Appendix 03.3 – Levels of Green Canopy and Heat Analysis

01 – QUANTIFYING CANOPY FOR THE LEVELS OF GREEN

01.01 – PURPOSE

The purpose of this analysis is to estimate the canopy coverage in the right-of-way provided by trees planted in the stormwater control measures (SCMs) associated with each Level of Green. The canopy coverage calculation methodology employed is also an example for future right-of-way projects.

01.02 – METHODS

1. Review green infrastructure projects completed in the City and County of Denver between 2017 and 2020 and identify the tree species that have been planted most frequently
2. Use the Denver Office of the City Forester's Approved Street Tree List to determine the maximum canopy diameter at maturity for the eight most frequently planted tree species
3. Determine an average canopy diameter at maturity to use in canopy coverage calculations
4. Use the engineering criteria and spacing identified previously in Appendices 03.1 and 03.2 to estimate a high and low number of trees that may be planted in a typical 400' long stretch of right-of-way
5. Compute canopy coverage ranges for each Level of Green for one side of the street using the following equation:

$$Caopy\ Cover\ at\ Maturity\ \% = 100 * \frac{Tree\ Canopy\ Diameter * Number\ of\ Trees}{400'\ Length}$$

The canopy coverage metric is length-based, rather than area-based, because the intent of the canopy is to provide shade over the sidewalk and bike lane which are linear features. Shade over the middle of a drive lane may help prolong the life of the street asphalt but is less relevant to cooling residents. See Figure A.03.3.1 for an example calculation. For simplicity, the example is performed for one side of the street only. If the methodology is repeated on future projects, the analysis should be performed for both sides of the street.

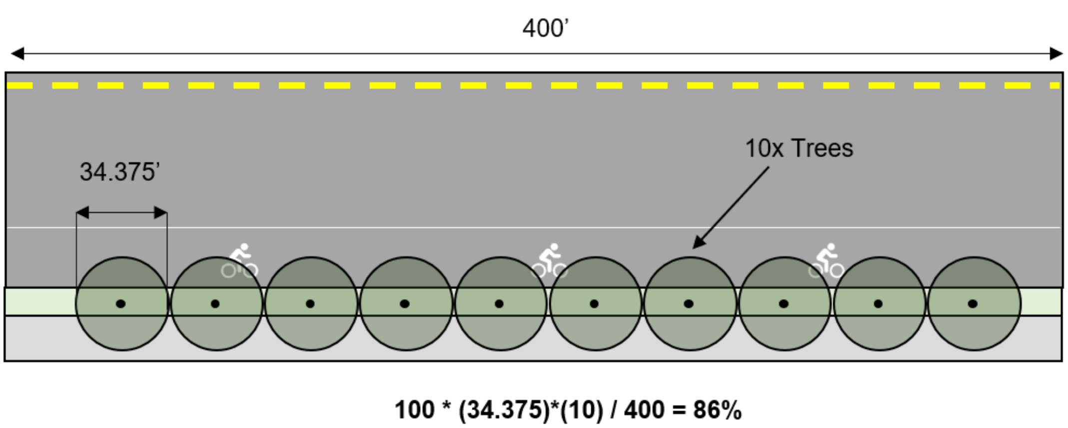


Figure A.03.3.1: Example canopy coverage calculation for 10 trees in a 400 ft right-of-way on one side of the street

01.03 – RESULTS AND CONCLUSIONS: CANOPY COVERAGE

The eight most frequently planted trees in Green Infrastructure facilities constructed between 2017-2020 are shown in Table A.03.3.1, along with their maximum canopy diameter at maturity according to the City and County of Denver's Office of the City Forester. The average diameter of these species is 34.375 ft, which will be used for the calculations.

Table A.03.3.1: Canopy diameter of the most frequently planted green infrastructure tree species

Species (Common Name)	Canopy Diameter at Maturity [ft]
Accolade Elm	50
Autumn Brilliance Serviceberry	15
Common Hackberry	35
Flash Fire Maple	40
Ginko	30
Goldenrain Tree	30
Kentucky Coffeetree	40
Western Catalpa	35
Average	**34.375**

Next, a low and high number of trees that can be planted for each Level of Green are determined. The numbers of trees selected, justification for selection, and the resulting canopy coverage are shown in Table A.03.3.2. Where the table lists "existing number of trees" this refers to a GIS analysis performed to determine the number of street trees on all the street segments in the City and County of Denver.

