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Heat Island Mitigation Assessment and Policy Development for the Kansas City Region

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Abstract

Lawrence Berkeley National Laboratory partnered with Mid-America Regional Council (MARC) to quantify the costs and benefits from the adoption of urban heat island (UHI) countermeasures in the Kansas City region (population 1.5 million), and identify the best regional implementation pathway for MARC. The team selected cool (high-albedo) roofs and increased vegetation as the two countermeasures to evaluate. For vegetation, there were two strategies: (1) planting new trees to shade building surfaces, and (2) increasing urban irrigation (a surrogate for the use of vegetation to manage stormwater) to increase evapotranspiration. Using the Weather Research and Forecasting (WRF) model we simulated selected weeks during summer time, across five years (2011 – 2015) representing a range of normal summer conditions. We also simulated six of the most intense heatwaves that occurred between 2004 and 2016. We found under typical summer conditions (non-heatwave) average daytime (07:00 – 19:00 local standard time) regional near-ground air temperature reductions of 0.08 and 0.28 °C for cool roofs and urban irrigation, respectively. We calculated the building electricity, electricity cost, and emission savings that result from the reduction in outdoor air temperature ("indirect" savings) and found maximum regional annual indirect electricity savings of 42.8 GWh for cool roofs and 85.6 GWh for urban irrigation—yielding maximum regional annual indirect electricity cost savings of $5.6M ($0.05/m^2 roof) and $11.1M ($0.01/m^2 irrigated land), respectively, and maximum regional annual CO_2 savings of 43.4 kt and 80 kt, respectively.

We next evaluated the building energy, energy cost, and emission savings from reducing direct absorbed radiation on the building surfaces using cool roofs and shade trees ("direct" savings). For cool roofs, we found regional annual direct energy cost savings of $10.9M ($0.15/m^2 roof) with regional annual CO_2 savings of 66.4 kt. For shade trees, the regional annual direct energy cost savings were $21M ($21/tree) with regional annual CO_2 savings of 126 kt. We investigated cool roof cost premiums (the additional cost for selecting a cool roof product in lieu of a conventional roof product, estimated to be zero to $2.15/m^2) and shade tree first costs (assumed to be $100 per tree). The regional cool roof cost premium was calculated using the regional roof area per roofing material type and the range of cool roof product premiums for each material type. The extra cost of selecting cool roofs across the region ranged from $4.33M to $87.1M, while the additional shade trees planted across the region were assumed to cost $102M. When we compared the regional annual direct cost savings to the regional cool-roof cost premium and the regional shade-tree first cost, we found regional simple payback times up to 8.0 years for cool roofs and 4.9 years for trees, respectively.

Since this comprehensive assessment of UHI countermeasures is a valuable methodology for other local governments to apply, we developed a step-by-step guide for others to follow. Based on the benefits and costs of the UHI countermeasures, MARC will pursue the inclusion of these countermeasures in existing regional plans where they can complement other regional priorities for transportation, climate resiliency, clean air, and hazard mitigation. They hosted a local workshop in 2016 for stakeholders to introduce the topic and will continue to share these resources to further appropriate adoption of UHI countermeasures.

Key Words: cool roofs, vegetation, urban heat islands, Kansas City, building energy savings, urban climate, simple payback

1 Introduction

The Mid-America Regional Council (MARC) is the regional and metropolitan planning organization serving the 119 local governments in the bi-state, 4,423-square mile Kansas City region. MARC was selected as a Climate Action Champion (CAC) following a competitive process led by the U.S. Department of Energy (DOE) in 2014. As a CAC, MARC was eligible to submit proposals for U.S. Department of Energy technical assistance projects. In 2015, MARC submitted a proposal to DOE to solicit technical assistance to quantify the benefits of urban heat island (UHI) countermeasures, and understand the linkages among green infrastructure, energy conservation and heat island abatement. The Heat Island Group at Lawrence Berkeley National Laboratory (LBNL) was uniquely positioned to assist MARC given its extensive history of research on the topic, and membership in the national laboratory system supported by DOE.

1.1 Project goal

MARC and LBNL partnered to advance their Climate Action Champion priorities by

- quantifying the impact of urban heat islands on energy use under different urban and suburban land use types and at different geographic scales;
- assessing costs and benefits of alternative UHI countermeasures; and
- developing a policy and planning framework for adoption by local governments to mitigate associated impacts while advancing regional climate resilience goals.

This study was conducted to generate data to inform the thoughtful integration cool building and cool city measures into regional and local initiatives.

1.2 UHI countermeasures considered

At the outset of the project, MARC and LBNL met to identify which UHI countermeasures would be investigated. Given finite project resources, we needed to focus on a few countermeasures. The selection process was driven by local interests of MARC, LBNL’s previous findings for similar studies elsewhere, and the feasibility of implementation of the countermeasures in the region. Given these criteria, the team selected to study cool (high-albedo) roofs and increased vegetation.

Cool roofs have been adopted in many places around the world for their ability to reflect sunlight. Reducing the roof’s solar heat gain directly saves air conditioning energy by lowering roof surface temperature. It also cools the outside air, indirectly reducing the need for air conditioning on a warm day by decreasing the air temperature difference across the building envelope.

Evapotranspiration is the combination of the evaporation of water from soils and surfaces, and transpiration by plants. This process cools the outside air. Increasing region-wide vegetation could boost evapotranspiration, lowering the outside air temperature. Plants can reduce the need for air conditioning directly by shading building surfaces, and indirectly by cooling the outside air. In addition, plants help manage stormwater by retaining the water until it filters through the soil, is absorbed by the plants, or evaporates. For this project, we consider two vegetation strategies: (1) planting new trees to shade building surfaces, and (2) increasing urban irrigation, which serves as surrogate for the utilization of vegetation to manage stormwater, to increase evapotranspiration.

2 Project tasks

To achieve the project goal, we completed one administrative and six technical tasks. The technical tasks were distinct yet complementary efforts to investigate the benefits, costs, and implementation of cool roofs and vegetation. Below we summarize each of the technical tasks, some of which are detailed in full-length reports (appendices).

2.1 Task 2: Quantify the relationship between ambient air temperatures and energy demand for metro Kansas City

Cool roofs and increased vegetation in urban areas can lower outdoor air temperature. This can reduce the need for air conditioning in a warm city, saving energy, decreasing emission of CO_2, and reducing peak power demand. We utilized the results from Task 3 (Quantify the relationship between UHI mitigation strategies and ambient air temperature) to calculate the maximum magnitudes of these benefits for the Kansas City region. We apply a method that uses as inputs (a) the city-wide electricity demands on a hot day and a mild day, (b) the temperature change caused by the increase in roof albedo and increased urban irrigation, and (c) the number of hours in a year that air conditioning is used. We found the maximum annual energy savings from cool roofs was 35.2 GWh for the suburban Kansas City area, 0.5 GWh for the rural area, and 7.1 GWh for the urban core, totaling 42.8 GWh for the region. We found the maximum annual energy savings from urban irrigation was 70.4 GWh for the suburban Kansas City area, 0.5 GWh for the rural area, and 1.0 GWh for the urban core, totaling 85.6 GWh for the region. The maximum regional annual indirect energy cost savings from cool roofs was $5.6M, and that from urban irrigation was $11.1M.

We also normalized the findings to roof and irrigated area for each of the three development density areas. The cool roof scenario maximum energy, energy cost, and CO_2 emission savings per unit roof area are presented Table 1. The analogous results from urban irrigation are presented in Table 2.

The complete study is presented in the Task 2 report: *Quantifying the relationship between ambient air temperatures and electric power demand for Kansas City region* (Appendix A).

Table 1. The electricity, electric cost, CO_2 savings per unit roof area for adoption of cool roofs for the three urban development density areas—suburban, urban core, and rural.

	Suburb	Core	Rural
Maximum electric energy savings per unit roof area (kWh/y·m^2)	0.35	0.30	0.10
Maximum electric cost savings per unit roof area (\$/y·m^2)	0.05	0.04	0.01
Maximum CO_2 emission savings per unit roof area (kg/y·m^2)	0.35	0.29	0.09

Table 2. The electricity, electric cost, CO_2 savings per unit irrigated area for adoption of green infrastructure for the three urban development intensity types—suburban, urban core, and rural.

	Suburb	Core	Rural
Maximum electric energy savings per unit irrigated area (kWh/y·m^2)	0.07	0.01	NA*
Maximum electric cost savings per unit irrigated area (\$/y·m^2)	0.009	0.002	NA*
Maximum CO_2 emission savings per unit irrigated area (kg/y·m^2)	0.07	0.01	NA*

* Aggregate irrigation benefits in rural areas are marked NA (not applicable) because these areas contain few air-conditioned buildings.

2.2 Task 3: Quantify the relationship between UHI mitigation strategies and ambient air temperature

We evaluated two UHI mitigation strategies for the Kansas City Metropolitan Area (KCMA). Using the Weather Research and Forecasting (WRF) model, we assessed the potential benefits of highly reflective cool roofs and urban irrigation on urban air temperature in typical summer conditions between years 2011 and 2015, and also during six of the strongest historical heat wave events over the past 12 years (2005 – 2016). Under the typical summer conditions, we simulated near-surface (2 m above ground level) air temperature for 10 summer weeks, finding average daytime (07:00 – 19:00 local standard time) temperature reductions of 0.08 and 0.28 °C for cool roofs and urban irrigation, respectively. Most (82%) of the Kansas City region is classified as a "low development" area, with less than 10% roof area fraction. Our results suggest that urban irrigation can be more efficient than cool roofs in mitigating the urban heat island in metropolitan regions that (like Kansas City) have substantially more vegetated area than roof area. Finally, we find the alteration of land surface conditions due to enhanced roof albedos affects local meteorology and precipitation patterns within the WRF simulation, particularly during heat waves. Further research would be necessary to determine the robustness of this last finding.

The complete study is presented in the Task 3 report: *Evaluation of urban heat island mitigation strategies for the Kansas City region* (Appendix B).

2.3 Task 4: Evaluate the costs and benefits of UHI abatement strategies

We evaluated for the MARC region the “direct” building energy and emission savings that result from cooling the surface of the building with tree shade or high-albedo roofing. We also assessed the regional cost premiums for cool roof products and first costs for shade trees, and compared these costs to the energy cost savings from deploying these cool strategies. We used the results of studies that were commissioned by our partner MARC in 2015, which report the direct building energy savings from cool roofs and shade trees for several common building types in the study region. The previously commissioned studies included several different building categories. Therefore we (a) determined total regional building count, building footprint area, and building perimeter length by land use classification; and (b) mapped each classification to one or more building categories. We also used recent emission factors and energy prices to evaluate the regional emission and energy cost savings potential. We investigated cool roof cost premiums and shade tree first costs; cool roof cost premiums ranged from zero to $\$0.20/ft^2$, while shade trees were assumed to cost $100 per tree. The benefit and cost data were combined to calculate simple payback times for cool roofs and shade trees. For cool roofs, we found regional annual direct energy cost savings of $10.9M. For shade trees, the regional annual direct energy cost savings were $21M.

When we compared the direct building annual cost savings to the cool-roof cost premiums and shade-tree first costs, we found regional simple payback times of up to 8.0 years for cool roofs and 4.9 years for trees. There were shorter simple payback times for older buildings because they yielded larger energy cost savings than did newer buildings. The simple payback time for cool roofs for medium offices built before 1980 was 0.6 to 3 years, and that for single-family homes built before 1980 was 0 to 12 years. For shade trees, the simple payback time for medium offices constructed before 1980 was 1.4 years, and that for single-family homes constructed before 1980 was 5.6 years. This is important for the MARC region since 57% of its buildings were constructed before 1980.

The complete study is presented in the Task 4 report: *Costs and Benefits of Cool Roofs and Shade Trees in Kansas City region* (Appendix C).

2.4 Task 5: Create a policy/planning framework to support local UHI abatement implementation efforts

After MARC reviewed the findings from the technical tasks in consultation with LBNL, MARC decided the findings would best be used to strengthen the incorporation of UHI countermeasures into existing regional planning efforts. Regional plans for transportation, air quality, green infrastructure, hazard mitigation, and climate resilience all consider related problems and solutions. Increasingly, regional plans are being more fully integrated than historically, with an emphasis on cross-cutting solutions transcending sectors and jurisdictions. Heat island countermeasures are a perfect example where they can be included in other regional plans to provide complementary co-benefits. The regional plans on which MARC will focus are the Regional Transportation Plan, Clean Air Action Plan, Regional Climate Resiliency Strategy, and the Regional Hazard Mitigation Plan.

More details on the regional plans are presented in Task 5: *Existing plans for metropolitan Kansas City to incorporate Urban Heat Island countermeasures* (Appendix D).

2.5 Task 6: Facilitate local implementation of UHI abatement strategies

MARC hosted a regional climate resilience workshop in Kansas City with stakeholders from the local government, non-profits, and the utility on 20 October 2016 that featured Dr. Levinson (LBNL). Levinson presented the origins and consequences of urban heat islands, and reviewed countermeasures that can cool buildings, vehicles, and entire cities. He also described the collaboration between MARC and LBNL. At the end of his presentation there was an opportunity to discuss possible approaches and policies for heat island mitigation in this region.

MARC plans to continue to share the findings after the project period. It will develop some local resources to share the findings of the project with their constituents. An initial resource will be the project fact sheet (online here) we drafted with a succinct summary of the activities and findings. MARC will also work on incorporating the findings, as appropriate, to support regional plans and policies.

2.6 Task 7: Develop guidance to support development of similar UHI research and policy efforts nationwide

Using our work with MARC as an example, we developed a step-by-step guide for other communities to follow to evaluate the benefits UHI countermeasures. This resource can help local governments, non-profits, and planning organizations.

The complete guide is presented in Task 7: *Evaluating the benefits of vegetation and cool roofs—A step-by-step guide developed from a case study of the Kansas City region* (Appendix E).

3 Conclusions

We found benefits to the adoption of cool community measures in the MARC region. However, the reductions to air temperature to mitigate the UHI were not as large as reported for other cities. Therefore, the effect of the studied UHI countermeasures on indirect building electricity, electricity cost, and emission savings were also small. This was due in part to the low density of urban development across the region. There was less area to install cool roofs and thereby increase the region’s albedo. Increased urban irrigation proved to be more efficient than cool roofs in mitigating the urban heat island in the region.

The results for the different development intensities within the region—suburban, urban core, and rural—support the regional findings. Temperature reductions from the urban irrigation scenario were consistently larger than those of the roof albedo scenario for all development intensity types. Urban irrigation had less effect on temperature in the urban core than in the rural and suburban areas. This was in part because the rural and suburban areas had low urban density and small roof area fractions (<10%), and therefore more land that could be irrigated than roofs that could be made reflective. Cool roofs had a greater effect in the urban core as compared to the suburban and rural areas because the urban core had a higher ratio of roof area to land area.

The direct economic benefits from cooling the surface of the building with tree shade or cool roofing for the MARC region were at least double the indirect economic benefits from cooling the air. We found maximum regional annual *indirect* electricity cost savings of $5.6M for cool roofs and $11.1M urban irrigation, while regional annual *direct* energy cost savings were $10.9M for cool roofs and $21M for shade trees.

Based on these direct annual energy cost savings alone, we calculated simple payback times of up to 8 years for cool roofs and 4.9 years for shade trees. There were shorter simple payback times for older buildings because they yielded larger energy cost savings than did newer buildings. This is important for the MARC region since 57% of its buildings were constructed before 1980.

Therefore, as MARC begins sharing and implementing these findings, we want to share some key points to keep in mind.

- The benefits from the UHI countermeasures varied by building category, building vintage, and development density. This is helpful to keep in mind when developing policies for effective implementation. Cool roofs performed best at lowering air temperature in areas of high building density. If the goal is to cool the city, prioritize cool roof adoption in high-density areas of the city. We also found that the medium office building category and pre-1980 building vintages yielded the greatest building energy savings and shortest simple payback times for cool roofs and shade trees.

- Integrate UHI countermeasures in policies and plans where the countermeasures' benefits can complement policy or plan goals. While it may be difficult to make a case for a UHI countermeasure policy solely based on UHI mitigation, it becomes easier to adopt these strategies when they provide co-benefits to other efforts. The more these strategies can be tied to other regional policy priorities, the easier it is to increase their adoption. For example, UHI countermeasures could be tied to clean energy policies with the added benefit of also contributing to community cooling.

Appendices

Appendix A: Quantifying the relationship between ambient air temperatures and electric power demand for Kansas City region (Task 2 report)

Appendix B: Evaluation of urban heat island mitigation strategies for the Kansas City region (Task 3 report)

Appendix C: Costs and Benefits of Cool Roofs and Shade Trees in Kansas City region (Task 4 report)

Appendix D: Existing plans for metropolitan Kansas City to incorporate Urban Heat Island countermeasures (Task 5 note)

Appendix E: Evaluating the benefits of vegetation and cool roofs—A step-by-step guide developed from a case study of the Kansas City region (Task 7 guide)

Appendix A

Task 2. Quantifying the relationship between ambient air temperatures and electric power demand for Kansas City region

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Abstract

It is known that cool roofs and increased vegetation in urban areas can lower outdoor air temperature. This can reduce the need for air conditioning in a warm city, saving energy, decreasing emission of CO_2, and reducing peak power demand. The question we address is the maximum magnitudes of these benefits for the Kansas City, MO metropolitan area. We apply a method that uses as inputs (a) the city-wide electricity demands on a hot day and a mild day, (b) the temperature change caused by increased roof albedo and increased irrigation, and the (c) number of hours in a year that air conditioning is used. The results are maximum city-wide annual savings. The maximum savings thus deduced may help decide whether cool roofs and irrigation are cost-effective measures in metro Kansas City.

1 Introduction

We set out to quantify the relationship between ambient air temperature and electric power demand, and to apply this relationship to calculate the maximum energy, carbon dioxide emission, peak-power, and resulting cost savings benefits of deploying cool roofs and increasing green infrastructure in the Kansas City metropolitan area.

Cool roofs have been adopted worldwide for their ability to reflect sunlight. Reducing the roof's solar heat gain directly saves air conditioning energy. It also cools the outside air, indirectly decreasing the need for air conditioning on a warm day. This task report focuses on the "indirect" energy savings that cool roofs provide by lowering the outside air temperature.

Evapotranspiration is the combination of the evaporation of water from soils and surfaces, and transpiration by plants. This process cools the outside air. The Kansas City metropolitan region is pursuing strategies to increase storm water infiltration. Instead of water running off into storm drains, they would like to increase green infrastructure, such as bioswales (vegetated ditches used to slow, collect, infiltrate, and filter storm water) and street trees, so the water is filtered by the soils and plants and absorbed locally. These strategies would both increase vegetation and soil moisture, leading to greater potential for evapotranspiration to cool the city's air temperatures.

2 Methodology

Cool roofs and green infrastructure can cool city air. Lowering summer air temperature can decrease demand for air conditioning (AC), thereby saving electricity. We utilize the relationship between ambient air temperature and the maximum electric power demand for the metropolitan area. This allows us to estimate the city-wide maximum energy, carbon dioxide (CO_2) emission, and energy cost savings benefits from the deployment of cool roofs and green infrastructure. For green infrastructure, we are only studying the effect of increased soil moisture which cools via evaporation. Our scope did not include the local cooling benefits via shade or the cooling effect from transpiration of trees. We estimate the maximum values because they give upper limits of benefits to use for comparison.

The method we used is described in the literature (Pomerantz et al. 2015; Pomerantz 2017). Simply stated

1. Find the maximum hourly city-wide power used for air conditioning (AC).
2. Find the maximum rate of change of AC power with respect to temperature.
3. Find the maximum reduction in temperature caused by the deployment of cool roofs and green infrastructure.
4. Multiply (3) and (2) and the maximum number of annual hours that AC is operating to obtain the maximum annual cooling energy savings.

Step 1 begins by obtaining the electrical power demand data from the local power utility company for a very hot day and a mild day that have similar sunlight, weather, and activity. A very hot day is chosen because the AC power and its temperature dependence are maximal on the hottest days (Pomerantz et. al. 2015). The two days are chosen to get equal sunlight by being equally spaced about the summer solstice; we also check the weather records to ensure that both days are clear and sunny. The variable controlling AC demand is not sunlight, but is temperature on these days. Often a good pair of days can be found in late July (hot) and early May (mild). Also, to control for people's behavior, we selected weekdays when business and personal activities are as similar as possible and maximal. Thus, we try to make temperature the only variable and make all other parameters the same on the two days.

