/10.1016/0378-7788\(88\)90054-0](https://doi.org/10.1016/0378-7788(88)90054-0)
- McPherson EG, Simpson JR. 1999. Carbon dioxide reduction through urban forestry: Guidelines for professional and volunteer tree planters. Albany (CA, USA): US Department of Agriculture, Forest Service, Pacific Southwest Research Station. General Technical Report PSW-GTR-171. 237 p. <https://doi.org/10.2737/PSW-GTR-171>
- McPherson EG, Simpson JR. 2003. Potential energy savings in buildings by an urban tree planting programme in California. *Urban Forestry & Urban Greening*. 2(2):73-86. <https://doi.org/10.1078/1618-8667-00025>
- Middel A, Chhetri N, Quay R. 2015. Urban forestry and cool roofs: Assessment of heat mitigation strategies in Phoenix residential neighborhoods. *Urban Forestry & Urban Greening*. 14(1): 178-186. <https://doi.org/10.1016/j.ufug.2014.09.010>
- Mohajerani A, Bakaric J, Jeffrey-Bailey T. 2017. The urban heat island effect, its causes, and mitigation, with reference to the thermal properties of asphalt concrete. *Journal of Environmental Management*. 197:522-538. <https://doi.org/10.1016/j.jenvman.2017.03.095>
- Myint SW, Zheng B, Talen E, Fan C, Kaplan S, Middel A, Smith M, Huang H, Brazel A. 2015. Does the spatial arrangement of urban landscape matter? Examples of urban warming and cooling in Phoenix and Las Vegas. *Ecosystem Health and Sustainability*. 1(4):1-15. <http://dx.doi.org/10.1890/EHS14-0028.1>
- National Weather Service: National Oceanic and Atmospheric Administration (NOAA). 2018. NOWData—NOAA Online Weather Data. Boulder (CO, USA): US Department of