Table A.03.3.2: Canopy coverage ranges for each Level of Green

Level of Green	Range in number of trees	Range in canopy coverage [%]	Justification for selection of the number of trees
1	8 to 11	70 to 95	8 = 75th percentile of existing number of trees / 400' street 11 = Maximum given 30' minimum tree spacing requirements / 400' street
2	5 to 8	40 to 70	5 = Median existing number of trees / 400' street 8 = Maximum amount given 1 tree / 40' long SCM* (+4' spacing between each)
3	3 to 4	17 to 35	3 = One fewer SCM* than 4 SCMs, the upper limit for the Level of Green 4 = Number of 40'x5' SCMs needed to treat the 400' street at 20:1 run-on ratio
4	2 to 3	11 to 17	2 = Low number of SCMs needed to store 60% of the WQCV for a 400' street 3 = High number of SCMs needed to store 60% of the WQCV for a 400' street
5	2 to 3	11 to 17	2 = Low number of SCMs needed to store 100% of the WQCV for a 400' street 3 = High number of SCMs needed to store 100% of the WQCV for a 400' street

*Assumes 1 tree planted / SCM

02 – QUANTIFYING HEAT MITIGATION FOR THE LEVELS OF GREEN

02.01 – PURPOSE

The purpose of this analysis is to estimate the heat mitigation provided by the trees and pervious areas in the public right-of-way associated with SCMs for each Level of Green. Mean radiant temperature

(MRT) is a measure of thermal comfort that accounts for the sun's radiation and is the metric used to characterize urban heat island perceived by humans in this study. MRT is an especially important outdoor comfort metric due to Denver's sunny, high altitude, and low humidity climate.

02.02 – METHODS

Model and Domain

The SOlar and LongWave Environmental Irradiance Geometry (SOLWEIG)[1] model was used to simulate MRT in the right-of-way to approximate cooling benefits associated with each of the Levels of Green. SOLWEIG simulates solar radiation and shadows through space and time to calculate MRT in complex urban settings. It can account for pervious vs. impervious ground cover and has been able to accurately predict MRT given the effects of vegetation and buildings[2].

Because the heat mitigation analysis is focused on the public right-of-way, the model domain was a 400' x 400' square containing an idealized city block. The model was discretized into 1600 1 ft^2 cells. A block length of 400' in the direction of traffic was chosen to align with the runoff modeling for the Levels of Green (Appendix 03.1) and because it is representative of the average and median street segment length in the City and County of Denver (346 ft and 473 ft, respectively). A right-of-way width of 80 ft was chosen again to align with the previous study (Appendix 03.1) and because it is the most commonly occurring right-of-way width in CCD, excluding residential streets. Each half of the synthetic right-of-way was divided into five zones in the direction perpendicular to traffic flow as in Figure A.03.3.2. The three (3) most important zones of these for this analysis are the (1) Landscape Zone which is home to trees and the SCMs that provide cooling and the (2) Walkway and (3) Adjacent Zones which are home to pedestrians and bicyclists that are intended to experience the cooling benefits of the vegetation.

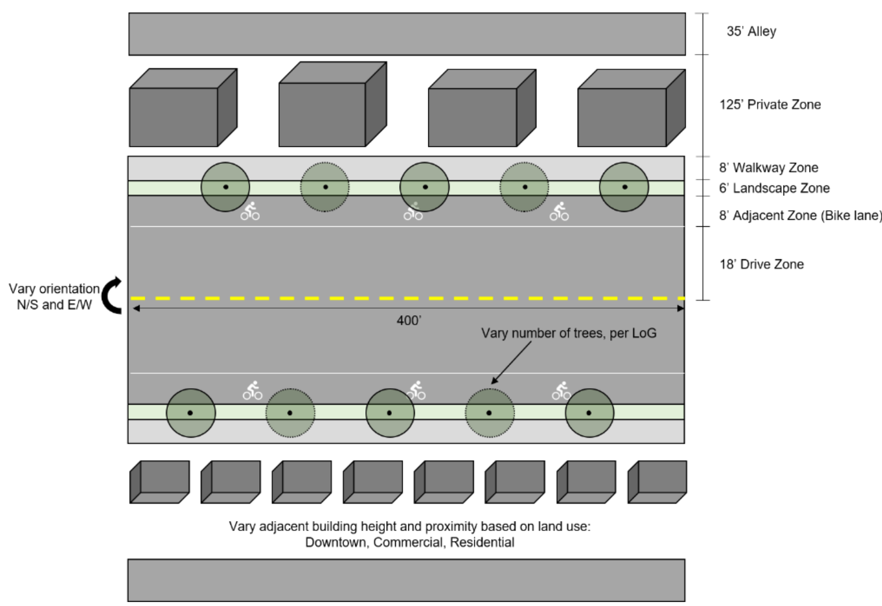


Figure A.03.3.2: Diagram of the model domain and graphical summary of the simulations (not to scale)

Simulations

The 400' x 400' synthetic block was arranged in 46 different configurations, summarized in Table A.03.3.3, to cover the SCMs associated with each of the 5 Levels of Green, street orientation, and adjacent land use. Because adjacent building geometry has a strong effect on shading and therefore MRT, three different adjacent land uses were considered: Downtown, Commercial, and Residential. The configuration of the buildings for each land use is described in Table A.03.3.3. For each land use, the number of trees was varied from 2 on the low end to 11 on the high end which represents the likely range across the Levels of Green (Table A.03.3.2). There were two 11 tree simulations for the Downtown and Commercial Land use types only which represented different ground covers: one with a 5' x 5' pervious opening for each tree, and one with a 15' x 5' pervious opening. The trees were modeled as honeylocust species, which is the most commonly occurring street tree in the City and County of Denver[3]. The canopy was assumed to be of a rounded shape, with a 30' diameter, a 6' bottom height, and a 40' top height[3]. Additionally, a zero tree control was modeled for each land use. The number of trees and these canopy layers were used to create Canopy Digital Surface Models and Trunk-zone Digital Surface Models as inputs to SOLWEIG for each of the model configurations. Each combination of land use and number of trees was modeled as both a north/south oriented street and east/west oriented street.