In Step 2, we subtract the hourly power demands on the mild day from those of the hot day to obtain the maximum amounts of hourly AC power, P, being used on the hot day. (For brevity we refer to this change in power as resulting from "AC". Precisely, it includes all the changes that may result from the change to hotter temperature, even the production of ice cream, etc.) We then find the hourly air temperatures, T, on the hot day from weather records. We regress the hourly

AC power demands against the temperatures to find the maximum rate of change of the AC demand vs. temperature, $(dddd/dddd)_{\text{max}}$.

In Step 3, we estimate of the temperature change from deploying these cooling strategies. This is accomplished in this project with meteorological simulations of the metropolitan area. One simulation is with current roof albedos and soil moisture. A second simulation is with an increase in albedo of the rooftops and increased soil moisture (representing additional green infrastructure). The difference is the predicted temperature change.

To complete Step 4 we need the maximum annual number of hours of operation of the AC. This is less than the annual number of cooling hours at temperatures above 18˚C (65˚F), which is found from weather records of the city. We symbolize the maximum annual cooling hours by CH18C.

We wish to find the annual citywide cooling energy savings attainable by lowering the outside air temperature. The citywide AC energy savings ΔEE in a given hour is

$$\Delta EE = (dddd/dddd)\,\Delta dd \cdot \Delta tt \qquad (1)$$

where dd is hourly citywide AC power demand, dd is hourly outside temperature, $(dddd/dddd)$ is the sensitivity of hourly citywide AC power demand to hourly outside air temperature, Δdd is *reduction* in outside air temperature, and time interval Δtt is one hour. We sum hourly citywide AC energy savings ΔEE over the entire year to obtain annual citywide AC energy savings ΔEE_{a}:

$$\Delta EE_{\text{a}} = \sum_{\text{year}} (dddd/dddd) \cdot \Delta dd \cdot \Delta t \qquad (2)$$

To find the maximum possible annual citywide AC energy savings, we break the right-hand side into three parts, and take the maximum of each part:

$$\Delta EE_{\text{a,max}} = \sum_{\text{year}} (dddd/dddd)_{\text{max}} \cdot (\Delta dd)_{\text{max}} \cdot (\Delta tt)_{\text{max}} \qquad (3)$$

$$= (dddd/dddd)_{\text{max}} \cdot (\Delta dd)_{\text{max}} \cdot \sum_{\text{year}} (\Delta tt)_{\text{max}}$$

Factors $(dddd/dddd)_{\text{max}}$ and $(\Delta dd)_{\text{max}}$ are taken out of the sum because they are constants.

The sum over $(\Delta tt)_{\text{max}}$ means the maximum time that AC is in use during the year. To get energy units of watt hours, the sum over time is in units of hours. The sum is approximated by the number of cooling hours (CH) in a year. Relative to the standard base temperature of 18˚C (65˚F), this is symbolized by CH18C. Thus, the final formula for the maximum annual citywide AC energy savings due to a temperature change caused by increased roof albedo and green infrastructure is

$$\Delta EE_{\text{a,max}} = (dddd/dddd)_{\text{max}} \cdot (\Delta \text{T})_{\text{max}} \cdot \text{CH18C} \quad (4)$$

Each of the factors on the right side of the equation is presented in detail below. The maximum temperature reduction due to cooler roofs and green infrastructure, $(\Delta dd)_{\text{max}}$, is obtained from meteorological simulations. Values for CH18C are obtained from weather records of the city. There remains to determine $(dddd/dddd)_{\text{max}}$, the maximum magnitude of change of AC power demand with air temperature.

3 Obtaining, processing, and analyzing utility power demand data

We wish to find the maximum electrical power demand for AC in a recent year; we chose 2015. We do this by subtracting the base demand on a mild day (which has minimal AC usage) from the demand on one of the hottest days (when AC demand is highest). To this end, we searched the weather records for the hottest days of the year, which usually occur in July or August in this climate. Then we found days at equal time intervals before the summer solstice. The mild day had the same sunlight as the hot day, but was in May or April, when the temperatures are usually milder. We found matching weekdays with clear skies so that the electrical demand by businesses and homes were as similar as possible. Ideally, the only difference between the two days is the air temperature. In our analysis, the days that best met these criteria were May 18, 2015 and July 28, 2015.

Our project partner, Mid-America Regional Council (MARC), contacted the local electric utility, Kansas City Power and Light (KCPL), to obtain hourly power demand data collected on 17, 18, 19 May and 27, 28, 29 July 2015, bracketing the selected study days. The KCPL records identify meter, date, time, and energy consumed in the previous hour. This is the average power for the previous hour, since nn kWh consumed in one hour corresponds to an hourly average demand of nn kW. KCPL provided data for more than 326,500 meters (or “monitors”, or “mon”)), each with about 24 hourly readings on each of the six days. There were thus about 47 million data points.

We also received a list of these meters and the ZIP codes in which they are located. No other spatially identifiable information was provided. MARC used the ZIP code information to sort the meters into either core, rural, or suburban development types. The populations and areas of the various development types are given in Table 1. The suburban area is the most populous.

Table 1. Land areas and populations (2004) of the various land uses in the studied region.

Development type	Area (mi²)	Area (km²)	Population in 2004
Core	116	300	289,530
Rural	1,535	3,976	105,559
Suburban	1,132	2,932	1,113,212
Total	2,783	7,208	1,508,301

We quickly noticed that there were about 2 million (about 25%) fewer records on July 27 than the other days. Therefore, we eliminated that day from the analysis. This left about 39 million data points to be analyzed and alerted us to be careful in evaluating the data. We followed the following procedure to calculate the hourly power demand by date and area type.

We processed five different files, one for each of five days: May 17, May 18, May 19, July 28, and July 29.

Each file contained hourly readings (24 hours in total) for more than 326,500 meters.

Thus, each measurement (row in file) contained:

- meter id ("Mon ID"),
- ZIP code,
- area type (Core, Suburban, or Rural),
- Date/Time (e.g. "2015-05-18 21:00:00"), and
- observation value (the power demand).

Since the number of rows/meters varied by date, each pair of dates was compared using only the meters and hours of day that were present in both dates. In Table 2, the total matched entries column gives the number of rows that were successfully matched between the dates. The same goes for the unique meters column.

To produce the 24-hour power demand profile for each date and area type, the power demands in each raw file were grouped (and added) by area type and by hour.

Table 2. The number of meter readings and meters in KCMA that matched on pairs of days in 2015.

Date 1	Date 2	Total matched hours	Unique meters	Unique ZIP codes
17 May	28 July	7,741,959	326,571	113
17 May	29 July	7,734,731	326,599	113
18 May	28 July	7,744,859	326,590	113
18 May	29 July	7,736,297	326,600	113
19 May	28 July	7,726,423	326,553	113
19 May	29 July	7,718,530	326,588	113

In greater detail, we compared each pair of dates (Table 2) using only the meters and hours of day for which data were present on both days ("matched"). In Table 2, for the entire Kansas City Metropolitan Area (KCMA), the *total matched hours* column presents the number of hours that were successfully matched between the dates, and the *unique meters* column presents the number of meters that matched on the two dates.

There are small variations among the days that had matching data; some meters did not match on all days. It turned out that these omissions were not a serious problem. From the data in Table 2, we found the mean value of the number of matching meter readings for all pairs of days is $7.733 \times 10^6 \pm 0.1\%$. The total number of matching meters is 326,583 ± 0.06%. Thus, the number of matching readings and meters is constant within a fraction of a percent. For the pair of days we chose (July 28 and May 19) the number of matching meter readings was 7.726×10^6 and the number of matching meters was 326,533. If every meter had 24 hourly readings there would have been 7.836×10^6 readings. Thus, we missed 0.1108×10^6 meter readings, or 1.6% of the total expected. Moreover, we found that, in the populous suburban region, KCPL did not provide data for 9 of the 68 ZIP codes; we lack about 13% of the region's data (Table 3). Nevertheless, we analyze the 87% for which we have data, and presume that the results apply to the entire region.

Table 3. Buildings, roof areas, and ZIP codes in various development regions. Columns labeled "total" include all buildings and ZIP codes, while those labeled "with meters" includes only those for which KCPL reported metered electricity use.

	Core (with meters)	Core (total)	Suburban (with meters)	Suburban (total)	Rural (with meters)	Rural (total)
Number of buildings	111,935	140,938	477,992	545,652	23,414	62,752
Footprint area [km^2]	24.4	28.7	101.2	112.2	4.6	12.4
Number of ZIP codes	23	25	59	68	8	22

Once satisfied that we were counting the vast majority of the meters in the KCMA, we then sorted the data for the chosen pair of days according to development type and by hour. We summed all the meter demands for a given hour to obtain the hourly power demand of an entire region for a day.

These power-demand numbers for the suburbs came out to be about 500,000 units. Regrettably, we received no information about what the units of measure for these power values are (if they are watts, kilowatts, etc.). We infer the units by comparison to known power demands and populations. For example, in 2016, with a population of 6,093,000 (US Census, 2018) the residential sector in MO consumed 34,354,932 MWh (EIA, 2018), yielding an average per-person electrical energy use of 5,688 kWh/y, or an average per-person electrical power demand of ~ 0.64 kW. For the KC suburbs, with a population of about 1 million, the hourly power demand should be of order of magnitude 1 million persons · 1 kW/person ~ 1 GW. Comparing to the number we obtained, we conclude that the unit of power reported by KCPL is kW. This gives, for the power for the suburbs, about 500,000 units = 500,000 kW = 0.5 GW. Any other choice of standard units (e.g., watts or megawatts) for the power records would give absurd magnitudes.

In Figure 1 we present, as an example, the electric power demand curves for the suburban development type in Kansas City for the two chosen days.

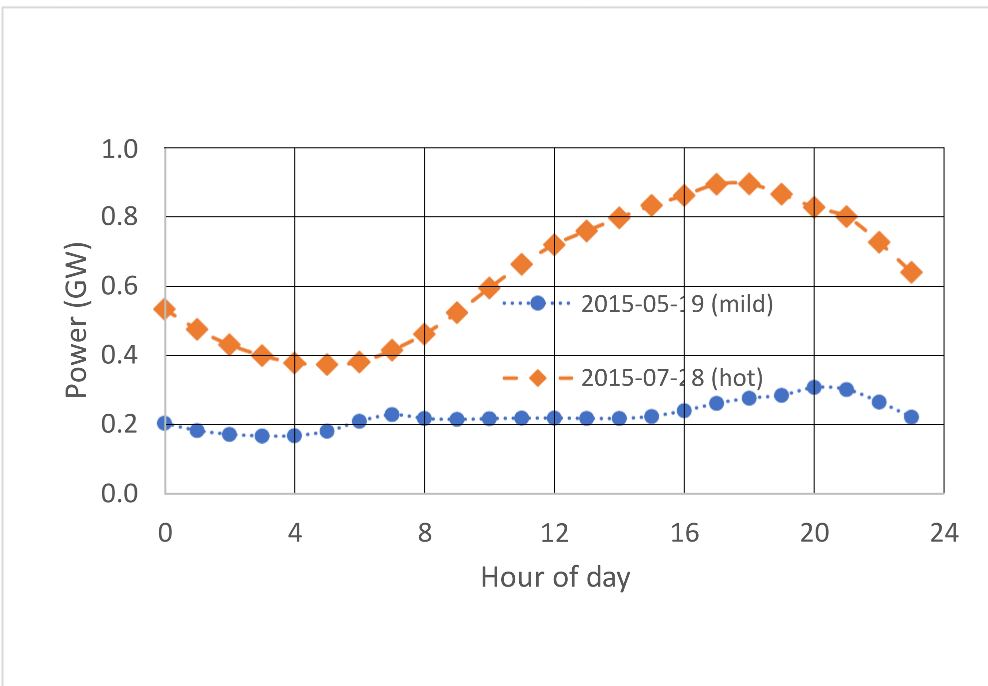


Figure 1. Hourly electric power demands on a hot day (2015-07-28) and a mild day (2015-05-19) in suburban Kansas City. Both are weekdays with about the same amount of sunlight.

To find the AC power demand, we subtract the demand on the mild day, May 19, from that of the hot day, July 28. The resulting demand is that attributed to AC; we denote this by *P*. When this hourly AC demand is plotted together with the hourly temperature on July 28 there is a similar shape to the curves, but the AC demand lags about 2 hours behind the temperature (Figure 2).

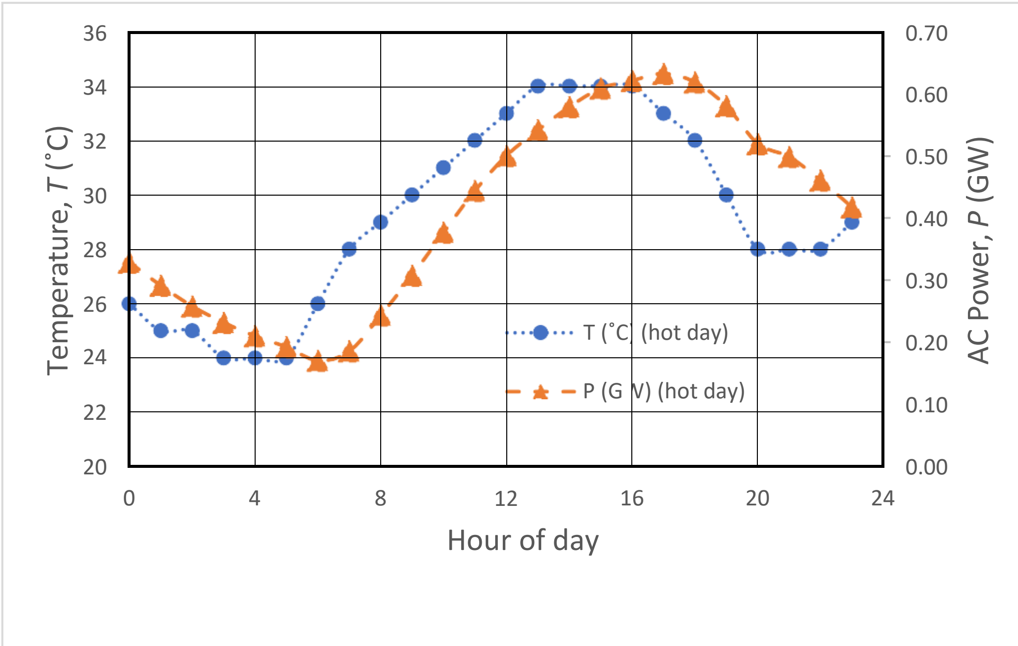


Figure 2. Hourly air temperature and AC power demand on a hot day (2015-07-28) in suburban areas of Kansas City.

Figure 3 plots the AC power data for the suburban areas, shifted two hours earlier, versus air temperature on the hot day. In Figure 3, the slope of the (dotted) trend line is $(dddd_{\text{suburban}}/dddd)_{\text{max}}$ = 0.044 GW/°C. As mentioned above, by choosing a very hot day, we obtain the maximum slope (see Appendix of Pomerantz et al. 2015). This is a parameter needed for Eq. (4). It is the maximum sensitivity of AC power demand to air temperature. It means that a 1 °C decrease in air temperature on a warm or hot day will reduce AC power demand in the suburbs by no more than 0.044 GW. The value of the coefficient of determination, R^2 = 0.96, indicates excellent linear correlation of dd with dd.

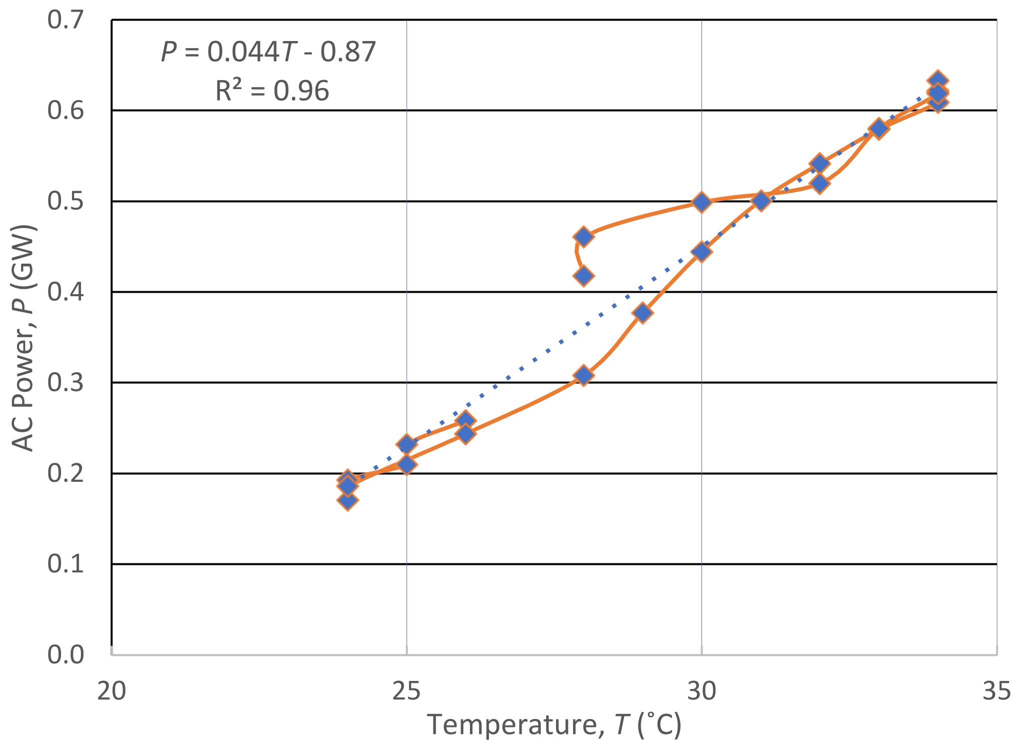


Figure 3. Hourly AC power demand, dd, vs. hourly outdoor air temperature, dd, on a hot day (2015-07-28) in suburban Kansas City, MO.

4 Effect of cool roofs and green infrastructure on city-wide temperature

A meteorological simulation program was used to find the air temperature under the present conditions (Jeoung et al. 2018). The simulations were repeated with increased roof albedos by 0.40 (0.2 to 0.6), and an urban irrigation scenario to increase soil moisture. The results depended on the land use, i.e., whether there was a high density of impermeable or of permeable land. For the roof albedo case, maximum *reduction* in daily average air temperature $(\Delta dd)_{max}$ was 0.07 °C (low roof density), 0.12 °C (medium roof density), or 0.15 °C (high roof density). For the irrigation case, $(\Delta dd)_{max}$ was 0.25 °C (high roof density) or 0.4 °C (low and medium roof density). For more information, please refer to the *Task 3 Evaluation of urban heat island mitigation strategies for the Kansas City metropolitan area* report (Jeoung et al. 2018). To estimate maximum possible savings, we assume air temperature reductions $(\Delta dd)_{max}$ = 0.2 °C due to roofs and $(\Delta dd)_{max}$ = 0.4 ºC due to green infrastructure.

5 Results

We now derive the maximum benefits attained by increased roof albedo and green infrastructure, including the savings in energy, peak-power, and CO_2 emission, for the Kansas City metropolitan area. The results are also summarized in Table 5.

5.1 Energy savings from deployment of cool roofs

We assume a maximum air temperature reduction $(\Delta dd)_{\mathrm{max}}$ of 0.2 °C for cool roofs. We found, from the power demand data for the suburban area, $(dddd_{\mathrm{suburban}}/dddd)_{\mathrm{max}}$ = 0.044 GW/°C. We assessed the weather data to find CH18C < 4000 h. We substitute these in Eq. (4) to find the maximum annual energy savings for the suburban Kansas City area,

$$\Delta EE_{\mathrm{a,max}} = (dddd_{\mathrm{suburban}}/dddd)_{\mathrm{max}} \cdot (\Delta dd)_{\mathrm{max}} \cdot \mathrm{CH18C} = 35.2 \text{ GWh} \qquad (5)$$

Performing similar analyses for $(dddd/dddd)_{\mathrm{max}}$ for the less-populous areas classified as "core" and "rural", we find, for the core area, $(dddd_{\mathrm{core}}/dddd)_{\mathrm{max}} = 8.9 \times 10^{-3}$ GW/˚C (R^2 = 0.95) and, for the rural area, $(dddd_{\mathrm{rural}}/dddd)_{\mathrm{max}} = 6 \times 10^{-4}$ GW/°C (R^2 = 0.98). Using the same temperature reduction $[(\Delta dd)_{\mathrm{max}} = 0.2°\mathrm{C}]$ and CH18C < 4000 h, the respective maximum annual electrical energy savings for the core and the rural areas are < 7.1 GWh and < 0.5 GWh.