- Commerce, NOAA. [Accessed 2021 January 10]. <http://w2.weather.gov/climate/xmacis.php?wfo=bou>
- Nelson C, McHale MR, Peterson MN. 2012. Influences of landscape and lifestyle on home energy consumption. *Urban Ecosystems*. 15:773-793. <https://doi.org/10.1007/s11252-012-0246-3>
- Nowak DJ. 2002. The effects of urban trees on air quality. Syracuse (NY, USA): USDA Forest Service. 5 p. [http://nrs.fs.fed.us/units/urban/local-resources/downloads/Tree\\_Air\\_Qual.pdf](http://nrs.fs.fed.us/units/urban/local-resources/downloads/Tree_Air_Qual.pdf)
- Nowak DJ. 2020. Understanding i-Tree: Summary of programs and methods. Madison (WI, USA): U.S. Department of Agriculture, Forest Service, Northern Research Station. General Technical Report NRS-200. 100 p. <https://doi.org/10.2737/NRS-GTR-200>
- Nowak DJ, Appleton N, Ellis A, Greenfield E. 2017. Residential building energy conservation and avoided power plant emissions by urban and community trees in the United States. *Urban Forestry & Urban Greening*. 21:158-165. <https://doi.org/10.1016/j.ufug.2016.12.004>
- Nowak DJ, Crane DE, Stevens JC, Hoehn RE, Walton JT, Bond J. 2008. A ground-based method of assessing urban forest structure and ecosystem services. *Arboriculture & Urban Forestry*. 34(6):347-358. <https://doi.org/10.48044/jauf.2008.048>
- Oke TR. 1982. The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*. 108(455): 1-24. <https://doi.org/10.1002/qj.49710845502>
- O'Neil-Dunne JPM, MacFaden SW, Royar AR, Pelletier KC. 2013. An object-based system for LiDAR data fusion and feature extraction. *Geocarto International*. 28(3):227-242. <https://doi.org/10.1080/10106049.2012.689015>
- The R Foundation. 2019. The R Project for Statistical Computing. Vienna (Austria): The R Foundation. <https://www.R-project.org>
- Rahman MA, Armson D, Ennos AR. 2015. A comparison of the growth and cooling effectiveness of five commonly planted urban tree species. *Urban Ecosystems*. 18:371-389. <https://doi.org/10.1007/s11252-014-0407-7>
- Rahman MA, Stratopoulos LMF, Moser-Reischl A, Zölch T, Häberle KH, Rötzer T, Pretzsch H, Pauleit S. 2020. Traits of trees for cooling urban heat islands: A meta-analysis. *Building and Environment*. 170:106606. <https://doi.org/10.1016/j.buildenv.2019.106606>
- Rasmussen S, Warziniack T, Neel A, O'Neil-Dunne J, McHale M. 2021. When small is not beautiful: The unexpected impacts of trees and parcel size on metered water-use in a semi-arid city. *Remote Sensing*. 13(5):998. <https://doi.org/10.3390/rs13050998>
- Santamouris M. 2014. On the energy impact of urban heat island and global warming on buildings. *Energy and Buildings*. 82:100-113. <https://doi.org/10.1016/j.enbuild.2014.07.022>
- Santamouris M, Cartalis C, Synnefa A, Kolokotsa D. 2015. On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings—A review. *Energy and Buildings*. 98:119-124. <https://doi.org/10.1016/j.enbuild.2014.09.052>
- Scholz T, Hof A, Schmitt T. 2018. Cooling effects and regulating ecosystem services provided by urban trees—Novel analysis approaches using urban tree cadastre data. *Sustainability*. 10(3):712. <https://doi.org/10.3390/su10030712>
- Simpson JR, McPherson EG. 1996. Potential of tree shade for reducing residential energy use in California. *Journal of Arboriculture*. 22(1):10-18. <https://doi.org/10.48044/jauf.1996.002>
- Speak A, Montagnani L, Wellstein C, Zerbe S. 2020. The influence of tree traits on urban ground surface shade cooling. *Landscape and Urban Planning*. 197:103748. <https://doi.org/10.1016/j.landurbplan.2020.103748>
- Su MA, Ngarambe J, Santamouris M, Yun GY. 2021. Empirical evidence on the impact of urban overheating on building cooling and heating energy consumption. *iScience*. 24(5):102495. <https://doi.org/10.1016/j.isci.2021.102495>
- Tan J, Zheng Y, Tang X, Guo C, Li L, Song G, Zhen X, Yuan D, Kalkstein AJ, Li F, Chen H. 2010. The urban heat island and its impact on heat waves and human health in Shanghai. *International Journal of Biometeorology*. 54:75-84. <https://doi.org/10.1007/s00484-009-0256-x>
- Troy AR, Grove JM, O'Neil-Dunne JPM, Pickett STA, Cadenasso ML. 2007. Predicting opportunities for greening and patterns of vegetation on private urban lands. *Environmental Management*. 40:394-412. <https://doi.org/10.1007/s00267-006-0112-2>
- United States Census Bureau. 2020. QuickFacts: Fort Collins city, Colorado; United States. Washington (DC, USA): US Department of Commerce, United States Census Bureau. [Accessed 2022 March 18]. <https://www.census.gov/quickfacts/fact/table/fortcollinscitycolorado,US/PST045221>
- Wang C, Wang Z-H, Yang J. 2018. Cooling effect of urban trees on the built environment of contiguous United States. *Earth's Future*. 6(8):1066-1081. <https://doi.org/10.1029/2018EF000891>
- Weng Q. 2001. A remote sensing? GIS evaluation of urban expansion and its impact on surface temperature in the Zhujiang Delta, China. *International Journal of Remote Sensing*. 22(10):1999-2014. <https://doi.org/10.1080/713860788>
- Wheeler SM, Abunnasr Y, Dialesandro J, Assaf E, Agopian S, Gamberini VC. 2019. Mitigating urban heating in dryland cities: A literature review. *Journal of Planning Literature*. 34(4):434-446. <https://doi.org/10.1177/0885412219855779>
- Winbourne JB, Jones TS, Garvey SM, Harrison JL, Wang L, Li D, Templer PH, Hutrya LR. 2020. Tree transpiration and urban temperatures: Current understanding, implications, and future research directions. *BioScience*. 70(7):576-588. <https://doi.org/10.1093/biosci/biaa055>
- Zhou D, Zhao S, Liu S, Zhang L, Zhu C. 2014. Surface urban heat island in China's 32 major cities: Spatial patterns and drivers. *Remote Sensing of Environment*. 152:51-61. <https://doi.org/10.1016/j.rse.2014.05.017>
- Zhou W, Troy A. 2008. An object-oriented approach for analyzing and characterizing urban landscape at the parcel level. *International Journal of Remote Sensing*. 29(11):3119-3135. <https://doi.org/10.1080/01431160701469065>

## ACKNOWLEDGMENTS

The authors would like to thank our city partners for providing data, guidance on analyses, and helping interpret results, and Shaundra Rasmussen for providing assistance with methodology and data analysis. This research was conducted in collaboration with the Denver Urban Field Station.

Lauren Z. Abram, MS (corresponding author)  
 Department of Ecosystem Science and Sustainability  
 Colorado State University  
 Fort Collins, CO, USA  
 571-215-8533  
 lauren.abram21@alumni.colostate.edu

Joshua P. Keller, PhD  
 Department of Statistics  
 Colorado State University  
 Fort Collins, CO, USA

Elizabeth A. Tulanowski, MS  
 Department of Ecosystem Science and Sustainability  
 Colorado State University  
 Fort Collins, CO, USA

Melissa R. McHale, PhD  
 Department of Ecosystem Science and Sustainability  
 Colorado State University  
 Fort Collins, CO, USA  
 Department of Forest Resources Management  
 Faculty of Forestry  
 University of British Columbia  
 Vancouver, BC, Canada

#### Conflicts of Interest:

The authors reported no conflicts of interest.