Table A.03.3.3: SOLWEIG Model Configurations

Orientations	Land use and Adjacent Buildings	Number of Trees per street side	Levels of Green
North/South	**Downtown**: 4 buildings / street side, 100' wide, 125' deep. 2 buildings are 5 stories, 2 buildings are 8 stories. Buildings abut the right-of-way. Landscape zone assumed impervious, except for the locations of the SCMs.	11 in 5'x5' pervious areas*	1
East/West	**Commercial**: 8 buildings / street side, 50 ft wide, 125 ft deep. 4 buildings are 3 stories (48') high, 4 buildings are 2 stories 28' (high). Buildings abut the right-of-way. Landscape zone assumed impervious, except for the locations of the SCMs.	11 in 15'x5' pervious areas*	1, 2
	Residential: 8 buildings / street side, 25 ft wide, 65 ft deep, spaced 20 feet apart. All buildings are 18' tall and are set back 20 ft from the right-of-way. Each building also has a 10'x10'x10'detached garage that abuts the Alley Zone. The rest of the private zone is assumed pervious, as well as the entire landscape zone.	8	2
		5	2, 3
		4	3, 4
		3	4, 5
		2	4, 5
		0	Control

*Downtown and Commercial land uses only. For residential, the entire walkway was assumed to be pervious.

Meteorological Data and Simulation Period

Sub-hourly meteorological data for 2020 from the Boulder Station of the US Climate Reference Network forced the SOLWEIG model. While it is not located in Denver, it was the closest station available with the meteorological variables required by SOLWEIG: incoming solar radiation, wind speed, temperature, relative humidity, barometric pressure, and rainfall. July 10, 2020 was selected for simulation because this day had the hottest air temperatures of 2020, some of the highest levels of incoming solar radiation, and low relatively humidity. July 10, 2020 was the hottest day in one of the top ten hottest months in Denver's history. Together these factors should produce the highest MRTs of the year. Negative public health outcomes of the urban heat island are likely to be experienced during the extreme conditions, so this very hot day was used to determine the cooling benefits of the SCMs. SOLWEIG was run from 6am to 6pm on this day at a 5 minute timestep.

Post Processing

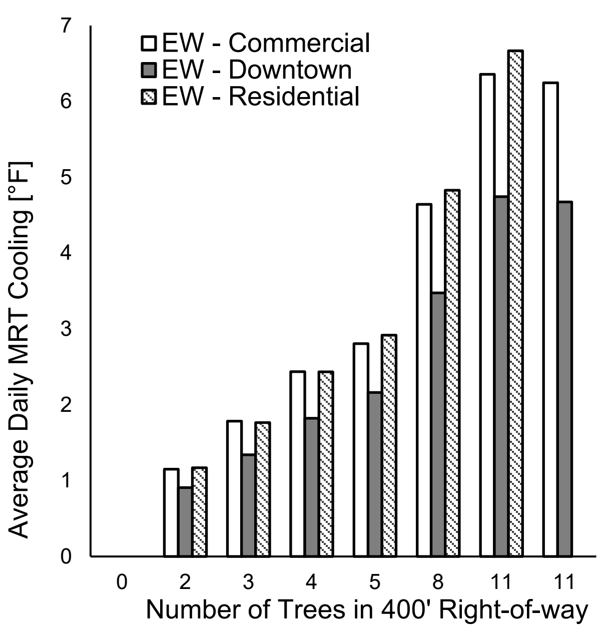
SOLWEIG generates an estimate of MRT in each of the 1600 1' x 1' grid cells at each of the 5 minute timesteps. However, because the goal of the SCMs is to provide cooling to pedestrians and bicyclists, only the MRT in the Walkway and Adjacent Zones were analyzed. The average daily MRT was determined for each zone on each side of the street (four zones total). To estimate the overall cooling provided by the SCMs, the average daily MRT from the four zones for each configuration was compared relative to the average daily MRT from the four zones for the no-tree control configuration.

Each of the configurations was then categorized into one or more Levels of Green (Table A.03.3.3). For each Level of Green the maximum and minimum degrees of MRT cooling was identified to characterize its cooling benefit range, assuming that only one Level of Green was employed on a given project.

In addition to the average daily cooling benefits, peak daily MRT were also analyzed. The average MRT simulated across each of the four zones was determined for every time step of the simulation. The maximum average was then determined to be the peak MRT for each of the four zones. For simplicity in communication of the results, these maximum values were then averaged across the four zones even though the maximum MRT for each zone likely occurred at different times of the day. Peak MRTs were compared across the configurations directly, rather than computing degrees of cooling, because the timing of the peak MRT for each of the zones varied for each simulation.