We further calculated the energy savings per square meter of modified roof area. We identified the roof areas using GIS tools and MARC geospatial data (Table 4). We extracted the roof areas in the ZIP codes in the KCMA for which we had power data and also those for which we did not have power data, in order to learn how much roof area we may have missed (Table 3).

Table 4. The MARC geospatial datasets.

GIS filename	**Description of file**
Building_Footprints	The building footprints for all buildings in MARC 's region as of 2015. A building footprint is the area defined by the perimeter of the building structure. It is taken to be the roof area.
Cities	All incorporated cities in MARC region.
Counties	All counties in the MARC region.
KCPL_ZIP_INFO	All ZIP codes in MARC region. Also includes population from 2004, the number of monitors tied to each ZIP code, the total number of readings taken over the 5 days, urban area type, and the land area of each ZIP code.
MARCBoundary	The area defined by the MARC regional boundary for the nine counties.
UrbanAreaBoundary	The delineation of core, suburban and rural urban development classifications within the MARC region.

The procedure we followed to obtain the roof areas, populations and number of buildings was to extract this data from *ArcGIS layers*:

KCPL layers: Highlights the geographical area covered by each ZIP code. For each ZIP code, it gives the population and the area type to which it belongs (Core, Suburban, or Rural). From the

KCPL layers, we selected the data only from the ZIP codes present in the power demand files. To obtain the populations, we grouped and added the population in the KCPL layers by area type.

Building footprints layers: For each building in the entire KC region, identifies the building and gives its footprint area. For simplicity, we assume that roof area equals footprint area.

In Table 3 we display the roof areas (footprint areas) for the ZIP codes for which we had meter readings. Also, we show the total footprint areas for all ZIP codes in each urban development area type, which is greater because we do not have matching meter readings for all ZIP codes. We are missing about 10% of the area buildings and roofs in the most populous suburbs and core regions. If we had the data for all the buildings and meters in the suburbs and core, the total energy savings might be about 10% larger, but the roof area would also be about 10% larger. Thus, the ratio of energy savings to roof area would be about the same. Clearly, the energy savings per unit roof area is the most relevant parameter. The roof area for which we have power data in suburban Kansas City = 101×10^6 m^2. The maximum annual energy saved per unit area of cool roof is < (35.2 GWh) / (101×10^6 m^2) = 0.35 kWh/m^2. The results for all regions are listed in Table 5.

5.2 Annual cooling energy monetary savings from deployment of cool roofs

To find the maximum annual cooling-energy monetary savings, we multiply the maximum annual cooling energy savings by the summer price of electricity charged by KCPL, $0.13/kWh for residences (KCPL 2018, and private communication from MARC). The rate for commercial buildings is about half of that. We do not disaggregate the residential from the commercial, but the cost saving we present is a maximum because we apply the higher residential rate. Per unit cool roof area, again for suburban Kansas City as an example, the maximum annual cooling-energy monetary savings = 0.35 kWh/m^2 · $0.13/kWh = $0.05/$m^2$. The results for all regions are listed in Table 5.

5.3 CO_2 emissions avoided from deployment of cool roofs

To find the maximum amount of CO_2 emission that could be avoided by the decrease in electrical energy consumed, we multiply the latter by the CO_2 emission factor, *e*, defined as the ratio of mass of CO_2 emitted to site electricity used. In Missouri, the ratio of CO_2 emitted to electricity *leaving the power plant* is 1,993 lb CO_2/MWh = 0.905 kg CO_2/kWh (USEPA 2018). Assuming transmission-and-distribution efficiency 90% yields emission factor *ee* = 0.905 / 0.90 = 1.01 kg CO_2/kWh.

For example, for suburban Kansas City we obtain maximum annual CO_2 emission reduction per unit cool roof area of 0.35 kWh/m^2 × 1.01 kg CO_2/kWh = 0.35 kg CO_2/m^2 .

The monetary value of the avoided CO_2 is found by multiplying the quantity of CO_2 avoided by the current price of avoided CO_2, which is about $15/tonne or $0.015/kg. For example, for suburban Kansas City the maximum annual monetary saving is (\$0.015/kg CO_2) × 0.35 kg CO_2/m^2 = \$0.0053/m^2. This, and the corresponding values for the core and rural regions, are listed in Table 5.

5.4 Peak-power reduction from the deployment of cool roofs

We define the peak power as the maximum power demand on the electric utility over the course of the year. This is an important quantity because the utility must have sources that can generate the peak power, or else there will be brown-outs or other disruptions of service. It is desirable to keep the peak power demand as low as possible, because the power plants activated to handle peak demand are usually the least efficient and most polluting, and are frequently idle. The maximum peak-power reduction attained by the installation of cool roofs is given by

$$(\Delta dd)_{\max} = (dddd/dddd)_{\max} \cdot (\Delta dd)_{\max} \quad (6)$$

For suburban Kansas City, $(\Delta dd)_{\max}$ = 0.044 GW/˚C × 0.2˚C = 0.0088 GW.

The fractional peak power reduction is $(\Delta dd)_{\max}/dd_{\max}$. From Figure 2 we observe that $dd_{\max}$ = 0.6 GW for suburban Kansas City, so that $(\Delta dd)_{\max}/dd_{\max}$ = 0.0088 GW/0.6 GW = 1.5% for suburban Kansas City. The results of savings due to roofs for all urban development types are collected in Table 5.

Note that these are all maximum values; the actual values are probably smaller.

Table 5. Input parameters and results for maximum electrical energy savings and CO_2 emission savings per year, and peak-power reduction due to cooler roofs creating cooler air.

	Suburb	**Core**	**Rural**	**Total**
$(dddd/dddd)_{\max}$ (GW/˚C)	0.044	0.0089	0.0006	
Maximum air temperature reduction (˚C)	0.2	0.2	0.2	
Maximum regional electrical energy savings (GWh/y)	35.2	7.12	0.48	42.8
Maximum regional cost savings (\$M/y)	4.58	0.93	0.06	5.56
Roof area (million m^2 = km^2)	101	24	5	
Maximum electric energy savings per unit roof area (kWh/y·m^2)	0.35	0.30	0.10	
Maximum electric cost savings per unit roof area (\$/y·m^2)	0.05	0.04	0.01	
Maximum CO_2 emission savings per unit roof area (kg/y·m^2)	0.35	0.29	0.09	
Maximum monetary value per unit roof area of CO_2 emission savings (\$/y·m^2)	0.005	0.004	0.001	
Maximum regional peak-power demand reduction (GW)	0.0088	0.0018	0.00012	0.011
Maximum fractional reduction in regional peak AC power demand (%)	1.5	0.3	0.02	1.8

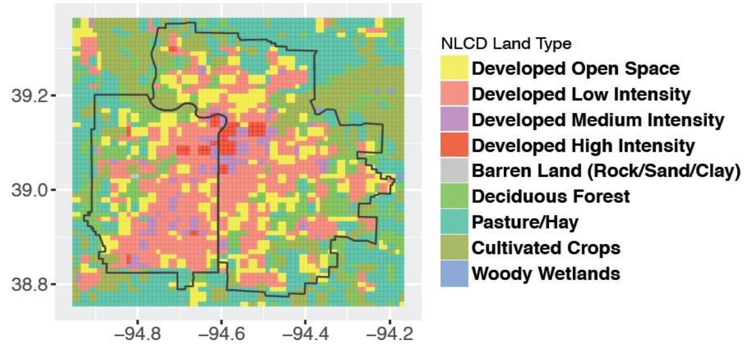
5.5 Benefits from utilization of green infrastructure

The effect of green infrastructure is represented in our meteorological simulations by increasing soil moisture through urban irrigation. This causes a maximum *reduction* in the air temperature of about 0.4 °C, according to Fig. 4 of the Task 3 report (Jeong et al. 2018). The maximum savings that this engenders are obtained by going through the steps described above. Effectively, it amounts to replacing $(\Delta dd)_{max}$ = 0.2 °C by $(\Delta dd)_{max}$ = 0.4 °C in Eqs. (4) - (6). Because the results depend linearly on Δdd_{max}, the answers can also be found by scaling the appropriate values for roofs by a factor of 2. The resulting values for the irrigation effect are collected in Table 6.

To evaluate the savings *per unit area* is somewhat problematic because the area considered in the meteorological simulations was not exactly the same as the area considered for the power dependence calculation. It is not clear whether the descriptions of the type of region “core, suburb, rural” in the power calculation are the same as “high, medium, low development” in the meteorological simulations. The data sources do not use the same geographical divisions. (The land-use data in the meteorological simulations are on a rectilinear grid, while the power data were segregated by ZIP code.)

To compare the areas used in the different parts of this report we display maps showing the areas in Figure 4. The inner domain considered in the meteorological simulation is shown in Figure 4a (also Figure 1c in Jeong et al. 2018). Figure 4b shows the MARC boundary and the included urban areas (cross-hatched) used in the power calculations. Panels a and b in Figure 4 are roughly to the same scale.

(a)



(b)

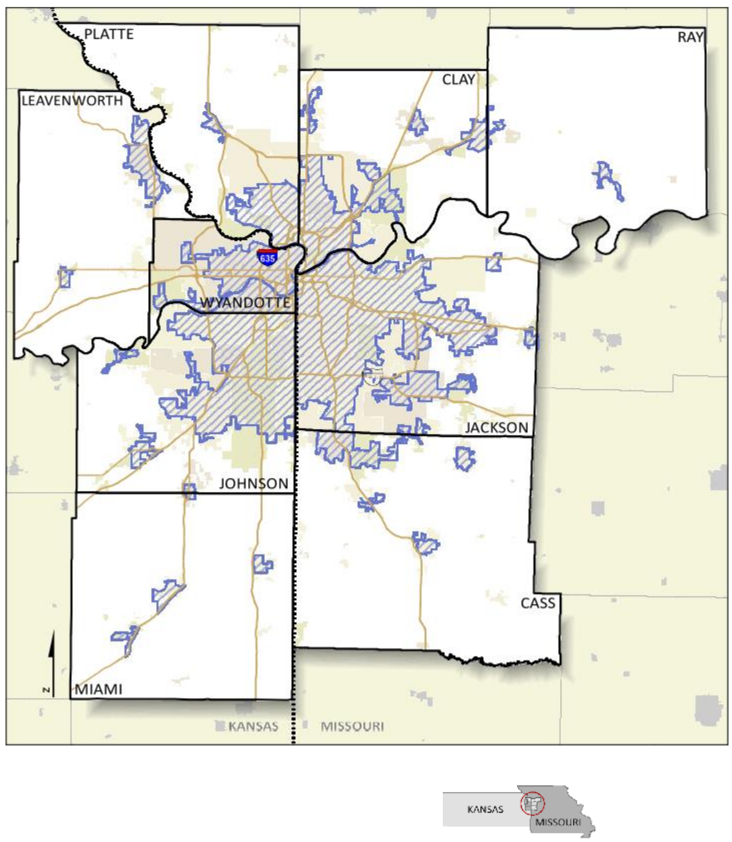


Figure 4. Maps of the urban areas as used in (a) the meteorological simulations (jagged black line is the outline of the urban areas) and (b) the power calculations (cross-hatched areas are urban).

The domain used in the meteorological simulation is about 70 km by 60 km, or about 5,600 km^2. The urbanized area is outlined by the black solid line in Figure 4a and is roughly 60 km by 55 km for a total of about 3,300 km^2. For the power calculations, we identified suburban plus core areas (urban areas where we had meter readings) of 3,200 km^2 (Table 1). The urbanized areas covered by both calculations are thus nearly the same, justifying the use of the results of the power calculations to obtain the energy benefits of irrigation. Of that total urbanized area, the meteorological simulation program identified about 1,000 km^2 of terrain that was permeable and thus suitable for irrigation. The vast majority is in the suburbs; we ignore the rural areas. (Irrigation is a proxy for increased vegetation, but rural areas are already completely vegetated and are not a candidate for modification. Moreover, there are so few air-conditioned buildings in the rural areas that savings are negligible there. This is indicated by NA, not applicable, for some results.)

The results for the savings resulting from increased irrigation are collected in Table 6.

Table 6. Input parameters and results for maximum electrical energy savings, CO_2 emission savings, and peak-power reduction due to increased irrigation creating cooler air.

Kansas City Metropolitan Region	**Suburb**	**Core**	**Rural***	**Total**
$(dddd/dddd)_{max}$ (GW/˚C)	0.044	0.0089	0.0006	
Maximum air temperature reduction (˚C)	0.4	0.4	0.4	
Maximum regional electrical energy savings (GWh/y)	70.4	14.2	1.0	85.6
Maximum regional cost savings ($M/y)	9.2	1.8	0.1	11.1
Irrigated areas (million m^2 = km^2)	~ 1000	~ 0	NA	~1000
Maximum electric energy savings per unit irrigated area (kWh/y·m^2)	0.07	0.01	NA	0.08
Maximum electric cost savings per unit irrigated area ($/y·$m^2$)	0.009	0.002	NA	0.01
Maximum CO_2 emission savings per unit irrigated area (kg/y·m^2)	0.07	0.01	NA	0.08
Maximum monetary value per unit irrigated area of CO_2 emission savings ($/y·$m^2$)	0.001	0.0002	NA	0.001
Maximum regional peak-power demand reduction (GW)	0.018	0.004	NA	0.022
Maximum fractional reduction in regional peak AC power demand (%)	3.0	0.6	NA	3.6

* Aggregate irrigation benefits in rural areas are marked NA (not applicable) because these areas contain few air-conditioned buildings.

5.6 Cumulative benefits from utilization of green infrastructure and deployment of cool roofs

In Table 7 we collect the total maximum savings from both cooler roofs and greener infrastructure. It shows that the rural areas, having few buildings with air conditioning, do not offer significant savings. Thus, to the accuracy of our data, the rural areas can be ignored. For simplicity, we combine the suburban and core areas into an “urban region”. Considering the possible omissions in the data and the necessary approximations, we estimate that our results are reliable to within a factor of two.

Table 7. Results for maximum electrical energy savings, CO_2 emission savings, and peak-power reduction due to both cooler roofs and greater irrigation creating cooler air, from Table 5 and Table 6.

Kansas City Urban Region (Core + Suburb)	**Total Savings**
Maximum annual effects of modified ROOFS	
electrical energy savings (GWh/y)	43
electrical cost savings ($M/y)	6
electric energy savings per unit roof area (kWh/y·m^2)	0.35
electric cost savings per unit roof area ($/y·$m^2$)	0.05
CO_2 savings per unit roof area (kg/y·m^2)	0.35
monetary value per unit roof area of CO_2 savings ($/y·$m^2$)	0.005
peak-power reduction (GW)	0.01
fractional reduction in peak AC power (%)	2
Maximum annual effects of modified IRRIGATION	
electrical energy savings (GWh/y)	86.0
electrical cost savings ($M/y)	11
electric energy savings per unit irrigated area (kWh/y·m^2)	0.08
electric cost savings per unit irrigated area ($/y·$m^2$)	0.01
CO_2 savings per unit irrigated area (kg/y·m^2)	0.08
monetary value per unit irrigated area of CO_2 savings ($/y·$m^2$)	0.001
peak-power reduction (GW)	0.02
fractional reduction in peak AC power (%)	4

References

EIA. (2018). Sales to Ultimate Customers (Megawatthours) by State by Sector by Provider, 1990 - 2016. US Energy Information Agency. https://www.eia.gov/electricity/data/state/sales_annual.xlsx, accessed 24 May 2018.

KCPL. (2018). Kansas City Power & Light. Residential rates for electricity in the KCPL-Missouri service area. https://www.kcpl.com/my-account/rate-information/rate-overviews/residential-rate-overview-missouri , accessed 06 September 2018.

Jeong, S., Millstein, D., & Levinson, R. (2018) Task 3: Evaluation of urban heat island mitigation strategies for the Kansas City Metropolitan Area. Prepared for U.S. Department of Energy and Mid-America Regional Council.

Pomerantz, M., Rosado, P. J., & Levinson, R. (2015). A simple tool for estimating city-wide annual electrical energy savings from cooler surfaces. Urban Climate, 14, 315–325. https://doi.org/10.1016/j.uclim.2015.05.007

Pomerantz, M. (2018). Are cooler surfaces a cost-effect mitigation of urban heat islands? Urban Climate, 24, 393–397. https://doi.org/10.1016/j.uclim.2017.04.009

US Census. (2018). US Census Bureau. Populations of geographical areas. Accessed online at https://www.census.gov/quickfacts/MO on 24 May 2018.

USEPA. (2018). eGrid 2016, US Environmental Protection Agency. Emissions resulting from electric power generation, https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid, accessed 31 March 2018.

Appendix B

Task 3: Evaluation of urban heat island mitigation strategies for the Kansas City region

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Abstract

We evaluate two mitigation strategies for urban heat island in the Kansas City Metropolitan Area (KCMA). Using the Weather Research and Forecasting (WRF) model, we assess the potential benefits of highly reflective cool roofs and urban irrigation on urban air temperature in typical summer conditions between 2011 and 2015, and also during six of the strongest historical heat wave events over the past 12 years (2005 – 2016). Under the typical summer conditions, we simulate near-surface (2-m) air temperature for 10 summer weeks, finding average daytime (07:00 – 19:00 local standard time) temperature reductions of 0.08 and 0.28 °C for cool roofs and urban irrigation, respectively. During the six heat-wave episodes, we also find similar daytime temperature reductions of 0.02 and 0.26 °C for the two scenarios compared to those of the typical summer conditions. Our results suggest that urban irrigation can be more efficient than cool roofs in mitigating the urban heat island in metropolitan regions where the majority of the urban land cover is comprised of areas with low urban (i.e., non-vegetated) fractions. Finally, we find the alteration of land surface conditions due to enhanced roof albedos impacts local meteorology and precipitation patterns within the WRF simulation, in particular during the heat wave periods. Further research would be necessary to determine the robustness of this last finding.

1 Introduction

Temperatures in urban regions are increasing due to a combination of global climate change and local factors such as the use of heat-trapping materials and anthropogenic heat sources [Hassid, S et al., 2000; Miller et al., 2008; Salamanca et al., 2013]. A recent study in North America suggests that urban expansion alone can increase regional temperature at a level similar to warming due to the increase of greenhouse gases in the atmosphere [Georgescu et al., 2014]. In addition, temperature increase in urbanized areas is known to be a source of air quality problems [Nazaroff, 2013] and heat-related public health problems [Luber and McGeehin, 2008; Li and Bou-Zeid, 2013; Yang et al., 2013].

Carefully planned urban growth strategies may provide an opportunity to mitigate urban heat stress. Increasing the solar reflectance (albedo) of roofs can cool buildings, reducing air conditioning use and lowering urban air temperatures [Parker and Barkaszi, 1997; Akbari et al., 1999; Levinson et al., 2005; 2010, Vahmani et al., 2016]. A second strategy to mitigate urban heat stress is to irrigate the urban vegetated landscape. Urban irrigation can reduce urban temperature by increasing evaporative cooling of the surface and near-surface air [Vahmani and Hogue, 2015; Vahmani and Ban-Weiss, 2016].

In this report, we evaluate potential temperature reductions from both highly reflective "cool" roofs and urban irrigation in the Kansas City Metropolitan Area (KCMA), a major metropolitan area in the Midwestern region of the United States. We examine air temperature reductions from each of the two mitigation strategies. We also show potential impact of changes in the land surface and near-surface atmospheric conditions on air temperature over the study domain.

This study tests the impacts of full, idealized, implementation of the mitigation strategies – in other words, all roofs are switched to cool roofs and all vegetated areas are irrigated. In practice, neither all roofs nor all vegetated areas would be treated in this manner. In the case of urban irrigation, urban irrigation serves as a surrogate for a strategy that supports stormwater infiltration practices via green infrastructure.

2 Method

2.1 WRF Urban Canopy Model

We use the Weather Research and Forecasting (WRF) model (version 3.8, [Skamarock et al., 2008]) to simulate different urban heat island mitigation strategies. The WRF model has been widely used for numerical weather prediction and also to investigate issues related to regional climate, atmospheric transport, air quality, and water resources [e.g., Chen et al., 2011; Jeong et al., 2016; 2017; Vahmani and Ban-Weiss, 2016; Bagley et al., 2017]. We use the single-layer urban canopy model (SLUCM, Kusaka et al., 2001; Kusaka and Kimura, 2004) to represent the urban physics. We use the Noah land surface model (LSM) [Chen and Dudhia, 2001], following a number of urban modeling studies (e.g., Millstein and Menon, 2011; Salamanca et al., 2013; Cao et al., 2015; Vahmani and Ban-Weiss, 2016). In the coupled WRF-SLUCM model, SLUCM is used to simulate the surface energy balance for the urban portion of each grid cell while the Noah LSM is used for the vegetated portion. WRF-SLUCM parameterizes the influence of urban canyons and building and pavement thermal properties on the surface energy budget [Chen et al., 2011].