**Résumé.** Contexte: La canopée d'arbres urbains (CAU) est souvent proposée comme une stratégie d'atténuation afin de réduire simultanément les émissions de carbone et le réchauffement urbain dans les villes. Les arbres peuvent, non seulement réduire les températures extérieures par l'ombrage et la transpiration, mais les recherches suggèrent également que la régulation du microclimat par les arbres entourant les bâtiments peut mener à des températures intérieures plus fraîches et à une potentielle diminution de la consommation énergétique estivale. Méthodes: Nous avons analysé la consommation d'électricité pour la climatisation estivale de 21 048 maisons unifamiliales dans une ville située dans une région semi-aride du nord du Colorado, aux États-Unis. À l'aide des coefficients de corrélation de Pearson et de modèles de régression linéaire multiple, nous avons évalué l'impact potentiel de la CAU sur la consommation d'électricité, aux fins de la climatisation, selon 16 zones distinctes autour de chaque maison. Nous avons émis l'hypothèse que les arbres les plus rapprochés de la maison ainsi que les arbres situés sur les côtés ouest et sud des maisons, auraient la plus grande influence sur la consommation d'électricité pour la climatisation. Résultats: La CAU dans toutes les 16 zones autour des bâtiments résidentiels était associée à des coefficients de corrélation négatifs, ce qui indique que la CAU réduit effectivement la consommation d'énergie. Nos résultats ont montré que la CAU positionnée du côté est des maisons unifamiliales avait les effets les plus importants. Conclusions: Bien que nos résultats indiquent que la présence d'arbres dans les aménagements autour des bâtiments résidentiels peut entraîner une certaine diminution de la consommation d'énergie des maisons, ces réductions n'étaient pas aussi

substantielles que les études précédentes l'avaient anticipé. Des recherches antérieures ont également montré que le positionnement des arbres est important. Nos résultats témoignent en effet que le positionnement de la CAU par rapport à un bâtiment peut faire varier l'impact des arbres sur la consommation énergétique. Cependant, nos résultats montrent également que les arbres situés du côté est des bâtiments ont le plus d'impact sur la consommation d'énergie des résidences pour une ville du Colorado au climat semi-aride pendant les mois d'été. Ces résultats s'opposent directement aux prévisions des modèles connus de services écosystémiques qui montrent que les arbres situés sur les côtés ouest et sud des bâtiments ont le plus d'impact sur la consommation énergétique dans l'hémisphère Nord. En outre, plusieurs études ont suggéré que les avantages énergétiques fournis par les arbres urbains l'emportent sur leur potentiel de séquestration du carbone et nos résultats indiquent que cette hypothèse n'est peut-être pas vérifiée dans toutes les villes.

**Zusammenfassung.** Hintergrund: Baumkronen in Städten werden häufig als Strategie zur gleichzeitigen Verringerung der Kohlenstoffemissionen und der städtischen Erwärmung in Städten vorgeschlagen. Bäume können nicht nur die Außentemperaturen durch Beschattung und Transpiration senken, sondern die Forschungen deuten auch darauf hin, dass die Regulierung des Mikroklimas durch Bäume in der Umgebung von Gebäuden zu kühleren Innentemperaturen und damit zu einer Verringerung des Energieverbrauchs im Sommer führen kann. Methoden: Wir analysierten den sommerlichen Stromverbrauch für die Kühlung von 21.048 Einfamilienhäusern in einer halbtrockenen Stadt im Norden Colorado, USA. Mithilfe von Pearson-Korrelationskoeffizienten und multiplen linearen Regressionsmodellen bewerteten wir die potenziellen Auswirkungen von städtischen Baumkronen auf den Stromverbrauch für die Kühlung in 16 verschiedenen Zonen um jedes Haus. Wir stellten die Hypothese auf, dass Bäume, die sich näher am Haus befinden, sowie Bäume an der West- und Südseite der Häuser den größten Einfluss auf den Stromverbrauch für die Kühlung haben würden. Ergebnisse: Die städtischen Baumkronen in allen 16 Zonen um Wohngebäude war mit negativen Korrelationskoeffizienten verbunden, was darauf hindeutet, dass die städtischen Baumkronen den Energieverbrauch reduziert. Unsere Ergebnisse zeigten, dass die städtischen Baumkronen an der Ostseite von Einfamilienhäusern die größten Auswirkungen hat. Schlussfolgerungen: Obwohl unsere Ergebnisse darauf hindeuten, dass Bäume in der Umgebung von Wohngebäuden zu einer gewissen Verringerung des Energieverbrauchs auf Haushaltsebene führen können, war die Verringerung des Stromverbrauchs nicht so erheblich, wie in früheren Studien vorhergesagt wurde. Frühere Untersuchungen haben auch gezeigt, dass der Standort von Bäumen eine Rolle spielt, und unsere Ergebnisse zeigen in der Tat, dass der Standort von städtischen Baumkronen in Bezug auf ein Gebäude den Einfluss von Bäumen auf den Energieverbrauch verändern kann. Unsere Ergebnisse zeigen jedoch auch, dass Bäume auf der Ostseite von Gebäuden den größten Einfluss auf den Energieverbrauch von Haushalten in einer halbtrockenen Stadt in Colorado während der Sommermonate haben. Diese Ergebnisse stehen in direktem Widerspruch zu den Vorhersagen gängiger Ökosystemdienstleistungsmodelle, denen zufolge Bäume auf der West- und Südseite von Gebäuden den größten Einfluss auf den Energieverbrauch in der nördlichen Hemisphäre haben.