02.03 – Results

Average Daily MRT Cooling and Levels of Green



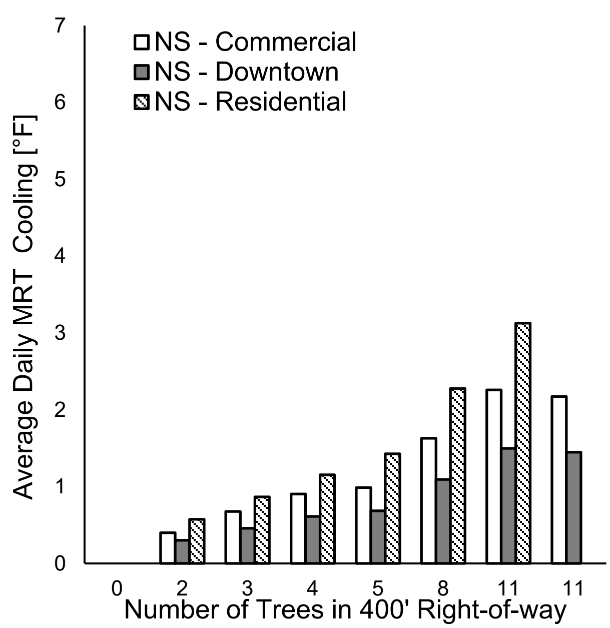


Figure A.03.3.3: Average Daily Mean Radiant Temperature (MRT) cooling caused by trees in a synthetic 400' right-of-way. Panel (a) shows results for an East/West oriented street, and panel (b) for a North/South oriented street.

Figure A.03.3.3 shows the average daily MRT cooling benefits in the Walkway and Adjacent Zones due to the right-of-way SCMs. Cooling benefits range from 0.3°F cooled from 2 trees/400 ft on a North/South oriented street to 6.7°F cooled from for 11 trees/400 ft on an East/West oriented street. Cooling benefits are higher on the East/West oriented streets than North/South as the sun is typically in the southern part of the sky shinning north. Therefore, the shade provided by the trees typically only provides cooling to the Adjacent Zone on the southern side of the street and the Walkway Zone on the north side of the street. Cooling due to street trees is most beneficial in residential areas, followed by commercial areas, and finally downtown areas. The buildings in downtown and commercial areas provide more shade due to their greater height and lower distance set back from the sidewalk, so the incremental shade provided by the trees is less. Table A.03.3.3 links ranges in average cooling in the Walkway and Adjacent zones to each Level of Green.

Table A.03.3.3: Range of Mean Radiant Temperature (MRT) Cooling Benefits by Level of Green

Level of Green	MRT Cooling benefit due to trees
Level of Green 1	1.1 to 6.7°F
Level of Green 2	0.7 to 4.8°F
Level of Green 3	0.5 to 2.9°F
Level of Green 4	0.3 to 2.4°F
Level of Green 4	0.3 to 1.8°F

Peak Daily MRTs

The peak daily MRTs averaged across the four Walkway and Adjacent zones are shown in Figure A.03.3.4. North/South oriented streets have hotter peak MRT than East/West streets because the shade from buildings and trees is cast on the Adjacent and Walkway zones at the beginning and end of the day, not during the middle of the day when the sun is the most intense. Estimates of cooling are not provided, as was done for the average daily MRT, because the peak MRT occurs at different times of day for the no-tree control compared to the configurations with trees. Additionally, the timing of the peak MRT across each of the four zones analyzed also varied. However, the overall trend presented in Figure A.03.3.4 which averages the peak MRT across zones is clear: more trees lead to a greater reduction in peak MRT.