The main physical options for WRF-SLCUM simulations in this study are set as follows: (1) radiation: Rapid Radiative Transfer Model RRTM scheme [Mlawer et al., 1997] for longwave radiation and Dudhia scheme [Dudhia, 1989] for the shortwave; (2) planetary boundary layer: UW (Bretherton and Park) scheme [Bretherton and Park, 2009]; (3) microphysics: Morrison double-moment scheme [Morrison et al., 2009]; and (4) cumulus: Grell-Freitas ensemble scheme [Grell and Freitas, 2014]. The initial and boundary meteorology conditions for WRF are provided by the North American Regional Reanalysis (NARR, Mesinger et al., 2006). A two-way nesting scheme for the three-level domains (13.5, 4.5 and 1.5 km) is used for the meteorology simulations (Figure 1). The atmosphere is divided into a total of 30 levels.

Figure 1 shows the entire modeling domain and the 1.5-km inner domain that includes KCMA. The National Land Cover Data (NLCD; Fry et al., 2011), which provides forty land cover types, is utilized to define land type in the study domains (Figure 1). We adopt the default urban fractions of 50%, 90%, 95% for the three urban types: low, medium and high development intensity, respectively. For a given model gird cell, the urban fraction is the ratio of the urban (pavement and buildings) portion to the total area of the grid cell. To better represent the urban canopy in WRF simulations, we use the urban parameter data (e.g., mean building height) from National Urban Database and Access Portal Tool (NUDAPT, Ching et al., 2009). Because the NUDAPT dataset was available only for the urban core area of KCMA, we extrapolate the existing dataset to cover the entire KCMA. In this extrapolation, we calculated median values by development intensity (i.e., low, medium, and high) from the available NUDAPT dataset and applied them to non-NUDAPT areas.

Using a spin-up of 18 hours, we simulate meteorological variables including 2-m temperature in typical summer conditions between 2011 and 2015 and during six of the strongest historical heat wave events over the past 12 years (2005 – 2016; see the supplemental Figure S1 for selected heat wave periods). The diagnostic 2-m temperature (hereafter air temperature) variable in WRF-SLCUM represents an air temperature near the height of the urban canopy [Li and Bou-Zeid, 2014].

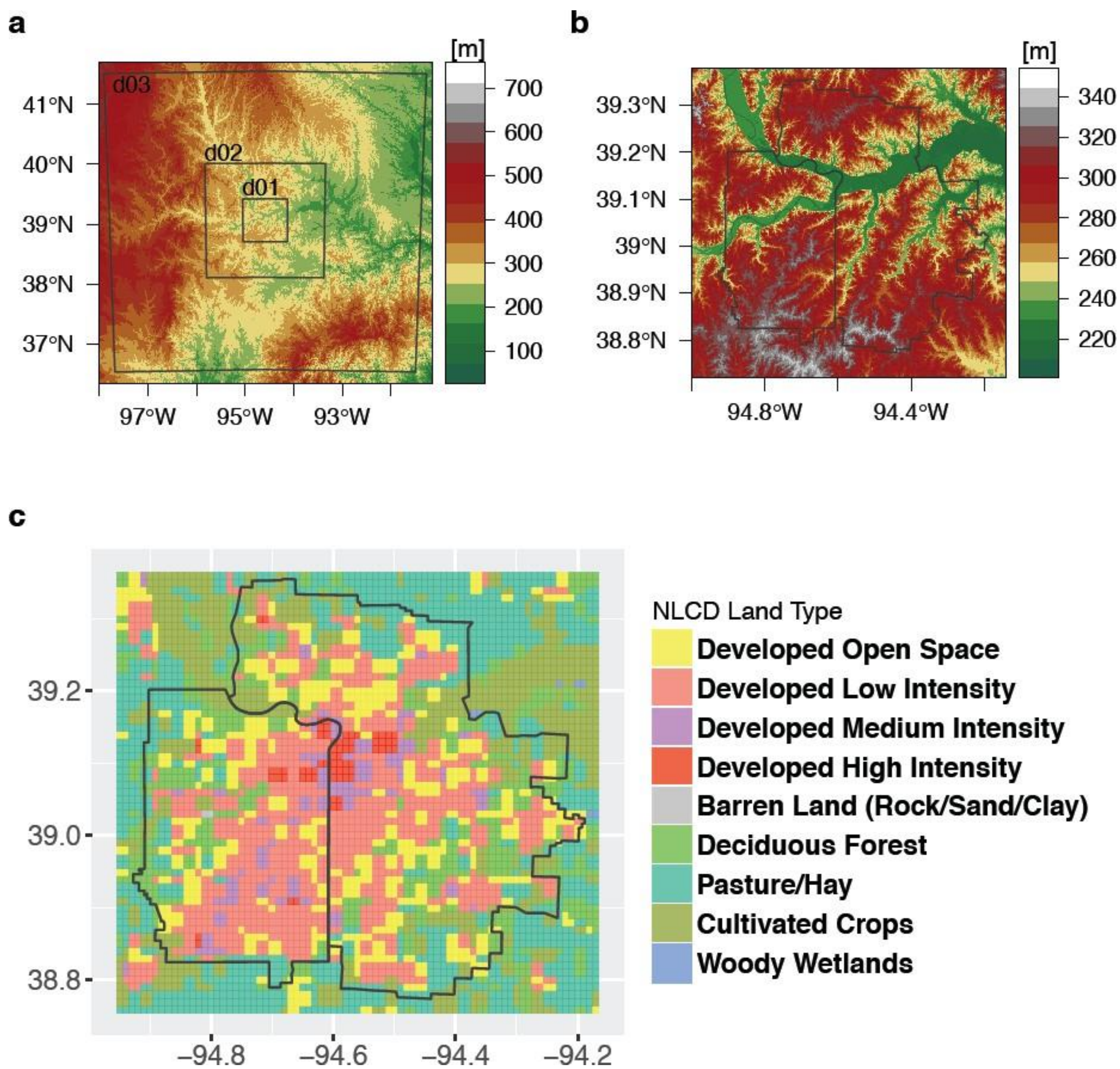


Figure 1. Maps showing (a) elevation of the entire modeling domain, at horizontal resolution of 1 arc-second (~30 m) [National Map, 2017]; (b) elevation of inner modeling domain; and (c) land type [Fry et al., 2011]. Boxes d01, d02, and d03 in panel (a) represent WRF modeling outer (d01) and nested (d02 and d03) domains, while the boundary (black solid line) in panels (b) and (c) represents the urbanized area in the Kansas City metropolitan region from the 2000 U.S. Census [Mid-America Regional Council, 2017].

2.2 Mitigation Strategies for WRF Simulations

We run a series of simulations to evaluate urban temperature reductions in KCMA upon raising roof albedo, and increasing urban irrigation. We ran 10 week long simulations representing typical summer conditions, selecting the 15th – 21st of July and August in 2011 – 2015. Separately, we identified and simulated six of the strongest historical heat-wave events over the past decade (2005 – 2016). For historic heat waves, we identified the episodic heat wave periods using measured near-surface air temperature data at the C. R. Wheeler Downtown Airport located in the urban area of KCMA (supplemental Figure S1), which are available from the Integrated Surface Database (ISD) of NOAA's National Centers for Environmental Information (NCEI, 2017). We selected six heatwave episodes by finding the periods with the highest seven-day moving average temperatures during 2005 – 2016 (supplemental Figure S1). For 2012, we identified two heat waves but selected the stronger episode in early July.

For each 7-day episode, we conduct independent WRF simulations for two mitigation scenarios: raising roof albedo and increasing urban irrigation. The mitigation scenarios are compared to the control scenario. Within the cool roof scenario, roof albedo is raised from 0.20, its value in the control scenario, to 0.60, following Cao et al. [2015]. For the irrigation scenario, we activate the WRF irrigation scheme, inactive in the control case, which causes the top two model layers to reach critical moisture content such that transpiration is not limited by water availability. The WRF irrigation scheme is implemented at 21:00 local standard time (LST) every day from May to September. The WRF irrigation scheme is essentially equivalent to a city actively watering all unpaved areas each evening.

3 Results and Discussion

3.1 Evaluation of Heat Island Mitigation Strategies

We use 2-m temperature simulations from WRF-SLCUM to evaluate the impact of heat island mitigation strategies. To check the performance of WRF using this set-up, we compare WRF-simulated near-surface (2-m) temperature with observations and the results are shown in the supplemental Figure S2. Overall, WRF simulations are well-correlated with observed temperature yielding values of 0.82 and 0.76 for the coefficient of determination (i.e., r^2) during normal and heat wave episodes, respectively. We found that average (i.e., arithmetic mean) temperatures across KCMA during both normal and heatwave conditions were sensitive to elevation, with lower elevations having higher temperatures; for example, compare the temperature maps in Figure 2a,b to elevation map in Figure 1b. However, the spatial patterns of temperature reductions from the two mitigation scenarios, for both normal and heat wave episodes, match the land-use type distribution; see the larger temperature reductions (Figure 2c-f) correlate with the higher density development land-use types (Figure 1c). We note, though, that most of the high intensity development is located near the river and at low elevation relative to the surrounding areas, thus the influence on temperature mitigation strategies of land-use type cannot be fully separated from the influence of topography.

The average daytime (07:00 – 19:00 LST) temperature reductions from the mitigation scenarios varies by urban development intensity (Figure 3). For the roof albedo scenario, the average temperature reduction for the normal episode ranges from 0.07 to 0.17 °C depending on the development intensity. For the heat wave episode, the temperature reduction varies from 0.01 to 0.09 °C, showing somewhat reduced mitigation effect compared to that of the normal episode (Figure 3a). This result is different from that reported in Cao et al. [2015] where they reported significantly larger temperature reductions from cool roofs during heat waves compared to normal summer conditions. The absence of increased temperature reductions during heatwaves in this work counters the generalization of a simple hypothesis that could be derived from Cao et al. [2015]: that urban mitigation strategies will produce larger temperature reductions given higher initial temperatures. This indicates that the geography of the city and regional meteorology conditions influences the performance of mitigation strategies during extreme conditions such as heatwaves relative to their performance during normal conditions. We expand this discussion in later sections.

Temperature reductions from the urban irrigation scenario (Figure 3b) are consistently larger than those of the roof albedo scenario for all development intensity types with mean temperature reductions being equal to or larger than 0.2 °C for all cases. As shown in Figure 3b, the interquartile ranges (IQR, or difference between upper and lower quartiles) for the normal and heat wave episodes overlap, suggesting that there is no significant difference in the effect of temperature reductions between the normal and heat wave episodes.

We applied the nonparametric Wilcoxon-Mann-Whitney test (WMW) [Mann and Whitney, 1947] to decide whether there is a statistically significant difference in the mean temperature between the control and mitigation scenarios. Using the WMW test, we can evaluate whether the population distributions are identical without normality assumptions for the data. For this test, we assumed that each of the control and mitigation scenarios is an independent group for which we can estimate the mean air temperature. Our assumption of independent grouping between control and mitigation scenarios is similar to the case to examine whether there is a difference in simulated mean temperature from a climate model due to different scenarios about atmospheric CO_2 concentration levels [Wilks, 2011]. Note that we used this nonparametric test because the temperature distribution may not be normally distributed across the study region. As indicated by the IQR in the boxplots of Figure 3, the Wilcoxon-Mann-Whitney test determined that, except for the roof albedo scenario during the heat wave episode, the temperature in each mitigation scenario was significantly different from that in the control case (p-value much less than 0.05). A significant result indicates that those mitigation cases were effective in cooling air temperature in KCMA.

Figure 3a shows that the mean daytime temperature reductions from the cool roof scenario across KCMA are 0.08 and 0.02 °C for the normal and heat wave episodes, respectively. The magnitude of temperature reductions from our cool roof simulation is smaller than those of Cao et al. [2015] and Vahmani et al. [2016]. However, we note that air temperature depends on many factors including the land surface conditions (e.g., level of urbanization) and influence from outside the urban area (e.g., sea breeze) as well as the assumption about the cool roof albedo. For example, Vahmani et al. [2016] reported a daytime temperature reduction of 0.9 °C from the adoption of cool roofs in Southern California which is based on a higher area ratio for the industrial/commercial area (33%) with a higher cool roof albedo of 0.85 than our study area. We note that although the land classification method of our study does not exactly match that of Vahmani et al. [2016], our high development area accounts for only 5% of KCMA, which is much smaller than the industrial/commercial area (~30%) used in Vahmani et al. [2016]. Cao et al. [2015] showed that the temperature reduction from a similar cool roof scenario was larger during the heat wave episodes than during the normal episodes while our results shows a higher temperature reduction during the normal periods than the heat wave. Possible reasons for this are discussed in Section 3.3.

The cooling effects of irrigation on daytime (07:00 – 19:00 LST) temperatures are evident over all three urban types for both the normal and heat wave episodes (Figure 3). The decrease in the air temperature from urban irrigation is largely due to increased evaporation. The mean temperature reduction for the normal episodes ranges from 0.21 to 0.29 °C while the heat wave episodes also show a similar range of temperature reduction (0.20 - 0.29 °C). The urban irrigation reduced average daytime temperatures across KCMA by 0.28 and 0.26 °C for the normal and heat wave episodes, respectively (Figure 3b). The high development area had the lowest effect of the irrigation strategy on the temperature reduction.

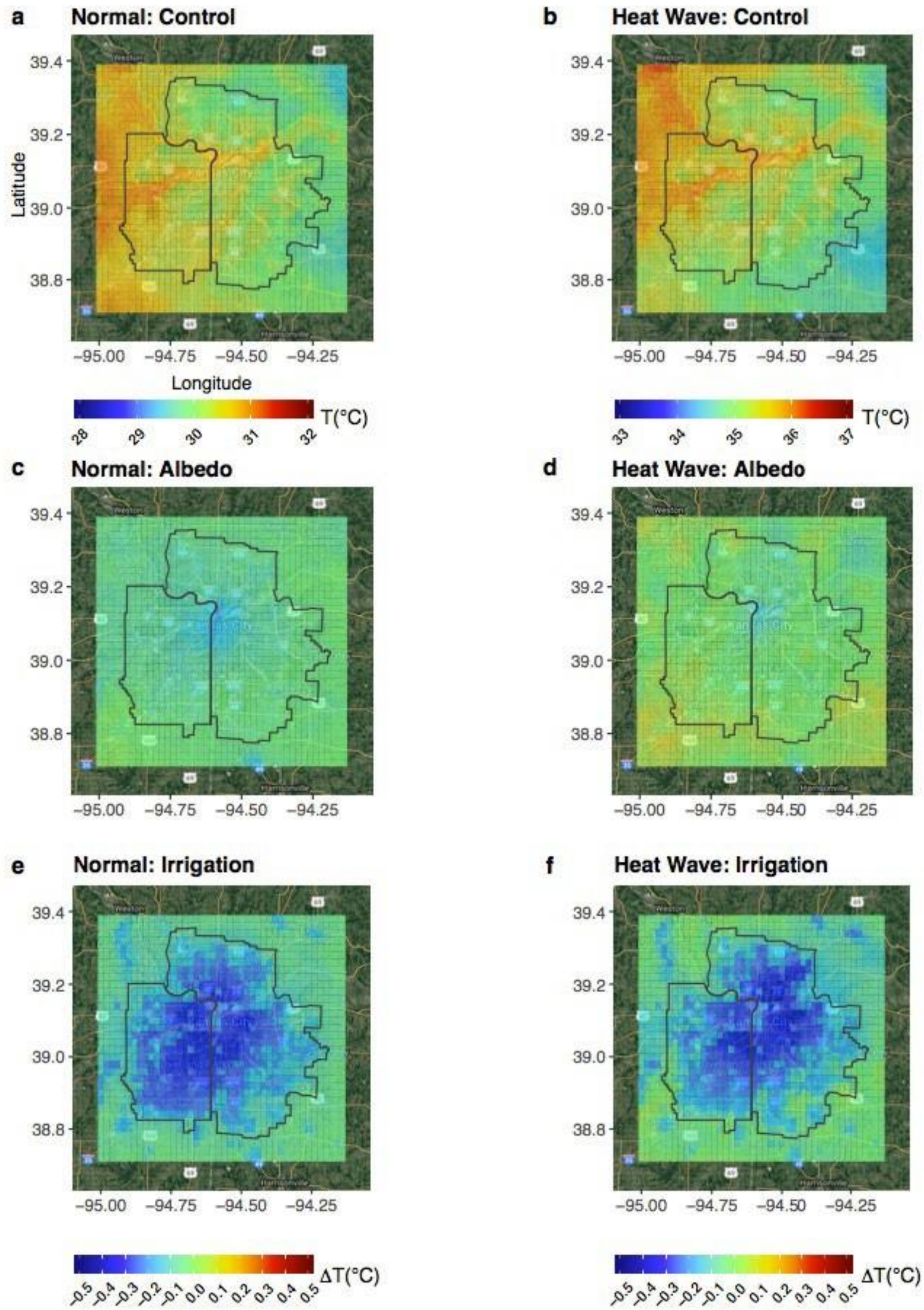


Figure 2. (a, b) Simulated average daytime (07:00 – 19:00 LST) 2-meter air temperature. (c-f) Temperature difference (°C, mitigation minus control) due to roof albedo and urban irrigation mitigation scenarios for the normal and heat wave episodes.

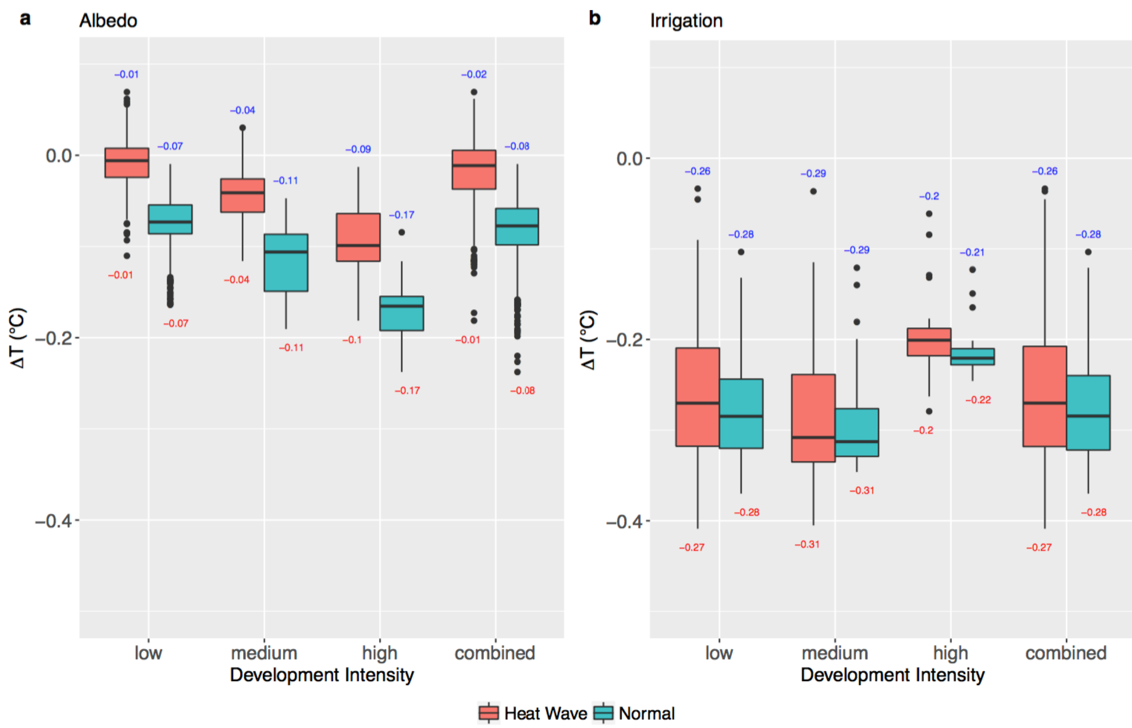


Figure 3. Boxplots of simulated daytime (07:00 – 19:00 LST) air temperature differences (ΔT, mitigation minus control) for (a) roof albedo, and (b) urban irrigation. For each scenario, the boxplot is shown for the low, medium and high development areas and the entire KCMA (i.e., "combined"). The numbers at the top (blue) and bottom (red) of the box represent mean and median values of the data, respectively.