Darüber hinaus haben viele Studien nahegelegt, dass bei der energetische Nutzen von Stadtbäumen ihr Kohlenstoffbindungspotenzial überwiegt, und unsere Ergebnisse deuten darauf hin, dass diese Annahme nicht in allen Städten zutrifft.

**Resumen.** Antecedentes: El dosel de árboles urbanos (UTC, por sus siglas en inglés) es propuesto con frecuencia como una estrategia de mitigación para disminuir simultáneamente las emisiones de carbono y la calefacción urbana en las ciudades. Los árboles no solo pueden reducir las temperaturas exteriores a través de la sombra y la transpiración, sino que la investigación también sugiere que la regulación del microclima por parte de los árboles que rodean los edificios puede conducir a temperaturas interiores más frías y una posterior disminución en el uso de energía en verano. Métodos: Analizamos el consumo de electricidad de enfriamiento en verano para 21,048 hogares unifamiliares en una ciudad semiárida en el norte de Colorado, USA. Utilizando los coeficientes de correlación de Pearson y los modelos de regresión lineal múltiple, evaluamos el impacto potencial de UTC en el uso de electricidad de enfriamiento en 16 zonas diferentes alrededor de cada casa. Planteamos la hipótesis de que los árboles más cercanos a la casa y los ubicados en los lados oeste y sur, tendrían el mayor impacto en el uso de electricidad de enfriamiento. Resultados: UTC en las 16 zonas alrededor de edificios residenciales se asoció con coeficientes de correlación negativos,

lo que indica que UTC reduce el uso de energía. Nuestros resultados mostraron que UTC en el lado este de las casas unifamiliares tuvo los mayores efectos. Conclusiones: Aunque nuestros resultados indicaron que los árboles en los paisajes alrededor de los edificios residenciales pueden conducir a algunas disminuciones en el consumo de energía a nivel de los hogares, las reducciones en el uso de electricidad no fueron tan sustanciales como los estudios anteriores han predicho. Investigaciones anteriores también han demostrado que la ubicación de los árboles importa y nuestros resultados muestran que el lugar donde se encuentra UTC en referencia a un edificio puede cambiar el impacto que tienen en el uso de energía. Sin embargo, nuestros resultados también muestran que los árboles en el lado este de los edificios tienen el mayor impacto en el consumo de energía de los hogares en una ciudad semiárida en Colorado durante los meses de verano. Estos resultados contradicen directamente las predicciones ofrecidas por los modelos populares de servicios ecosistémicos que muestran que los árboles en los lados oeste y sur de los edificios tienen el mayor impacto en el uso de energía en el hemisferio norte. Además, muchos estudios han sugerido que los beneficios energéticos proporcionados por los árboles urbanos superan su potencial de secuestro de carbono y nuestros resultados indicaron que esta suposición puede no ser cierta en todas las ciudades.

### Arboriculture & Urban Forestry Quiz Questions

To complete this quiz, go to the ISA website, log into your MyISA account, and make your way to the page for *Arboriculture & Urban Forestry* CEU Quizzes ([www.isa-arbor.com/store/ceuquizzes/113](http://www.isa-arbor.com/store/ceuquizzes/113)).

Add the quiz to your cart, proceed through checkout, and look for the content to appear on your personal dashboard under the header, "My Quizzes." If you need a username and password, send us an e-mail ([isa@isa-arbor.com](mailto:isa@isa-arbor.com)).

A passing score for this quiz requires sixteen correct answers. Quiz results will display immediately upon quiz completion. CEU(s) are processed immediately. You may take the quiz as often as is necessary to pass.