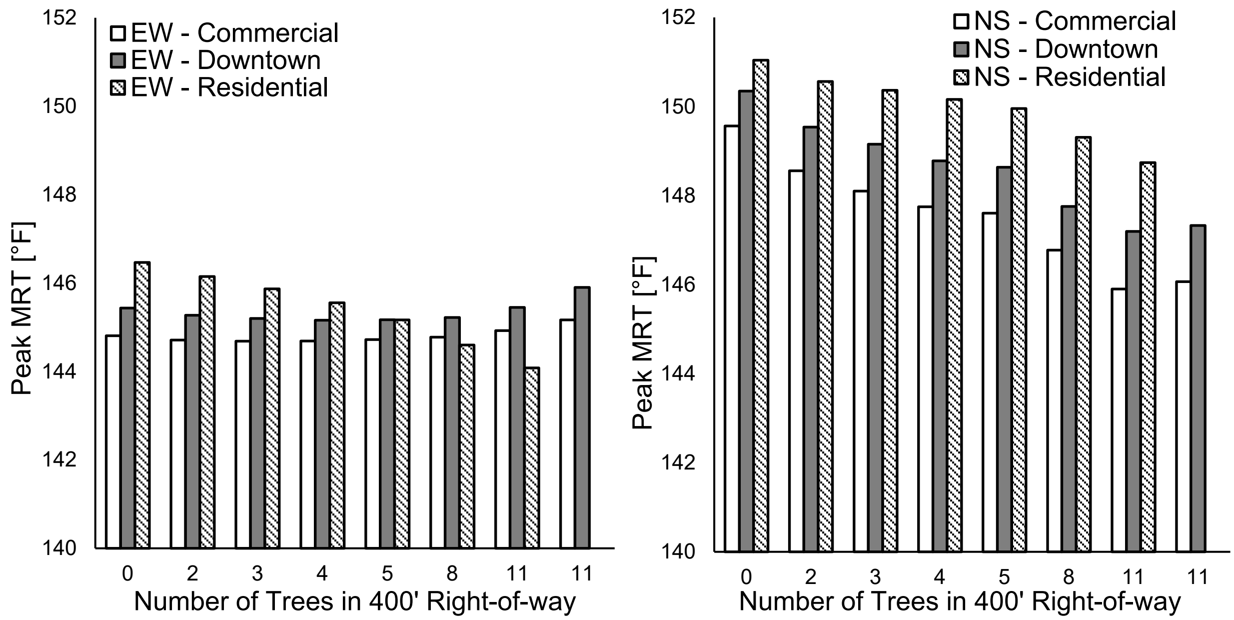


Figure A.03.3.4: Peak Daily Mean Radiant Temperature (MRT) changes with the number of trees planted on each street side. Left panel shows results for an East/West oriented street; right panel for a North/South street.

03 – LAND SURFACE TEMPERATURE EMPIRICAL RELATIONSHIPS

03.01 – PURPOSE

There are three intended outcomes of this analysis. The first is to use remotely sensed land surface temperatures (LST) to identify the hottest street segments in the City and County of Denver, as these should be targeted for green infrastructure capital improvement to reduce temperatures. The second is to quantify the relationship between right-of-way canopy coverage and LST for each street segment as it will help characterize the street segments that are the most likely to experience cooling benefits from added canopy. The third outcome is to quantify the relationship between impervious surface coverage and LST in each of the 1658 Municipal Separate Stormwater Sewer (MS4) subbasins.

03.02 – METHODS

<u>Quantifying annual maximum LST for each Street Segment</u>

The data used to quantify LST across the city over a 20 year period was acquired from the Landsat program. The Landsat program is sponsored by the United States Geological Survey (USGS) and the National Aeronautical and Space Administration (NASA) to use satellites to collect images of the earth's surface at 30m x 30m pixel resolution. The Landsat program has launched eight missions since 1972. Satellite imagery from the Landsat 7 and Landsat 8 missions were used in this analysis as they both have sensors that collect data from the thermal infrared electromagnetic bands that allows for estimation of LST. Together, these satellites collect an image of a single location on earth every 8 days (each having a 16 day return period, offset by 8 days).

Landsat data was used to estimate annual maximum LSTs for each street segment and each of the 1654 sub-basins that make up the City and County of Devner's MS4 by:

1. Identifying all Landsat images taken in the months of July and August during the years 2000-2019 covering the City and County of Denver
   - Only observations from July and August were used because these are the hottest months of the year and populations vulnerable to heat would be most affected during these times
   - No data was available for 2012
2. Using a Google Earth Engine processing methodology[4] to compute LST for each of the Landsat images
3. Using Google Earth Engine processing to find the hottest LST observation for each pixel in the images from July and August for each year (called "the annual maximum") and composite these hottest LST pixel values into one single image
   - Again, only the hottest LST observation was used because temperature extremes are the most significant for public health
   - The code corrects for the presence of clouds
   - This process is summarized in Figure A.03.3.5