To provide a more complete picture of the statistical distribution of the simulated temperature differences from the adoption of different mitigation strategies, we show histograms of temperature changes where the relative amount of data (i.e., number of grid cells in the modeling domain) for each development type and the range of data values from individual model grid cells. Figure 4 shows histograms for daytime temperature changes (ΔT, mitigation minus control) from all mitigation scenarios by development intensity for both the normal and heat wave episodes. For the roof albedo scenario, the high development intensity area shows the largest temperature reduction (i.e., ΔT) for both the normal and heat wave episodes. This result is expected because the high development area, on average, is associated with a larger roof area ratio within a given pixel. Also, the range of ΔT in the high development area is larger than those of the medium and low development areas, showing larger variability in temperature reductions.

In KCMA, the low development area has low roof area fractions (<10%). For both the normal and heat wave episodes, the high development density area shows the smallest temperature reduction from urban irrigation (Figure 4). This is likely because low and medium development areas have larger available irrigated (urban vegetation) areas than those of the high development intensity area when we use the same irrigation scheme across the development intensity types. This result suggests that at the regional level the mitigation benefits from urban irrigation may be maximized when focusing more on the low and medium development intensity areas for which irrigation strategies can be implemented relatively easily compared to the high development area. For some cases (e.g., medium development for the albedo scenario during the normal episodes), the distribution of ΔT is bimodal, suggesting that there is spatial variability in the effect of mitigation strategies within the same development intensity, perhaps depending on land surface conditions and local atmospheric conditions. Characterizing this spatial variability with a similar development level through future studies would help planning detailed mitigation plans. Additional detailed land cover classification could be useful in understanding the urban heat island and evaluating the mitigation strategies applied.

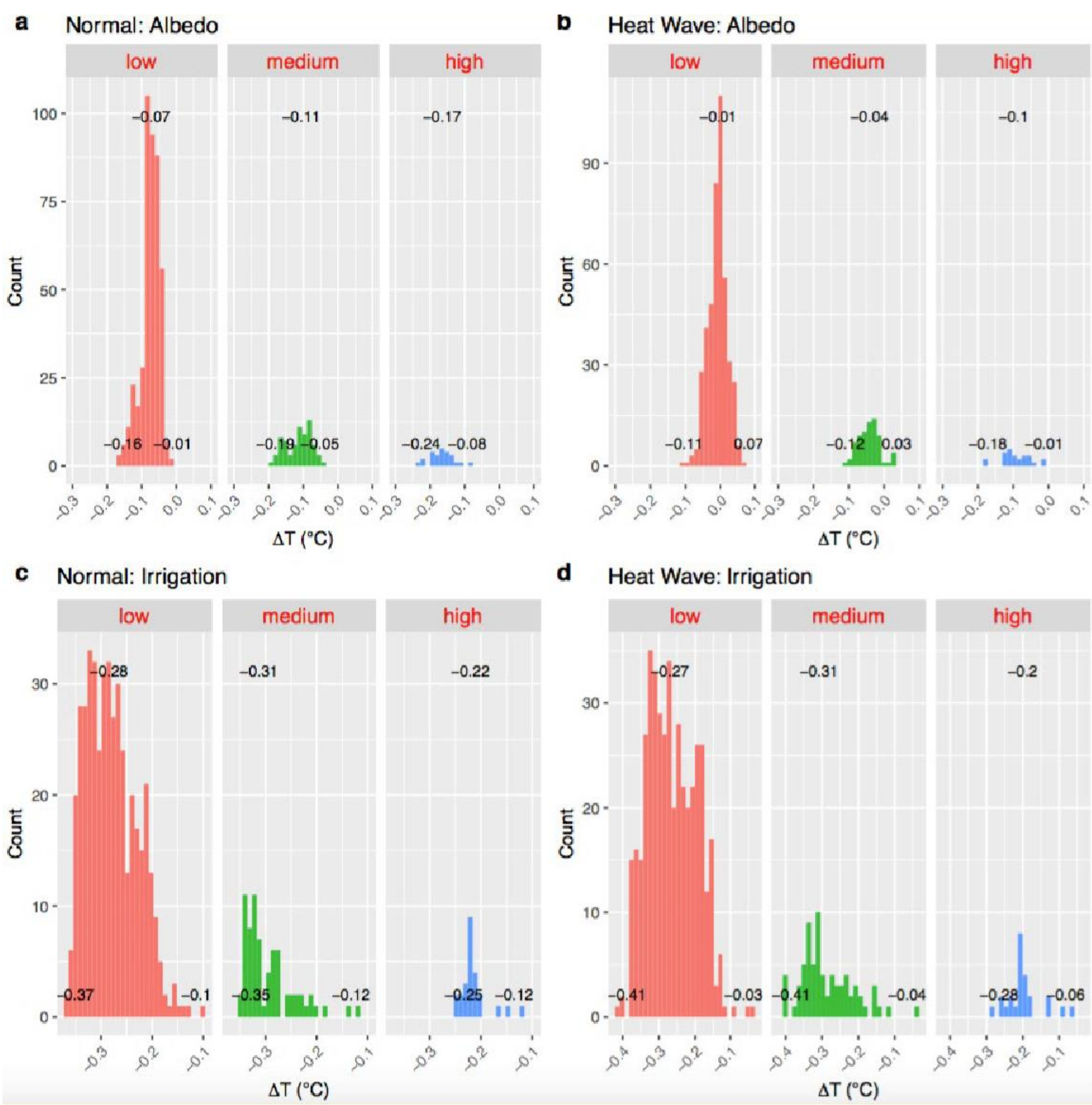


Figure 4. Histogram of daytime (07:00 – 19:00 LST) temperature differences (°C) by mitigation scenario for the normal (a and c) and heat wave (b and d) episodes. “Albedo” and “Irrigation” in the plot titles denote the cool roof albedo and urban irrigation mitigation scenarios, respectively. The numbers at the bottom of each plot represent the minimum and maximum ΔT values within the boundary of KCMA. The number at the top of each plot shows the median ΔT values.

3.2 Diurnal Cycles of Mitigation Effects

Cool roofs and urban irrigation produce different diurnal patterns of cooling in KCMA (Figure 5, Supplemental Figures S3 – S6). During normal episodes, cool roofs provide peak cooling during the middle of the night, whereas urban irrigation provides the most cooling during the daylight hours. During heat waves, we see the largest cooling impacts during early morning hours prior to sunrise. During heat waves we see increased temperatures under both the cool roof and urban irrigation scenarios during the late afternoon and early evening hours. Both the later afternoon temperature increases and the early morning temperature reductions are potentially related to changes in local meteorological patterns including a decrease in precipitation that was found in the cool roof mitigation scenario during the heat wave episodes. We discuss this precipitation effect further in Section 3.3.

Urban irrigation (irrigated at 21:00 LST) reduces temperatures reduction more during the daytime and evening than the early morning (Figure 5). This is likely due to irrigation induced evaporation peaking with large available surface energy during the daytime, which lowers the air temperature. The low temperature reduction from urban irrigation during the early morning hours, in particular for the normal case, is consistent with the result in Vahmani and Ban-Weiss [2016] where they reported warming during the nighttime relative to the daytime due to increased nocturnal upward ground heat fluxes.

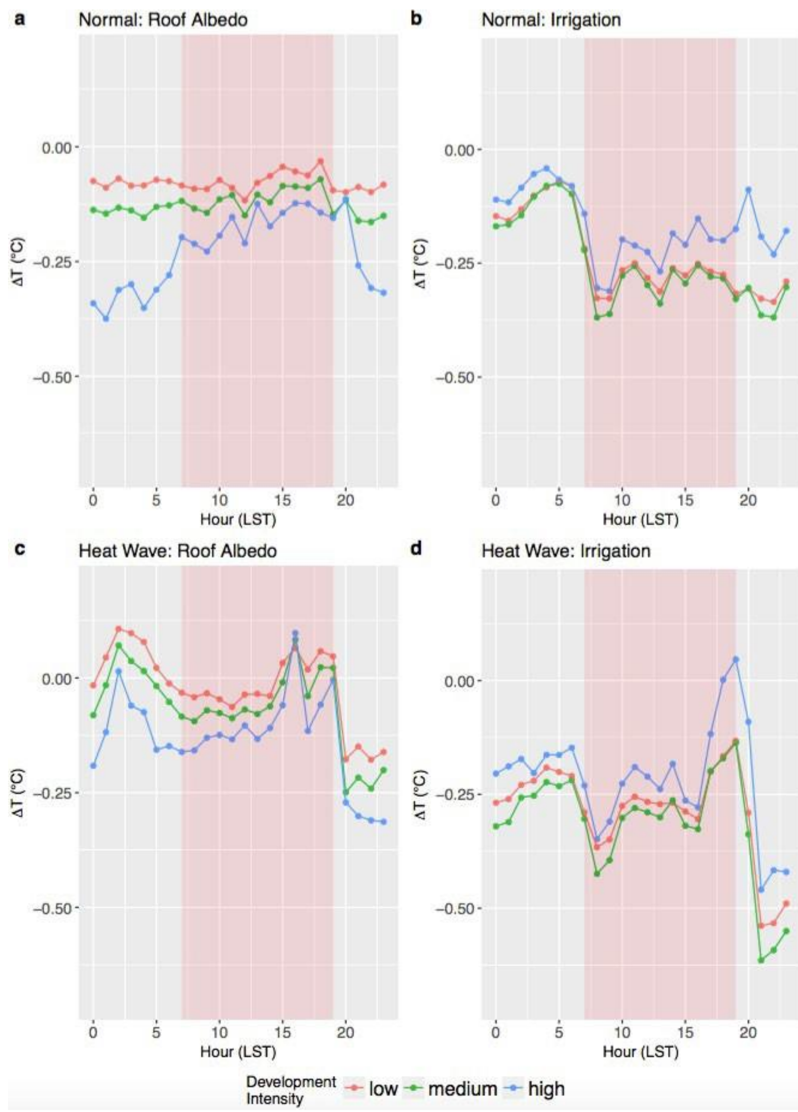
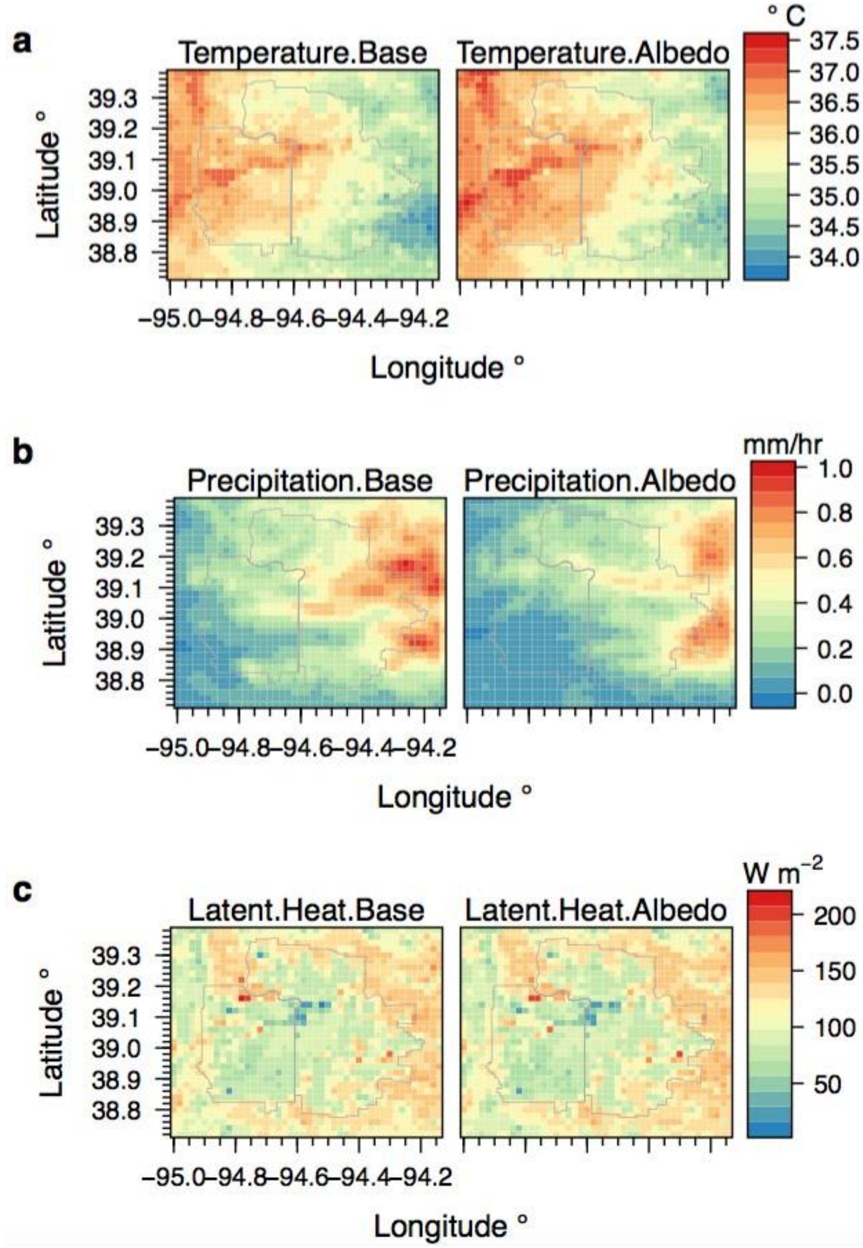


Figure 5. Diurnal cycles of differences in the air temperature (ΔT, mitigation – control) for the mitigation strategies during the normal (a and b) and heat wave (c and d) episodes. The shaded region in light red shows the hours of sunlight (07:00 – 19:00 LST).

3.3 Impact of Mitigation Strategies on Local Weather

We found that during heat waves the cool roof scenario showed higher air temperature than the control case during early evening hours (15:00 – 19:00 LST) (Figure 5c). Figure 6a shows the simulated average air temperature for the control case and the cool roof albedo scenario during 15:00 – 19:00 LST hours of the heat wave episodes. In Figure 6a, the average air temperature is higher in the cool roof albedo scenario than in the control case, which was also shown in the diurnal cycle of ΔT for the cool roof scenario during the heat wave episodes (Figure 5c). We explored a few meteorological variables related to air temperature and found that simulated precipitation is reduced in the cool roof scenario during 15:00 – 19:00 LST hours of the heat wave episodes (Figure 6b), likely causing the corresponding increase to air temperature. When the surface is moist due to the increased precipitation, latent heat flux also increases, reducing air temperature (Figure 6c). It is possible that this change in precipitation is an artifact of the WRF modeling, as preliminary analysis indicates that the control scenario has a higher frequency of late afternoon/early evening precipitation than is observed. Also, it is possible that these changing meteorological conditions also impact the early morning temperature reductions seen in the mitigation scenarios during heat waves. These changes to local meteorological patterns are interesting and further study could potentially improve our understanding of how urban form interacts with local meteorological patterns.



Figures 6. Comparison of early evening (15:00 – 19:00 LST) mean air temperature (a), non-convective precipitation (b) and latent heat (c) between the control case and the roof albedo scenario during the heat wave episodes. “base” and “albedo” denotes the control and cool roof albedo cases, respectively.

3.4. Research and Policy Implications

Using high-resolution meteorological simulations, we have shown that a policy of enhancing roof albedo by 0.4 in KCMA could reduce regional average daytime (7:00 – 19:00 LST) temperatures by 0.08 and 0.02 °C for the normal summer conditions and heat wave episodes, respectively, showing different mitigation impacts on temperature reduction depending on the land development type. We also found that during heatwaves, temperature reductions might be larger during the early morning hours, but that a few hours of increased temperature might occur during the late afternoon and early evening as a result of decreased precipitation. These particular patterns found during heatwaves deserve additional study due to uncertainty about the interaction between cool roofs and precipitation patterns.

These results suggest that regions with relatively low roof area fractions such as KCMA may benefit from reflective cool roofs only marginally although the benefit for the high development area is higher than the regional average. Recall that for KCMA, the majority of the region is low development area (82%), which has low roof area fractions (<10%), and this further reduces the impact of reflective cool roofs on temperature reduction. Compared to the reflective cool roof scenario, however, the urban irrigation scenario showed significantly larger temperature reductions, with average daytime temperatures reductions of 0.28 and 0.26 °C for the normal and heat wave episodes, respectively. These results suggest that for regions with low roof fractions urban irrigation may be a more efficient policy to be adopted to mitigate urban heat island than reflective cool roofs although reflective cool roof can be still effective in localized areas with high development density. We note, however, that these results presume all roofs are available for albedo modification and there exists ample water availability for urban irrigation.

References

Akbari, H., Konopacki, S., and Pomerantz, M. (1999), Cooling energy savings potential of reflective roofs for residential and commercial buildings in the United States. Energy 24 (5), 391−407.

Bagley, J. E., et al. (2017), Assessment of an atmospheric transport model for annual inverse estimates of California greenhouse gas emissions, J. Geophys. Res. Atmos., 122, doi:10.1002/2016JD025361.

Bretherton, C. S. and Park, S. (2009), A New Moist Turbulence Parameterization in the Community Atmosphere Model. J. Climate, 22, 3422–3448, doi: 10.1175/2008JCLI2556.1.

Chen, F. and Dudhia, J. (2001), Coupling an advanced land surface- hydrology model with the Penn state-NCAR MM5 modeling system: I. Model implementation and sensitivity, Mon. Weather Rev., 129 569–85

Chen, F., et al. (2011) The integrated WRF/urban modelling system: development, evaluation, and applications to urban environmental problems. Int J Climatol 31:273–288.

Ching, J., et al. (2009), National Urban Database and Access Portal Tool (NUDAPT), Bulletin of American Meteorological Society, 90(08), 1157-1168.

Li, D., Bou-Zeid, E. and Oppenheimer, M. (2014), The effectiveness of cool and green roofs as urban heat island mitigation strategies, Environ. Res. Lett. 9, 055002, doi:10.1088/1748-9326/9/5/055002

Dudhia, J. (1989), Numerical study of convection observed during the Winter Monsoon Experiment using a mesoscale two dimensional model, J. Atmos. Sci., 46, 3077–3107.

Georgescu, M., Morefield, P. E., Bierwagen, B. G., and Weaver, C. P. (2014),Urban adaptation can roll back warming of emerging megapolitan regions. Proc. Natl. Acad. Sci. U. S. A. 111 (8), 2909−2914.

Grell, G. A. and Freitas, S. R. (2014), A scale and aerosol aware stochastic convective parameterization for weather and air quality modeling, Atmos. Chem. Phys., 14, 5233-5250, doi:10.5194/acp-14-5233-2014.

Hassid, S. et al. (2000), The effect of the Athens heat island on air conditioning load Energy Build., 32, 131–41.

Jeong, S., et al. (2016), Estimating methane emissions in California's urban and rural regions using multi-tower observations, J. Geophys. Res. Atmos., 121, 13,031-13,049, doi:10.1002/2016JD025404.

Jeong, S., et al. (2017), Estimating methane emissions from biological and fossil-fuel sources in the San Francisco Bay Area, Geophys. Res. Lett., 44, 486–495, doi:10.1002/2016GL071794.

Kusaka H, Kondo, H, Kikegawa, Y and Kimura, F. (2001), A simple single layer urban canopy model for atmospheric models: comparison with multi-layer and slab models Bound.-Layer Meteorol., 101 329–58.

Kusaka, H. and Kimura, F. (2004), Coupling a single-layer urban canopy model with a simple atmospheric model: impact on urban heat island simulation for an idealized case J. Meteorol. Soc. Japan 82 67–80.

Levinson, R., Akbari, H., Konopacki, S., and Bretz, S. (2005), Inclusion of cool roofs in nonresidential Title 24 prescriptive requirements. Energy Policy 33, 151−170.

Levinson, R., and Akbari, H. (2010), Potential benefits of cool roofs on commercial buildings: conserving energy, saving money, and reducing emission of greenhouse gases and air pollutants. Energy Efficiency, 3 (1), 53−109.

Li, D and Bou-Zeid, E. (2013), Synergistic interactions between urban heat islands and heat waves: the impact in cities is larger than the sum of its parts J. Appl. Meteorol. Climatol. 52 2051–64.

Li, D., and E. Bou-Zeid (2014), Quality and sensitivity of high-resolution numerical simulation of urban heat islands, Environ. Res. Lett., 9, 055001.

Luber, G. and McGeehin, M. (2008), Climate change and extreme heat events. Am. J. Prev. Med., 35(5), 429−435.

Mann, H. B. and Whitney, D.R. (1947), On a test of whether one of two random variables is stochastically larger than the other, Annals of Mathematical Statistics, 18, 50-60.

Mesinger, F., et al. (2006), North American regional reanalysis, Bull. Am. Meteorol. Soc., 87, 343–360, doi:10.1175/BAMS-87-3-343.

Mid-America Regional Council (2017), GIS Datasets, http://www.marc.org/Data-Economy/Maps-and-GIS/GIS-Data/GIS-Datasets (accessed in January 2017).

Miller, N. L., Hayhoe, K., Jin, J., and Auffhammer, M. (2008), Climate, extreme heat, and electricity demand in California. Journal of Applied Meteorology and Climatology, 47, 1834−1844.

Millstein, D. and Menon, S. (2011), Regional climate consequences of large-scale cool roof and photovoltaic array deployment Environ. Res. Lett. 6, 034001.

Mlawer, E. J., Taubman, S. J., Brown, P. D., Iacono, M. J., and Clough, S. A. (1997), Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave, J. Geophys. Res., 102, 16,663–16,682, doi:10.1029/97JD00237.

Morrison, H., Thompson, G. and Tatarskii, V. (2009), Impact of cloud microphysics on the development of trailing stratiform precipitation in a simulated squall line: Comparison of oneand two-moment schemes. Mon. Wea. Rev., 137, 991–1007, doi:10.1175/2008MWR2556.1.

National Centers for Environmental Information (2017), The Integrated Surface Database, https://www.ncdc.noaa.gov/isd (accessed in January 2017).

National Map (2017), National Elevation Data, https://nationalmap.gov/elevation.html (accessed in January 2017).

Nazaroff, W. W. (2013), Exploring the consequences of climate change for indoor air quality Environ. Res. Lett. 8 015022, doi:10.1088/1748-9326/8/1/015022.

Parker, D. S. and Barkaszi, S. F. (1997), Roof solar reflectance and cooling energy use: field research results from Florida. Energy Build. 25, 105−115.

Salamanca F, Georgescu, M., Mahalov, A., Moustaoui, M., Wang, M. and Svoma, B. M. (2013), Assessing summertime urban air conditioning consumption in a semiarid environment Environ. Res. Lett. 8 034022

Skamarock, W. C., et al. (2008), A description of the advanced research WRF Version 3, NCAR Tech. Note NCAR/TN-475 + STR, doi:10.5065/D68S4MVH.

Vahmani, P., and Hogue, T. S. (2015), Urban irrigation effects on WRF-UCM summertime forecast skill over the Los Angeles metropolitan area, J. Geophys. Res. Atmos., 120, 9869–9881, doi:10.1002/2015JD023239.

Vahmani, P., and Ban-Weiss, G. (2016), Climatic consequences of adopting drought-tolerant vegetation over Los Angeles as a response to California drought, Geophys. Res. Lett., 43, 8240–8249, doi:10.1002/2016GL069658.

Vahmani, P., Sun, F., Hall, A. and Ban-Weiss, G. (2016), Investigating the climate impacts of urbanization and the potential for cool roofs to counter future climate change in Southern California, Environ. Res. Lett. 11 (124027), doi:10.1088/1748-9326/11/12/124027.

Wilks, D. S. (2011), Statistical methods in the atmospheric sciences. Oxford: Academic Press, pp. 704.

Yang, J., et al. (2013), Impact of heat wave in 2005 on mortality in Guangzhou, China. Biomed. Environ. Sci. 26, 647−654.

Supplemental

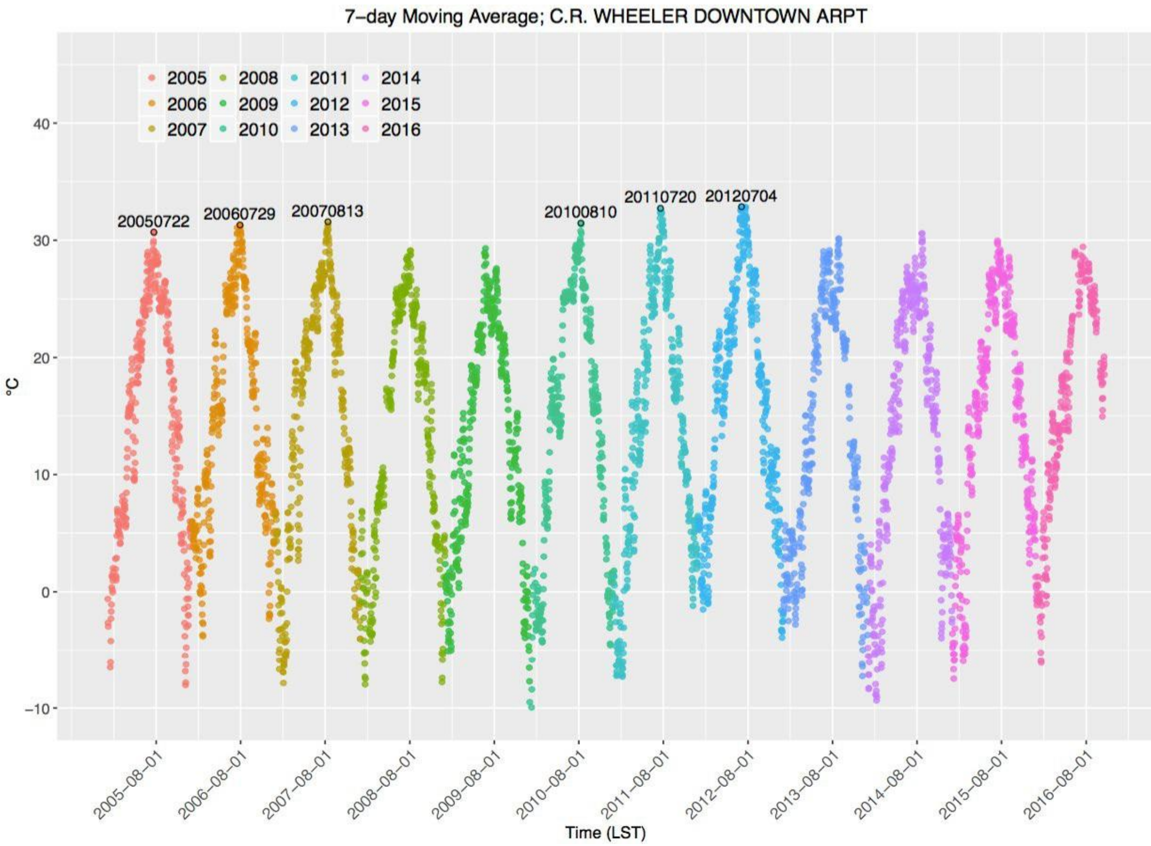


Figure S1. Seven-day moving average for daily temperature (plotted at the center date) at C. R. Wheeler Airport in Kansas City, MO. The black open circles represent the center date of each identified heat wave spanning seven days.

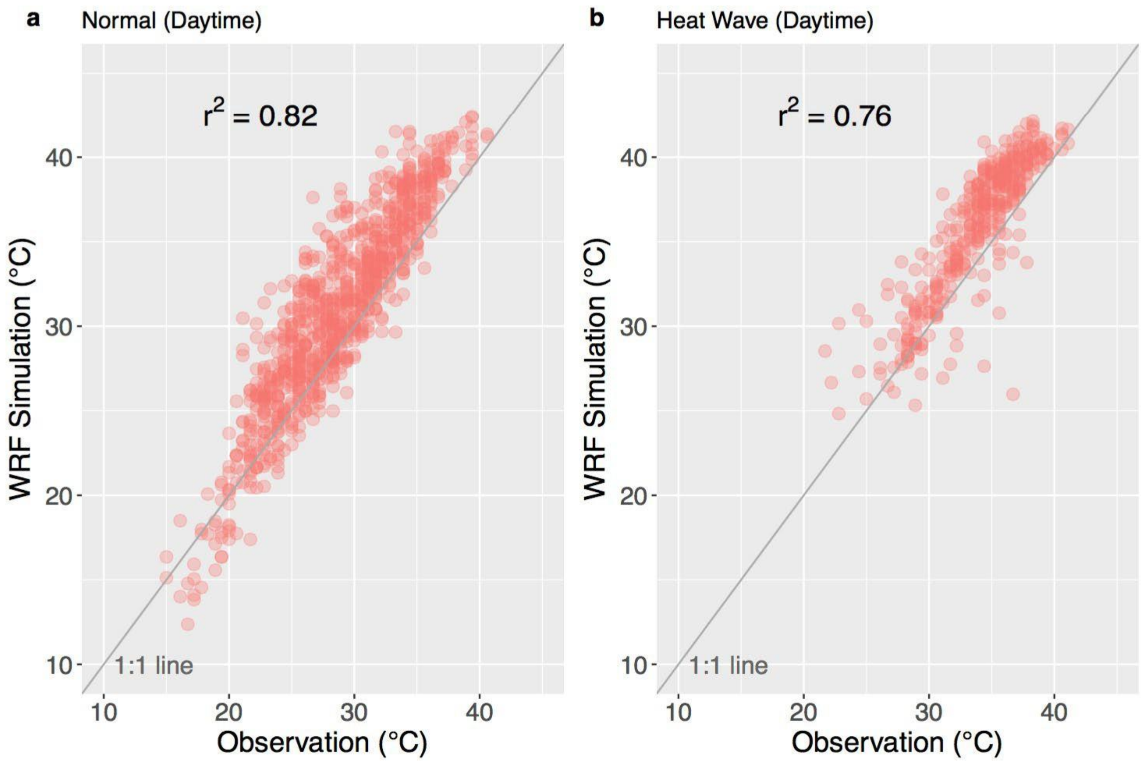


Figure S2. Comparison of temperature between WRF simulations and observations at C. R. Wheeler Airport in Kansas City, MO. The data points shown in the plots represent all hourly data during normal (10 weeks) and heat wave (6 weeks) episodes.

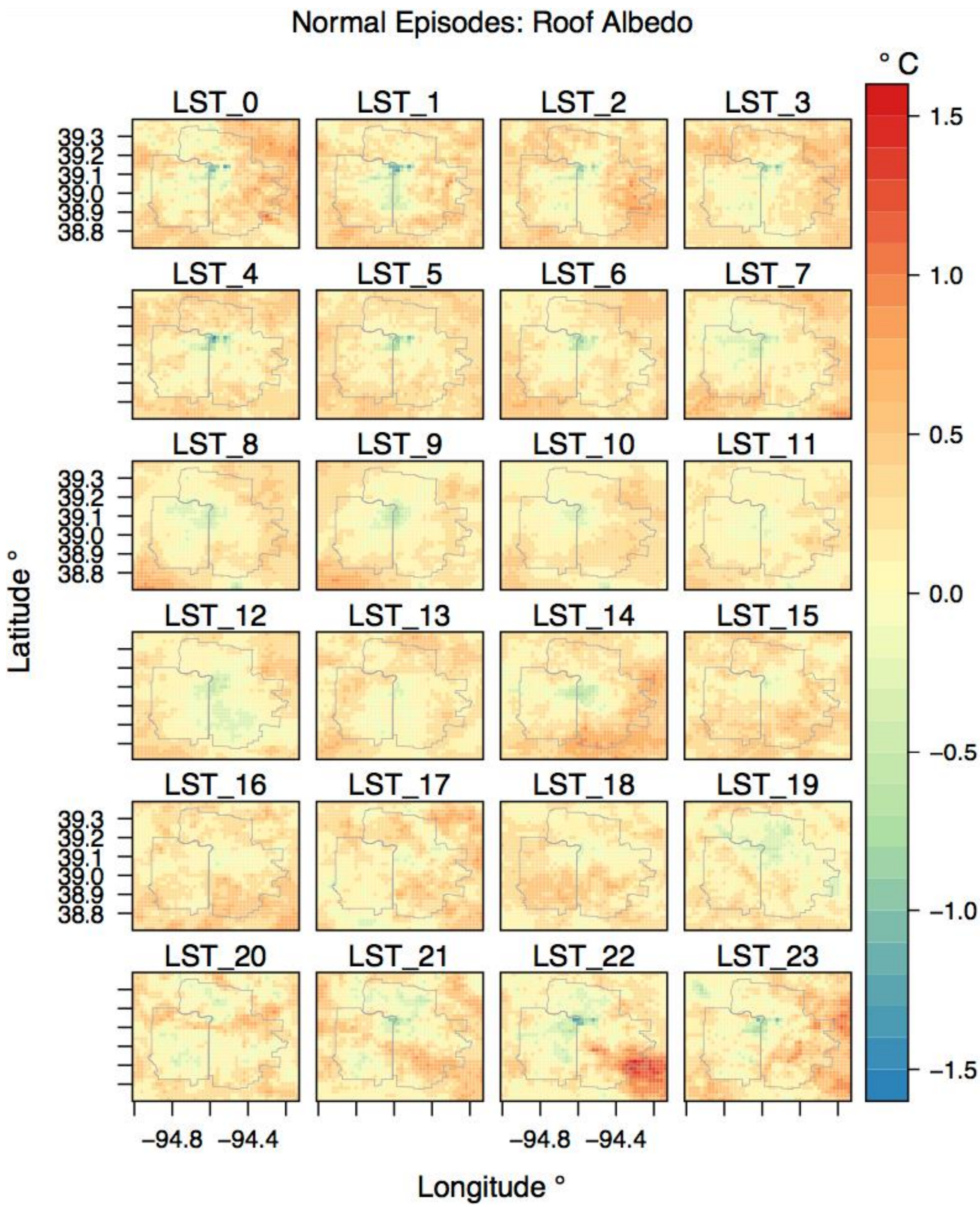


Figure S3. Diurnal cycles of change in temperature (mitigation – control, °C) for the normal episode based on the cool roof mitigation scenario.

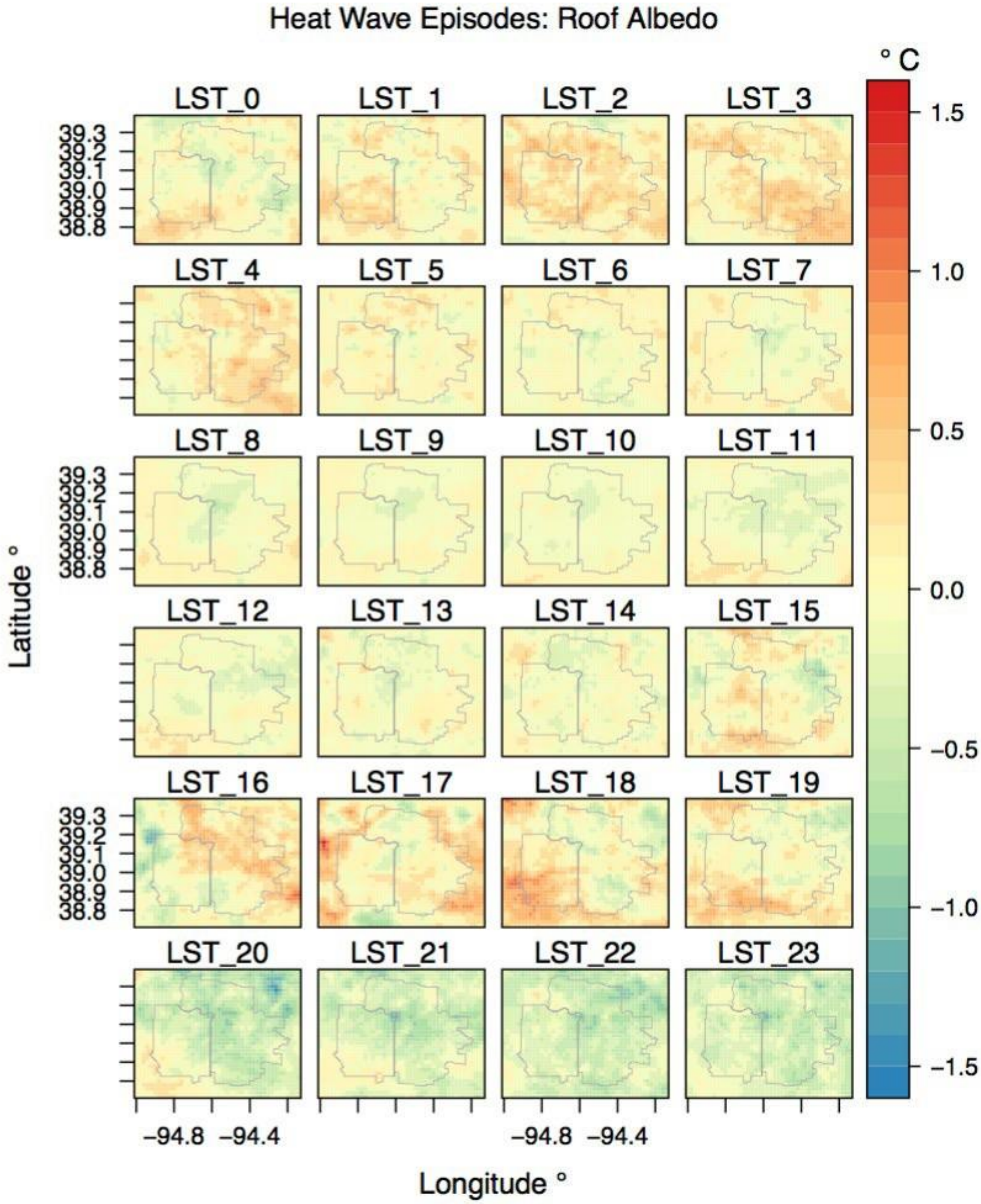


Figure S4. Diurnal cycles of change in temperature (mitigation – control, °C) for the heat wave periods based on the cool roof mitigation scenario.

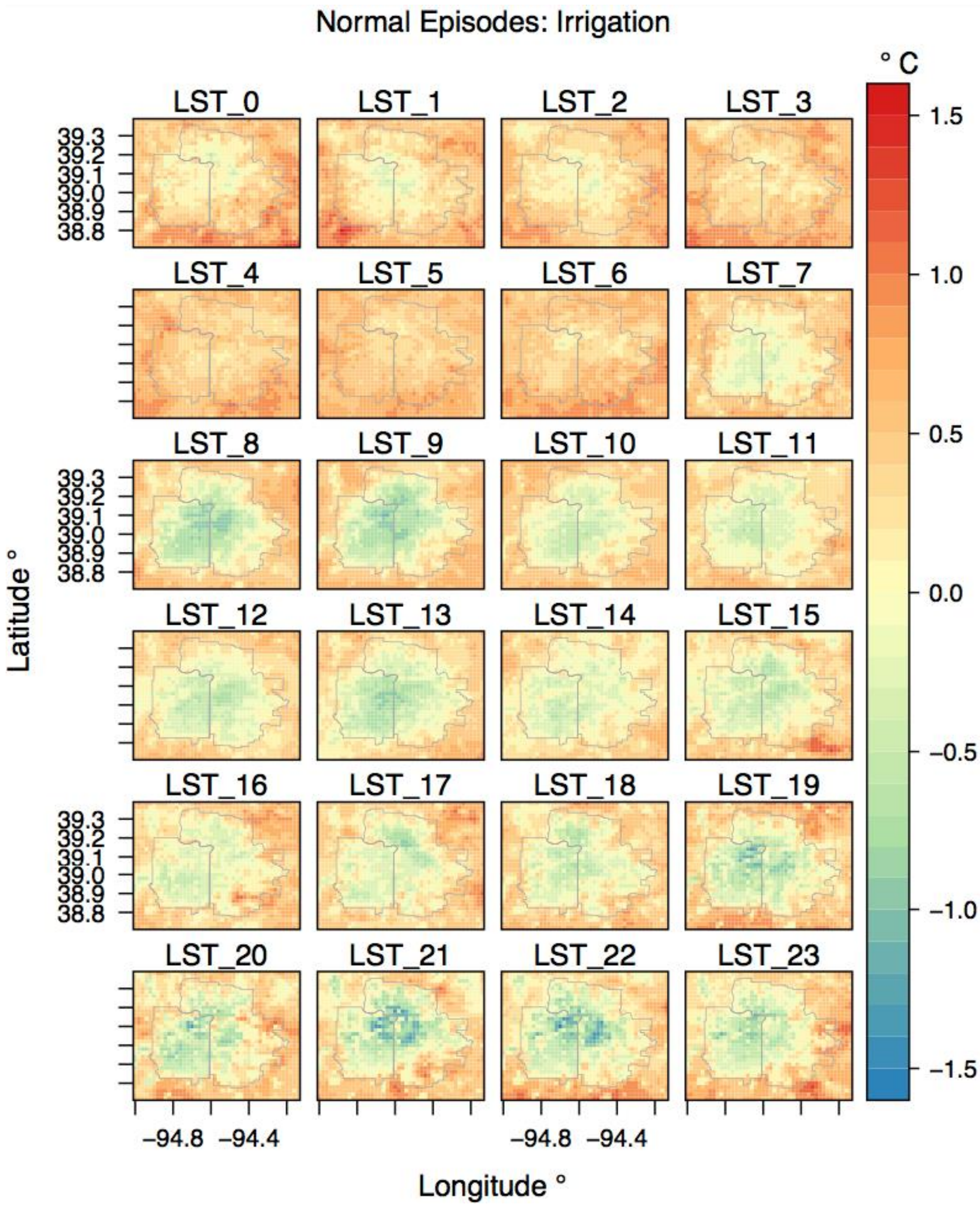


Figure S5. Diurnal cycles of change in temperature (mitigation – control, °C) for the normal episode based on the urban irrigation mitigation scenario.