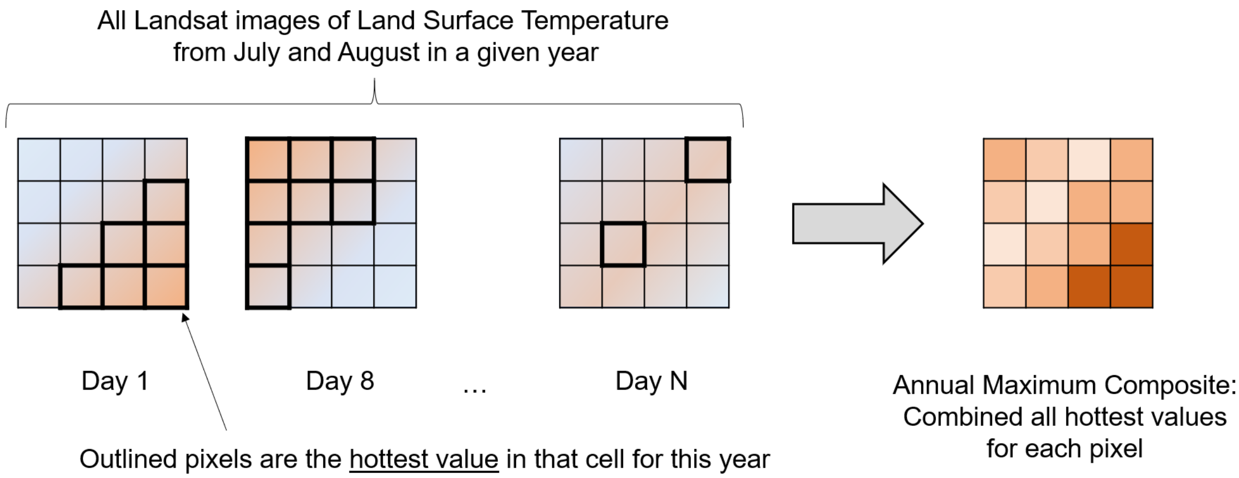


Figure A.03.3.5: Diagram showing how annual maximum composite land surface temperature layer was developed

4. Calculating the average of the annual maximum LST raster values for all the Landsat pixels that overlapped each street segment for each year
   - This process is summarized in Figure A.03.3.6

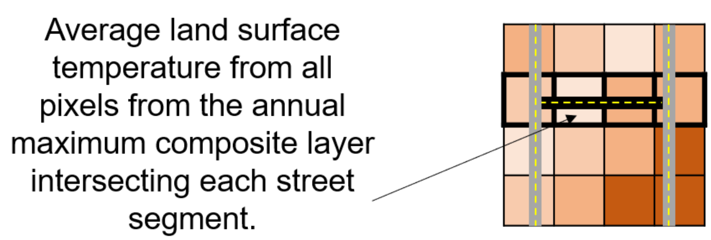


Figure A.03.3.6: Diagram showing how average annual maximum land surface temperature layer was determined for each street segment

5. Calculating the average of the annual maximum land surface temperature raster values for all the Landsat pixels that overlapped each MS4 subbasin for each year in a process similar to that shown in Figure A.03.3.6, but using the subbasin layer in place of the street segment layer.

Special thanks are owed to Dr. Katie Spahr of Colorado School of Mines for the Google Earth Engine processing in steps 1-3 above.

Identifying the city streets with the highest LST from 2000-2019

With average annual maximum LST quantified for each street segment for each year, the data across the 20 years were used to identify the hottest streets by:

1. Ranking the average annual maximum temperatures for each street segment and year, and assigning the segments a percentile based on average temperature
   - Percentiles were used rather than absolute temperatures because this is a prioritization exercise that seeks to identify the hottest streets year after year. For example, it is more important to know that a given street is hotter than all the neighboring streets year in and year out than it is to know how much hotter that street is
2. Averaging the percentiles for each street segment across all 20 years
3. Assigning a percentile to the multi-year average percentile, producing the final percentiles used for ranking the streets

Relationships between right-of-way canopy coverage, orientation, and LST

The 2014 average annual LST for each street segment was used to analyze the relationship between canopy coverage, street orientation, and LST.

1. The orientation of each street was assigned as either North/South, East/West, Northeast/Southwest, Southeast/Northwest
2. A 40ft buffer was applied to each street segment, creating a modeled 80’ right-of-way width from the street segment center
3. The City and County of Denver’s Tree Canopy GIS layer documents canopy coverage in 2014. This layer was intersected with the modeled right-of-way to determine the percent covered by tree canopy for each street segment.
4. Since the canopy layer is from 2014, the maximum annual LST for each street in 2014 was linearly regressed against the right-of-way canopy coverage in 2014 to determine the overall relationship between right-of-way canopy cover and LST
5. An analysis of variance test and post-hoc pair-wise t-test were performed on the residuals of the regression model with street orientation as the explanatory variable to determine the effects of street orientation on LST with the effect of canopy removed
6. Further, the street segments were binned into 10 groups based on canopy coverage: 0-10% in the first bin, 10-20% in the second bin, etc. Smaller linear regressions were performed for just the street segments in each bin. The bins with the steepest regression slopes are the ranges in canopy coverage that are likely to benefit the most from increases in canopy.

Relationships between MS4 subbasin impervious coverage and LST

The 2019 average annual LST for each MS4 subbasin was used to analyze the relationship between impervious coverage and LST.

1. The City and County of Denver's Comprehensive Citywide Impervious Surfaces layer maps impervious areas throughout the city. This layer is updated regularly, so the data is as close to real-time as possible given staff limitations.
2. The City and County of Denver has divided the MS4 service area into 1658 sub-basins.
3. These two layers were clipped to the boundaries of the City and County of Denver, and intersected to determine the percent of each subbasin that is covered by impervious surfaces
4. The average maximum LST values from 2019 within each subbasin was linearly regressed against the impervious cover in each subbasin

03.03 – Results and Discussion

Identifying the city streets with the highest LST from 2000-2010

Figure A.03.3.7 shows the relative heat classes of all street segments in the City and County of Denver. The hottest 25% of streets, shown in orange and red, are deemed to be in the greatest need of heat mitigation through canopy planting. These street segments generally fall in the "inverted L" along the South Platte Reiver / I-25 corridor running north/south and the I-70 corridor running easts/east.

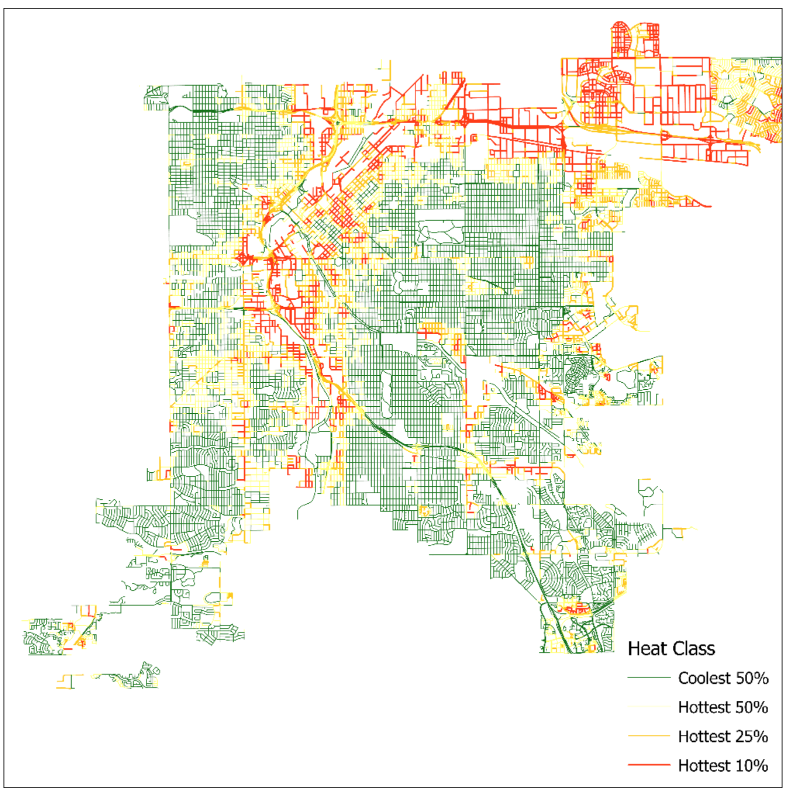


Figure A.03.3.7: Map of Denver street segments coded by relative heat classes.

Relationships between right-of-way canopy coverage, orientation, and LST

The significant ($p<<0.001$, $R^2 = 0.32$) linear regression model between all street segment canopy coverage and LST is shown in the red line in Figure A.03.3.8 (a). The slope of the linear model (-0.204) indicates **an approximately 2°F decrease in LST for every 10% increase in canopy coverage**. While the relationship was significant across the range of canopy coverages observed, there were very few street segments with canopy coverage > 65%. Therefore, the model should be ignored beyond this canopy coverage and is not plotted in Figure A.03.3.8 (a).

In additional to the overall trend, the distribution of LST for each canopy bins is shown in the boxplots in Figure A.03.3.8 (a). The differences in the mean LST of each bin is shown with a blue dashed line on Figure A.03.3.8 (a) and summarized in Table A.03.3.4. The slope of linear regressions constructed using just the data of each bin (all significant, p<<0.001) is also presented in Table A.03.3.4. Analyzing the difference in the means between canopy bins and the regression slopes of each bin indicates **that increasing canopy coverage on streets with the lowest canopy (0-10%) are likely to see the greatest reductions of LST**. This also true, to a lesser extent, for the next canopy bin (10-20%), after which the decreases in LST are relatively constant. This corresponds well with the Denver Urban Forest Initiative's 10% tree canopy goal for the Downtown Denver area.