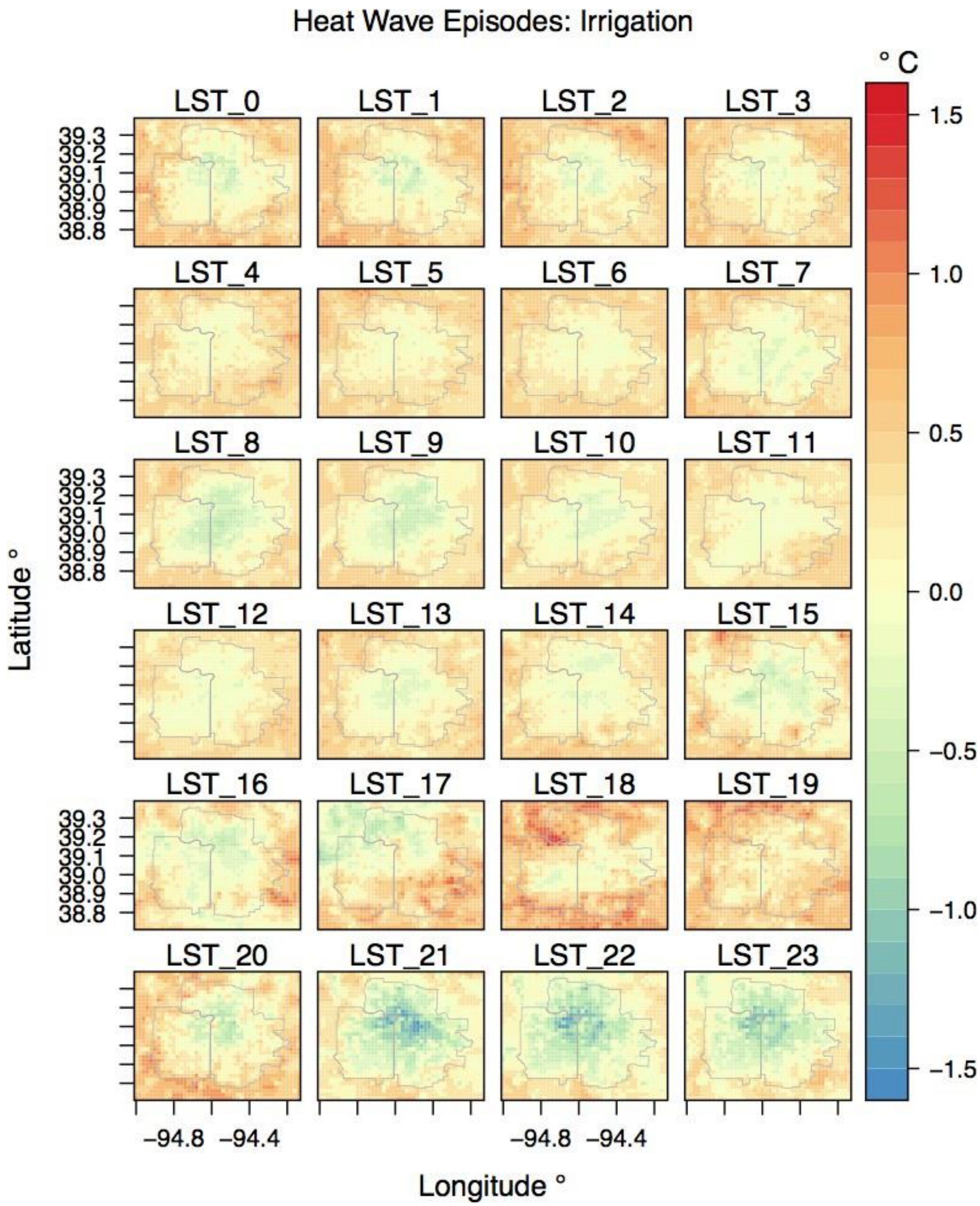


Figure S6. Diurnal cycles of change in temperature (mitigation – control, °C) for the heat wave periods based on the urban irrigation mitigation scenario.

Appendix C

Task 4: Costs and Benefits of Cool Roofs and Shade Trees in Kansas City region

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1 Introduction

This report is part of a larger project to assess the benefits of urban heat island (UHI) countermeasures in the MARC region. Cool (high-albedo) roofs and increased vegetation were selected by the team as suitable countermeasures for the region based on local interest and feasibility of implementation. The current study complements the other project reports that describe the team's activities to assess the city-wide air cooling obtainable from these countermeasures and the "indirect" (air cooling) building energy and emission savings that could result.

This report will evaluate the "direct" building energy and emission savings that result from cooling the surface of the building with tree shade or high-albedo roofing. It calculates the regional annual site energy, energy cost, and emission saving benefits of deploying cool roofs and planting shade trees, and compares energy cost savings to cool roof cost premiums and shade tree first costs. If the savings outweigh the costs, our project partner, Mid-America Regional Council (MARC) will be positioned to use this data to develop appropriate regional implementation policies or programs.

1.1 Location

The nine-county MARC region serves as the study area. The region centers on the Kansas City metropolitan area with counties in the states of Kansas and Missouri (Figure 1). The region contains a mix of urban, rural and agricultural land-uses.

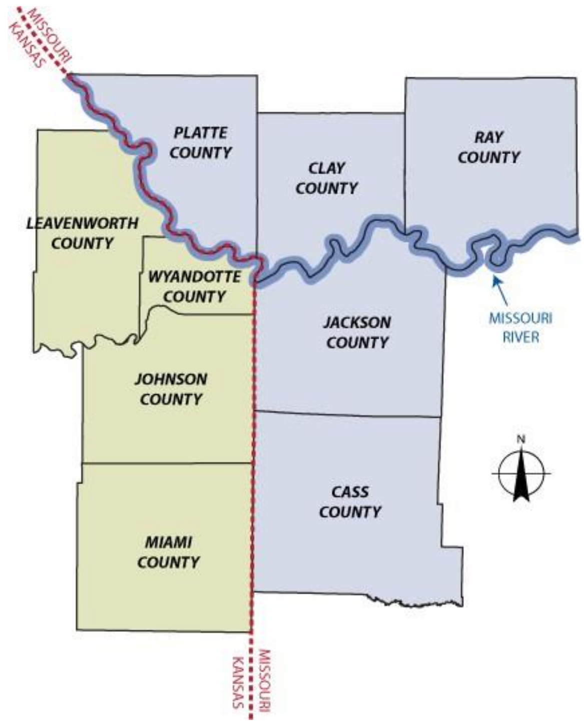

Figure 1. A map of Mid-America Regional Council's nine member counties in Kansas and Missouri.

2 Methodology

We set out to calculate the regional building site energy and emission benefits of cool roofs and shade trees in the study area. We also assessed the regional cost premiums for cool roof products and first costs for shade trees, and compared these costs to the energy cost savings from deploying these UHI countermeasures. We utilized the results of studies that were commissioned by our partner MARC in 2015, which report the direct building site energy savings from cool roofs and shade trees for several common building categories in the study area (Leidos 2015a, b, c). We matched the building categories to MARC land use classifications. We could then apply the building site energy savings intensities to estimates of roof area (cool roofs) or building perimeter (shade trees) for each of the land-use classifications to extrapolate the findings to the region. We also updated emission factors and energy prices to evaluate the regional emission and energy cost savings benefits. We collected data to evaluate cool-cost premiums and shade-tree first costs. The benefit and cost data were combined to provide simple payback times for cool roofs and shade trees.

2.1 Regional building footprint area, building perimeter lengths and building counts

We obtained from MARC values for building footprint area, building perimeter length, and building count by land use classification (Table 1). MARC developed an ArcGIS geospatial shapefile containing the building information for the MARC region by collecting parcel data from each county in 2016. Each county maintains its own parcel land use data, and the classifications do not always align; therefore, MARC converted each county's land use classifications to a regional set of common land use classifications. MARC next transferred the land use classification for each parcel to the buildings within the parcel.

Table 1. Building footprint area, perimeter length, and count by land-use classification in the study region reported to three significant figures.

Land-use classification	Regional building footprint area [million ft²]	Regional building perimeter length [million ft]	Regional building count [thousands]
Commercial	60.4	2.56	7.89
Condo	1.33	0.085	0.299
Industrial /Business Park	101	2.71	7.18
Mixed Use	0.147	0.014	0.076
Multi-Family	41.9	3.48	16.4
Office	13.4	0.612	1.74
Public/Semipublic	57.3	0.393	6.35
Single Family	420	2.34	266
Single Family Low Density	56.2	0.447	29.6

2.2 Changes to building energy consumption, emissions, and costs

1.1.1 Building energy consumption

In 2015, MARC commissioned Leidos, a consulting company, to conduct a building energy consumption study analyzing the direct building site energy effects of cool roofs, nearby cool ground cover, and nearby tree shading measures for commercial and residential buildings. They used a whole building energy modeling tool to evaluate the effect of these UHI countermeasure strategies for several common commercial and residential building categories based on models developed by the U.S. Department of Energy (DOE) (Table 2). These building categories were adapted to the Kansas City region to model changes to building energy consumption (Leidos 2015a).

Table 2. The Leidos building categories, and corresponding Leidos-defined building groups, referenced in this study.

Leidos building category	Leidos building group
Large Office	Commercial

Medium Office	Commercial
Mid Rise Apartment	Commercial
Stand-Alone Retail	Commercial
Multi Family	Residential
Single Family	Residential

Leidos modeled several cool roof and shade tree strategies that varied roof albedo (fraction of sunlight reflected; also known as solar reflectance) or tree canopy cover. We selected within each strategy the scenario we found to be most realistic from previous studies and professional experience. For residential cool roofs, we picked scenario RR-2 which modeled energy savings upon raising the albedo of an asphalt shingle roof to 0.30 from 0.14 (increase 0.16). For commercial cool roofs, we selected scenario CR-2 which raised the albedo of a smooth bitumen roof to 0.55 from 0.06 (increase 0.49) (Leidos 2015b). For shade trees, we chose scenarios RS-1 (residential) and CS-1 (commercial) with 25% tree shade cover along the east, west, and south facades (Leidos 2015c).

The Leidos study evaluated several building vintages for the commercial and residential building categories, and two heating systems for residential buildings. Therefore, we needed to select the prototypes best aligned with the regional distribution of building vintages and heating types. To understand the regional composition of building vintages and heating systems, we referenced the most recent versions of the Commercial Building Energy Consumption Survey (CBECS) (year 2012) and Residential Energy Consumption Survey (RECS) (year 2015). We focused on the Midwest - West North Central census division which includes Kansas and Missouri. CBECS and RECS specify year or year-range of construction and primary heating equipment (EIA 2012; EIA 2015).

The Leidos study modeled three vintages of commercial buildings: pre-1980, post-1980, and new construction. We classified commercial buildings constructed before 1979 as pre-1980, those constructed 1980 – 2007 as post-1980, and those constructed 2008 – 2012 as new construction (Table 3). The Leidos study also modeled four vintages of residential buildings: pre-1980, post-1980, IECC 2006, and IECC 2012.[1] We classified residential buildings constructed before 1979 as pre-1980, those constructed 1980 – 1999 as post-1980, those constructed 2000 – 2009 as IECC 2006, and those constructed 2010 – 2015 as IECC 2012 (Table 3).

The Leidos study included two types of residential heating systems: furnaces and heat pumps. We evaluated the RECS microdata again to investigate the distribution of heating systems in the regional building stock. We found that heat pumps are uncommon and found only in 5% of homes

[1] The International Energy Conservation Code (IECC) is a building energy code that is commonly adopted by state and local governments to improve building energy efficiency. Each version improves upon the last with additional and more strict measures intended to further reduce building energy consumptions (IECC 2018).

while furnace heating systems were found in more than 81% of homes (EIA 2015). Therefore, we decided to reference the findings from the residential prototypes with furnaces.

The annual electricity and natural gas (hereafter, simply "gas") site energy savings intensities (savings per unit roof area, or per tree) from the cool roof and shade tree scenarios are listed in Table 4. The savings are presented for prototypes of each vintage of medium office building and single-family home. The Leidos study did not report annual peak power demand savings nor hourly electrical energy savings so we were unable to investigate the benefits from reductions to energy consumption during peak times on the electrical grid.

Table 3. The distribution and ranges of year of construction matched to Leidos study building prototypes. Fractions may not sum to 100% because individual values are rounded.

Non-residential		
Leidos study building vintage group	**Year of construction**	**Distribution of buildings in census division [%]**
Pre-1980	up to 1979	54
Post-1980	1980-2007	40
New construction	2008-2012	5

Residential		
Leidos study building vintage group	**Year of construction**	**Distribution of buildings in census division [%]**
Pre-1980	up to 1979	58
Post-1980	1980-1999	25
IECC 2006	2000-2009	13
IECC 2012	2010-2015	3

Table 4. Annual electricity and gas site energy savings intensities resulting from installation of cool roofs and shade trees for the prototypes simulated by Leidos (2015 b,c) for each vintage of medium office building and single-family home.

	Cool roof savings per unit roof area		**Shade tree savings per tree**	
Leidos building category & vintage prototype	**Electricity savings intensity [kWh/1000 ft²]**	**Gas savings intensity [therm/ 1000 ft²]**	**Electricity savings intensity [kWh/tree]**	**Gas savings intensity [therm/ tree]**
Medium Office				
Pre-1980	266	2.13	548	14.5
Post-1980	190	0.657	372	5.29
New construction	97.0	(3.98)	272	3.08

Single Family				
Pre-1980	136	(6.03)	222	(9.03)
Post-1980	73.9	(3.56)	159	(6.33)
IECC 2006	33.3	(2.27)	118	(5.37)
IECC 2012	23.9	(1.58)	116	(3.70)

1.1.1.1 Regional building energy consumption

To aggregate the building energy savings to the region, we matched land-use classifications from MARC to the Leidos-modeled building categories (Table 3 and Table 5) Some land-use classifications did not directly match building categories so we used our professional judgement to complete the alignment. For example, the MARC land-use classifications include residential and non-residential (i.e., industrial, commercial) building uses (Table 5). However, the Leidos study was narrower in its scope and only included commercial and residential building categories. Therefore, we did not have a direct match for some of the land-use classifications, and used our judgement to complete the alignment, like mapping the “industrial/business park” land-use classification to “medium office” building category (Table 5).

The Leidos results were reported per unit roof area while MARC provided building footprint area per building category. Therefore, we needed to convert building footprint area to roof area. We assumed that (a) all residential buildings and those commercial buildings with asphalt shingles and metal roofing products are steep, with a typical slope of 5:12 and a roof area to footprint area ratio of $13/12 \approx 1.08$; and (b) other roofs are essentially horizontal, with roof area equal to footprint area. To know which portion of our commercial building stock was steep-slope, we used the 2012 CBECS microdata to find the distribution of major roofing materials on buildings in the West North Central census division (EIA 2012) (Table 6). We found that 69% of the commercial buildings had either asphalt shingle or metal roofs, so we applied our steep slope roof area ratio to this fraction of the commercial building footprint area. We applied these assumptions to estimate the regional roof surface areas shown in Table 7.

Next, we multiplied the fraction of the distribution for each building prototype by the building roof area. This gave us the regional roof area by building category and vintage prototype. Lastly, we multiplied the building prototype electricity savings intensity and gas savings intensity by the corresponding regional roof area for the cool roof results.

Leidos (2015c) reported shade-tree savings per unit tree; therefore, we needed to calculate the number of trees to complete our analysis for the 25% shade cover scenario. Leidos (2015a) appears to have computed the number of shade trees per building by dividing the length of the building's perimeter ("shade length") by the width of a single tree canopy (assumed to be 15'), then multiplying this result by the building's "shading fraction" (0%, 25%, 50%, or 75%). Therefore, we used the total building perimeter length for each building prototype to calculate the number of trees needed for the region. We divided the perimeter length total for each prototype by the width of a single tree canopy (assumed to be 15') to obtain the tree count for each prototype. The tree count by building category is listed in Table 7. We could then multiply the Leidos report results by the regional tree count for each building prototype.

Table 5. Mapping of MARC land use classifications to building uses (residential v. non-residential) and the Leidos (2015a) study building categories.

MARC land use classification	Building uses	Leidos building category
Commercial	Non-residential	50% Stand-Alone Retail & 50% Medium Office
Condo	Non-residential	Mid-rise Apartment
Industrial /Business Park	Non-residential	Medium Office
Mixed Use	Non-residential	Medium Office
Multi-Family	Residential	Multi Family
Office	Non-residential	Large Office
Public/Semipublic (e.g. churches)	Non-residential	Medium Office
Single Family	Residential	Single Family
Single Family Low Density	Residential	Single Family

Table 6. The distribution of major roofing material types in the Midwest - West North Central census division (EIA 2012 and 2015).

Commercial	
Major roofing material type	**Fraction of buildings with this type of roofing material [%]**
Shingles (composition or asphalt)	26
Metal surfacing	43
Synthetic or rubber	21
Built-up	8.1

Residential	
Major roofing material type	**Fraction of buildings with this type of roofing material [%]**
Shingles (composition or asphalt)	89
Metal surfacing	6.8
Wood shingles or shake	4.1

Table 7. The table lists the values and fractional distributions of the regional building footprint area, shade tree count, and building count by building category. It also lists the estimated roof area and total building perimeter length for each of the building categories.

Leidos building category	Total footprint area [million ft²]	Fraction of regional footprint area [%]	Estimated roof area [million ft²]	Total perimeter length [million ft]	Shade tree count [k]	Fraction of regional shade-tree count [%]	Building count [k]	Fraction of regional building count [%]
Medium Office	189	25	195	6.34	106	10	17.5	5.2
Mid-rise Apartment	1.33	0.18	1.38	1.28	21.3	2.1	3.94	0.09
Large Office	13.4	1.8	13.9	0.085	1.42	0.14	0.299	0.52
Stand-Alone Retail	30.2	4.0	31.3	0.612	10.2	1.0	1.74	1.2
Multi Family	41.9	5.6	45.2	3.48	57.9	5.7	16.4	4.9
Single Family	476	63	515	49.2	821	81	295	88

1.1.2 Building energy costs

Once we calculated the changes to building energy consumption, we multiplied the savings or penalties by current electricity and gas prices for residential and commercial sector customers in the Kansas City area. We used year-2016 average electricity and gas prices by sector for Missouri and Kansas reported by the U.S. Energy Information Administration (SEEAT 2018) (Table 8). We averaged the two state rates as inputs for the energy cost benefit calculations.

Table 8. The year-2016 average electricity and gas rates by sector for Missouri and Kansas, and the two-state average (SEEAT 2018).

State	2016 price of electricity sold to residential customers [$/kWh]	2016 price of electricity sold to commercial customers [$/kWh]	2016 price of gas sold to commercial customers [$/therm]	2016 price of gas sold to residential customers [$/therm]
Kansas	0.131	0.131	0.810	0.950
Missouri	0.112	0.093	0.770	1.07
Average	0.121	0.112	0.790	1.01

1.1.3 Air emissions

In addition to building energy consumption and costs, we calculated power-plant and local emissions of air pollutants from on-site consumption of electricity or gas. We referenced the Carbon Management Information Center Source Energy and Emissions Analysis Tool, Version

7.3 (SEEAT) for recent (year 2016) Missouri and Kansas emission factors (Table 9). We averaged the two state rates as inputs for the emission calculations.

Table 9. Electricity and gas emission factors for Missouri and Kansas, and the two-state average (SEEAT 2018).