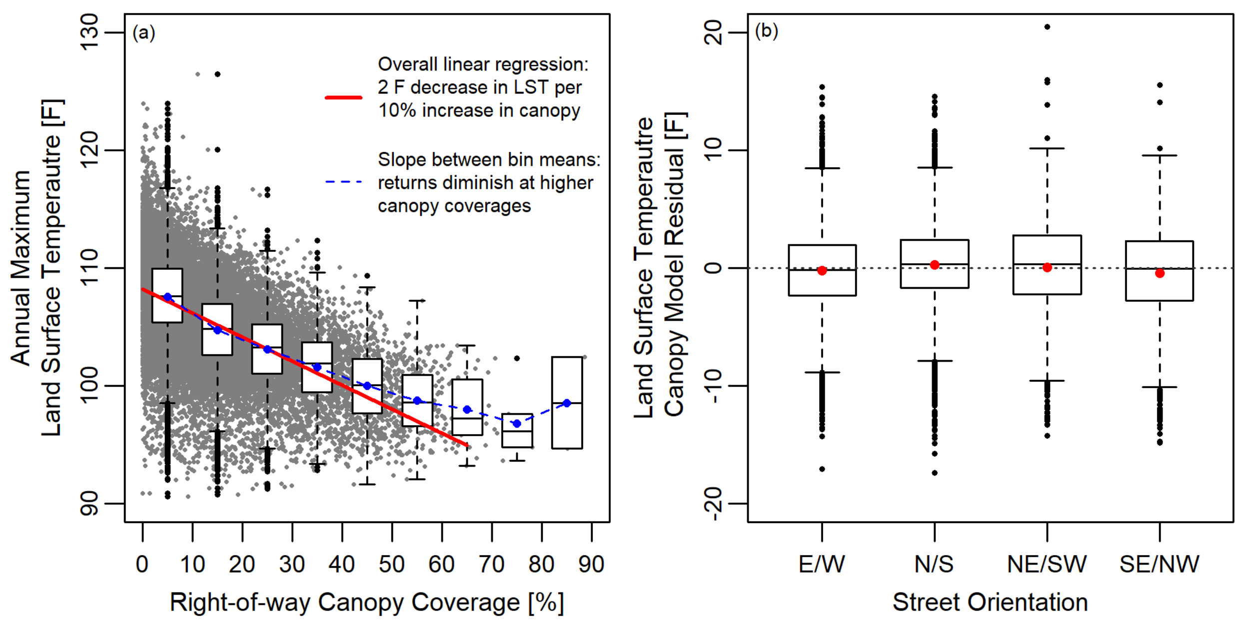


Figure A.03.3.8: (a) Relationships between annual maximum land surface temperature (LST) and canopy coverage for each street segment. Grey dots indicate measurements for each street segment, and the boxplots summarize each canopy coverage decile bin. (b) Boxplot of the linear model residuals shown by street segment orientation.

Table A.03.3.4: Summary of land surface temperature (LST) changes between canopy bins

Canopy Bin [%]	Mean LST [°F]	Difference in Bin Mean [°F]	Slope of Regression for Bin [°F/%]
0-10	107.6	-2.8	-0.376
10-20	104.7	-1.6	-0.196
20-30	103.1	-1.5	-0.101
30-40	101.6	-1.6	-0.155
40-50	100.0	-1.3	-0.150
50-60	98.7	-0.8	0.009
60-70	98.0	-1.2	-0.043
70-80	96.8	1.8	-0.415

80-90	98.6	NA	2.24

The residuals of the overall linear regression models were analyzed for the effects of street orientation on LST. Boxplots of the LST model residuals by street orientation are shown in Figure A.03.3.8 (b). Table A.03.3.5 shows a numerical comparison of the LST model residual between each street orientation. A key takeaway is that North/South oriented streets are 0.5°F hotter on average than East/West oriented streets. However, a 0.5°F is relatively small compared to the effects of canopy, as a 2.5% increase in canopy coverage would result in a 0.5°F cooling. Further, street orientation only explains 0.4% of the overall variance in the data of LST from 2014.

Table A.03.3.5: Comparison of land surface temperature by street orientation, after the canopy trend has been removed. Significance determined at $p < 0.05$.

	… East/West	… Northeast/Southwest	… Southeast/Northwest
North/South vs…	LARGER by 0.50 degrees F	No significant difference	LARGER by 0.69 degrees F
East/West vs…	--	SMALLER by 0.28	No significant difference
Northeast/Southwest vs …	--	--	LARGER by 0.47 degrees F

Relationships between MS4 subbasin impervious coverage and LST

The significant ($p<<0.001$, $R^2 = 0.34$) linear regression model between all subbasin impervious coverage percent and the average of the annual maximum LST from 2019 is shown in the red line in Figure A.03.3.9. The slope of the linear model indicates **an approximately 1.3°F increase in LST for every 10% increase in impervious surface coverage**.

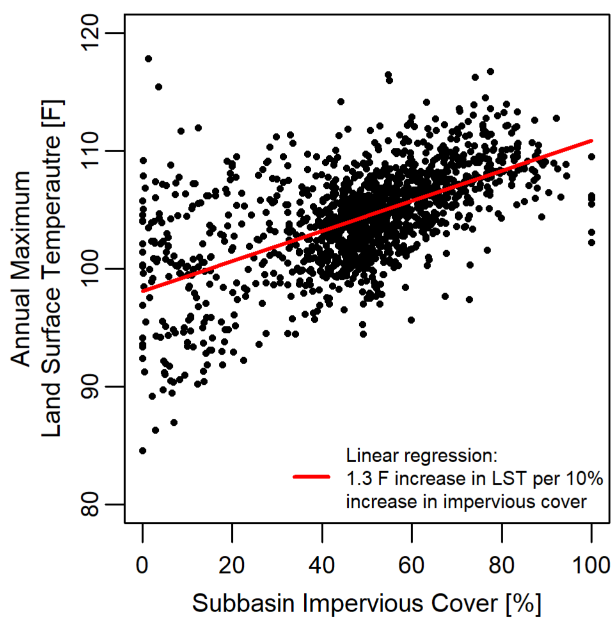


Figure A.03.3.9: Relationships between the average annual maximum land surface temperature (LST) measured in 2019 and impervious coverage for the city's MS4 subbasins

04 – REFERENCES

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