	Electricity				Gas			
State	**CO_2 [kg/kWh]**	**NO_x [g/kWh]**	**SO_2 [g/kWh]**	**CO_2e [kg/kWh]**	**CO_2 [kg/therm]**	**NO_x [g/therm]**	**SO_2 [g/therm]**	**CO_2e [kg/therm]**
Kansas	0.585	0.199	0.468	0.615	5.91	1.32	7.81	6.77
Missouri	0.825	1.27	0.844	0.866	5.91	1.32	7.81	6.77
Average	0.705	0.656	0.735	0.741	5.91	1.32	7.81	6.77

2.3 Cool roof cost premiums and service lives

To assess cost premiums for cool roof products, we evaluated the distribution of roofing materials currently installed on buildings in the region, and referenced existing resources to find price information for cool roof materials.

To assess the distribution of major roofing materials, we used the 2012 CBECS microdata for commercial buildings, and 2015 RECS microdata for residential buildings for the Midwest - West North Central census division to calculate the fraction of roofing material type for the region (Table 6) (EIA 2012; EIA 2015). For simplicity, we omitted from the analysis roofing materials present on less than 2.5% of the buildings.

We note in Table 10 the estimated regional roof area per roofing material type. We calculated these values by multiplying the fraction of each roofing material type for the commercial and residential building categories by the corresponding roof area. We summed the roofing material type roof areas for the commercial and residential building categories to obtain a combined regional total.

The next step was to calculate cost premiums (if any) for cool versions of each of the major roofing material types found in the region. We began with cost premiums for metal products, wood shingles or shakes, synthetic products, and built-up roofing products reported by Levinson et al. (2002) (Table 10).

However, since the market for cool asphalt shingles has evolved and matured in the 16 years since that study was published, we sought more updated cost premiums from current resources. We looked up cool asphalt shingle products and comparable conventional shingle products using http://Lowes.com for a Kansas City store location (Lowes 2018). Cool asphalt shingle products reflect more sunlight than conventional shingle products, thereby reducing transfer of heat into the building. Cool asphalt shingles can either be (1) light-colored with high reflection in the visible and invisible parts of the solar spectrum, or (2) cool-colored with the look of darker colors but with pigments that reflect sunlight in the invisible near-infrared spectrum. Therefore, we sought cool-colored and light-colored ENERGY STAR-labeled asphalt shingle products from two different manufacturers. Once we found the cool asphalt shingle products, we searched within that brand for a conventional product of comparable color, quality, and durability (Figure 2). To ensure similar quality and durability, all the products selected were architectural laminated shingles. These shingles differ from three-tab shingles because they are thicker with a distinctive three-dimensional, textured appearance. Therefore, they weigh more, cost more, and have longer product warranties. Once we found the comparable cool and conventional products, we assessed the cost premium (cool product cost – conventional product cost) (Table 11).

Table 10. Cool roof cost premiums for the most common roofing material types in the Kansas City region, adapted from Tables 4 and 6 of Levinson et al. (2002). The estimated regional roof area for each of the roofing material types is noted.

Major roofing material type	LOW cool roof cost premium [$/ft²]	HIGH cool roof cost premium [$/ft²]	Estimated regional roof area [million ft²]
Built-up	0.10	0.20	43.3
Metal surfacing	0.00	0.05	107
Shingles (composition or asphalt)	0.00	0.13	544
Synthetic or rubber	0.00*	0.05*	83.9
Wood shingles or shake	0.00	0.00	230

* We populated these values with cost premium estimates for single-ply thermoplastic from Levinson et al. (2002) since this is a broad category.

Table 11. The cost breakdown for cool asphalt shingles and comparable conventional products (Lowes 2018).

Laminated architectural asphalt shingle material cost		Cool roof cost premium
Cool-colored asphalt shingle (manufacturer A, color Slate, aged solar reflectance 0.26) [$/ft²]	Comparable conventional asphalt shingle (manufacturer A, color Slate) [$/ft²]	Cool asphalt shingle cost premium [$/ft²]
0.71	0.59	0.13
Light-colored asphalt shingle (manufacturer B, color Shasta White, aged solar reflectance 0.28) [$/ft²]	Comparable conventional asphalt shingle (manufacturer B, color Sierra Gray) [$/ft²]	Cool asphalt shingle cost premium [$/ft²]
1.27	1.27	0.00

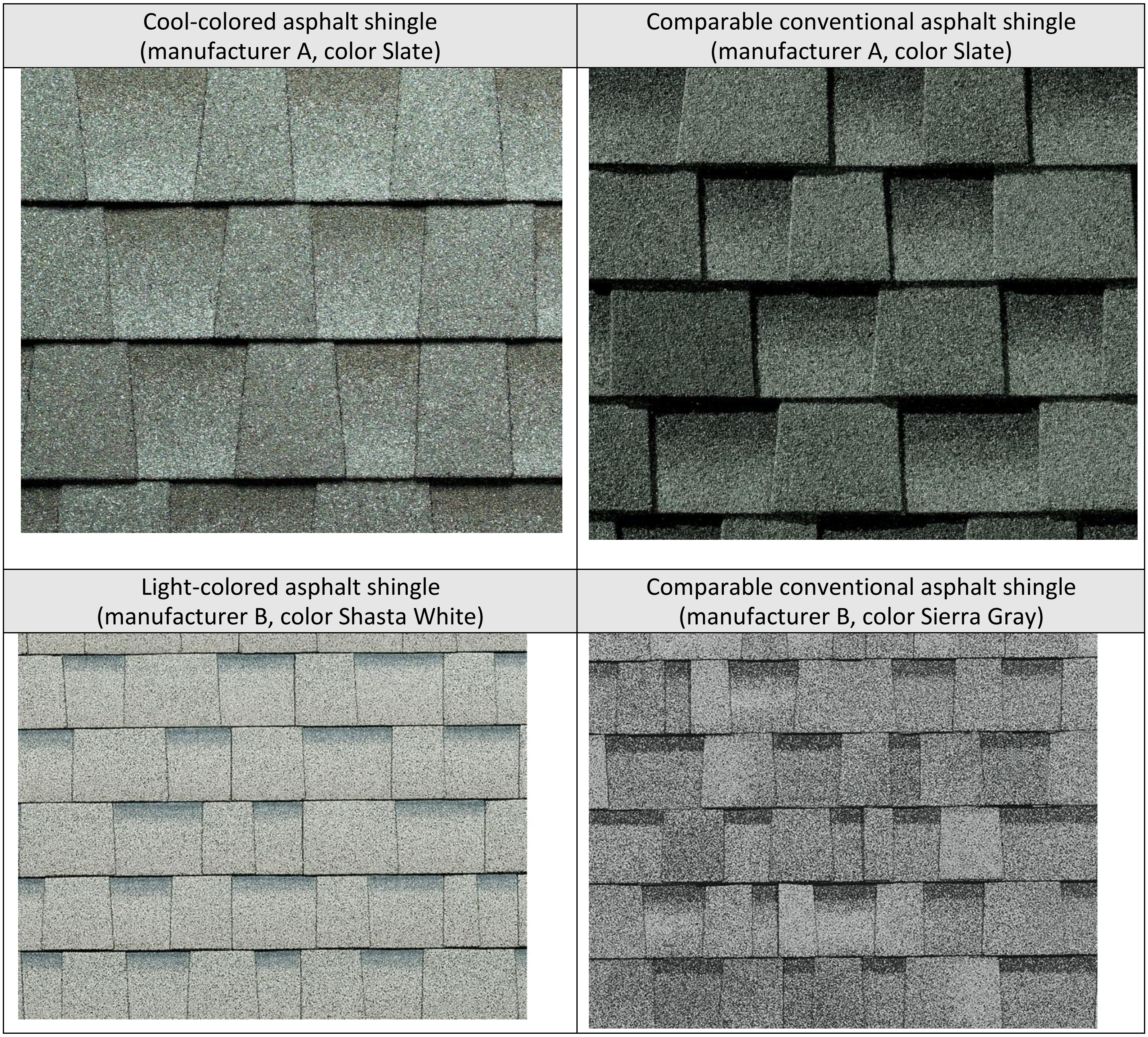

Figure 2. Comparable cool and convential asphalt roof products. Cool-colored product in image (a) is comparable to conventional product in image (b) and the light-colored product in image (c) is comparable to conventional product in image (d). Product (a) and (b) were from different product lines but the two product lines were both laminated architectural shingles. Products (b) and (c) came from the same product line.

The regional costs premiums to install cool roofs were calculated by multiplying the estimated roof area for residential and commercial buildings by the corresponding roofing material fraction, which yielded the regional roof area per roofing material type (Table 6 and Table 10). Next, we multiplied the regional roof area per roofing material type by the product's low and high cool roof cost premium estimates. This produced the estimated regional costs to install cool roof products in lieu of conventional products at the time of roof replacements.

2.4 Shade tree first costs

We referenced the findings from the Leidos report (2015c). They used first costs of $100 per tree (Leidos 2015c). This figure was also confirmed by MARC. Therefore, we multiplied this first cost by our regional tree counts per building prototype to calculate the regional first cost to install shade trees (~$102M).

2.5 Simple payback time for cool roof and shade trees

We calculated simple payback times for the regional adoption of cool roofs and shade trees. To do so, we divided the regional cool roof material cost premium by the regional annual HVAC energy cost savings. For cool roofs, we evaluated simple payback times for residential and non-residential buildings uses (as defined in Table 5). We also evaluated simple payback times for different vintages of single-family homes and medium office buildings.

For the simple payback time for shade trees, we followed a similar procedure by dividing the regional shade tree first cost by the regional annual HVAC energy cost savings. We also report the simple payback times for each building category.

3 Results

3.1 Normalized changes to building site energy use, energy cost savings, and emissions

1.1.4 Cool roofs

Cool-roof savings per unit roof area for the residential and commercial building prototypes are reported in Table 12 and Table 13, respectively.

1.1.5 Shade trees

Shade-tree savings per unit tree for the residential and commercial building prototypes are reported in Table 14 and Table 15, respectively.

3.2 Regional changes to building energy use, energy cost savings, and air emissions

1.1.6 Cool roofs

Regional cool-roof savings by building category, and regional totals (sums over all categories), are listed in Table 16.

Regional annual electricity savings by building category ranged from 0.43 GWh for mid-rise apartments to 53.1 GWh for single-family homes. The regional total annual electricity savings was 119 GWh.

Regional annual gas deficits by building category ranged from 5.01 ktherm (thousand therms) for large office buildings to 2,450 ktherm for single-family homes. However, there were regional annual gas savings of 237 ktherm for medium office buildings. The regional total annual gas deficit was 2,930 ktherms.

Regional annual HVAC energy cost savings by building type ranged from $21.5K for mid-rise apartments to $5.1 for medium offices. The regional total HVAC energy cost saving was $10.9M.

The regional annual emissions resulting from changes in building energy are also listed in Table 16. There were emission reductions for every building category across the region.

The regional building category results depend on the category's total roof area and HVAC energy savings and penalties per unit roof area. For example, single-family homes comprise 64% of the regional roof area. Their regional heating energy cost penalty was roughly 38% of the regional cooling energy cost savings—resulting in annual HVAC energy cost savings of $4.0M for single-family homes. This was smaller than the annual HVAC energy cost savings for medium offices, $5.1M, which only comprised 25% of the regional roof area. The difference was that medium office air conditioning electricity benefits were large, in addition to gas heating savings. Leidos noted,

> For the building types with multi-zone reheat systems (hospital, large office, medium office, and primary school), some net heating energy savings can be seen. This is because the high albedo roof reduces the difference in cooling requirements between the zones with roof exposure and those without. The result is that the zones without roof exposure require less reheat during the cooling season. (Leidos 2015a, p.9)

1.1.7 Shade trees

Regional shade-tree savings by building category, and regional totals (sums over all categories), are listed in Table 17.

Annual regional electricity savings by building category ranged from 0.3 GWh for mid-rise apartments to 155 GWh for single-family homes. The regional total annual electricity savings was 234 GWh.

Regional annual gas deficits by building category ranged from 21 ktherms for mid-rise apartments to 6,310 ktherms for single-family homes. However, there were also regional gas savings for large and medium office buildings—127 ktherms and 1,080 ktherms, respectively. The regional total annual gas deficit was 6,600 ktherms.

Regional annual HVAC energy cost savings by building category ranged from $215K for mid-rise apartments to $12.4M for single-family homes. The regional total HVAC energy cost saving was $21.5M.

The regional annual emissions resulting from changes in building energy are also listed in Table 17. There were air emission reductions for every building category across the region.

The greatest regional benefits from shade trees were for single-family homes, but trees planted next to medium and large offices provided the largest per-tree annual HVAC energy cost savings—$64 and $32 per tree, respectively.

Table 12. The annual site energy, energy cost, and emission savings by roof area for each of the residential prototypes from the installation of cool roofs instead of conventional roofs (scenario RR-2 in Leidos 2015b) reported to three significant figures.

Building prototype	**Electricity savings [kWh/ 1000 ft^2]**	**Gas savings [therm/ 1000 ft^2]**	**CO_2 emission savings [kg/ 1000 ft^2]**	**NO_x emission savings [g/ 1000 ft^2**	**SO_2 emission savings [g/ 1000 ft^2]**	**CO_2e emission savings [kg/ 1000 ft^2]**	**2016 electricity cost savings [$/1000 ft^2]**	**2016 gas cost savings [$/1000 ft^2]**	**Annual HVAC energy cost savings [$/1000 ft^2]**
Single Family									
Pre-1980	136	(6.03)	60.6	42.5	92.4	60.3	16.6	(6.09)	10.5
Post-1980	73.9	(3.56)	31.1	20.7	49.7	30.7	8.97	(3.59)	5.38
IECC 2006	33.3	(2.27)	10.0	4.10	21.5	9.28	4.04	(2.30)	1.75
IECC 2012	23.9	(1.58)	7.52	3.34	15.5	7.01	2.90	(1.60)	1.31
Multi Family									
Pre-1980	114	(4.98)	50.6	35.6	77.0	50.4	13.8	(5.03)	8.75
Post-1980	58.1	(2.77)	24.6	16.5	39.1	24.3	7.05	(2.79)	4.26
IECC 2006	24.9	(1.69)	7.59	3.16	16.1	7.02	3.02	(1.70)	1.32
IECC 2012	19.5	(1.20)	6.68	3.44	12.8	6.34	2.37	(1.21)	1.16

Table 13. The annual site energy, energy cost, and emission savings by roof area for each of the commercial prototypes from the installation of cool roofs instead of conventional roofs (scenario RR-2 in Leidos 2015b) reported to three significant figures.

Building prototype	Electricity savings [kWh/ 1000 ft^2]	Gas savings [therm/ 1000 ft^2]	CO_2 emission savings [kg/ 1000 ft^2]	NO_x emission savings [g/ 1000 ft^2]	SO_2 emission savings [g/ 1000 ft^2]	CO_2e emission savings [kg/ 1000 ft^2]	2016 electricity cost savings [$/1000 ft^2]	2016 gas cost savings [$/1000 ft^2]	Annual HVAC energy cost savings [$/1000 ft^2]
Large Office									
Pre-1980	245	4.00	196	192	185	208	27.3	3.16	30.5
Post-1980	126	(5.79)	54.5	37.3	84.9	54.0	14.0	(4.57)	9.47
New Construction	102	(3.62)	50.4	38.5	70.1	50.9	11.4	(2.86)	8.50
Medium Office									
Pre-1980	266	2.13	200	191	198	211	29.6	1.68	31.3
Post-1980	190	0.657	138	130	141	145	21.2	0.52	21.8
New Construction	97.0	(3.98)	44.9	32.5	66.1	44.9	10.8	(3.14)	7.68
Mid Rise Apartment									
Pre-1980	369	(27.8)	95.8	25.0	235	85.1	41.1	(21.9)	19.2
Post-1980	257	(21.7)	52.7	-1.1	160	43.2	28.7	(17.2)	11.5
New Construction	168	(11.9)	48.3	17.5	108	44.0	18.7	(9.38)	9.36
Stand-Alone Retail									
Pre-1980	648	(20.6)	336	265	450	341	72.4	(16.2)	56.1
Post-1980	269	(11.9)	120	84	183	119	30.1	(9.41)	20.7
New Construction	156	(7.42)	66.4	44.6	105	65.6	17.4	(5.86)	11.6

Table 14. The annual site energy, energy cost, and emission savings reported per unit shade tree for each of the residential prototypes for 25% shade coverage (scenario RS-1 in Leidos 2015c) reported to three significant figures.

Building prototype	Electricity savings [kWh/ tree]	Gas savings [therm/ tree]	CO_2 emission savings [kg/ tree]	NO_x emission savings [g/ tree]	SO_2 emission savings [g/ tree]	CO_2e emission savings {kg/ tree]	2016 electricity cost savings [$/tree]	2016 gas cost savings [$/tree]	Annual HVAC energy cost savings [$/tree]
Single Family									
Pre-1980	136	(6.03)	60.6	42.5	92.4	60.3	16.6	(6.09)	10.5
Post-1980	73.9	(3.56)	31.1	20.7	49.7	30.7	8.97	(3.59)	5.38
IECC 2006	33.3	(2.27)	10.0	4.10	21.5	9.28	4.04	(2.30)	1.75
IECC 2012	23.9	(1.58)	7.52	3.34	15.5	7.01	2.90	(1.60)	1.31
Multi Family									
Pre-1980	114	(4.98)	50.6	35.6	77.0	50.4	13.8	(5.03)	8.75
Post-1980	58.1	(2.77)	24.6	16.5	39.1	24.3	7.05	(2.79)	4.26
IECC 2006	24.9	(1.69)	7.59	3.16	16.1	7.02	3.02	(1.70)	1.32
IECC 2012	19.5	(1.20)	6.68	3.44	12.8	6.34	2.37	(1.21)	1.16

Table 15. The annual site energy, energy cost, and emission savings reported per unit shade tree for each of the commercial prototypes for 25% shade coverage (scenario CS-1 in Leidos 2015c) reported to three significant figures.

Building prototype	Electricity savings [kWh/ 1000 ft^2]	Gas savings [therm/ 1000 ft^2]	CO_2 emission savings [kg/ 1000 ft^2]	NO_x emission savings [g/ 1000 ft^2]	SO_2 emission savings [g/ 1000 ft^2]	CO_2e emission savings [kg/ 1000 ft^2]	2016 electricity cost savings [$/1000 ft^2]	2016 gas cost savings [$/1000 ft^2]	Annual HVAC energy cost savings [$/1000 ft^2]
Large Office									
Pre-1980	245	4.00	196	192	185	208	27.3	3.16	30.5
Post-1980	126	(5.79)	54.5	37.3	84.9	54.0	14.0	(4.57)	9.47
New Construction	102	(3.62)	50.4	38.5	70.1	50.9	11.4	(2.86)	8.50
Medium Office									
Pre-1980	266	2.13	200	191	198	211	29.6	1.68	31.3
Post-1980	190	0.657	138	130	141	145	21.2	0.52	21.8
New Construction	97.0	(3.98)	44.9	32.5	66.1	44.9	10.8	(3.14)	7.68
Mid Rise Apartment									
Pre-1980	369	(27.8)	95.8	25.0	234.6	85.1	41.1	(21.9)	19.2
Post-1980	257	(21.7)	52.7	-1.1	160.3	43.2	28.7	(17.2)	11.5
New Construction	168	(11.9)	48.3	17.5	107.9	44.0	18.7	(9.38)	9.36
Stand-Alone Retail									
Pre-1980	648	(20.6)	336	265	450	341	72.4	(16.2)	56.1
Post-1980	269	(11.9)	120	84	183	119	30.1	(9.41)	20.7
New Construction	156	(7.42)	66.4	44.6	105.2	65.6	17.4	(5.86)	11.6

Table 16. Regional annual site energy, energy cost, and emission savings by roof area for each building category from the installation of cool roofs instead of conventional roofs (scenario RR-2 and CR-2 in Leidos 2015b) reported to three significant figures.

Building category	Sum of roof area [million ft^2]	Annual electricity savings [GWh]	Annual gas savings [k therm]	CO_2 emission reductions [kt]	NO_x emission reductions [t]	SO_2 emission reductions [t]	CO_2e emission reductions [kt]	2016 electricity cost savings [US$K]	2016 gas cost savings [US$K]	Annual HVAC energy cost savings [US$K]
Single Family	515	53.1	(2,450)	23.0	15.7	35.9	22.8	6,450	(2,470)	3,980
Multi Family	41.9	3.55	(162)	4.83	3.01	8.15	4.71	431	(163)	267
Large Office	13.9	2.62	(5.01)	1.82	1.68	1.92	1.91	293	(3.96)	289
Medium Office	195	44.2	237	32.6	30.9	32.8	34.4	4,930	187	5,120
Mid Rise Apartment	1.38	0.432	(33.8)	0.105	0.019	0.273	0.091	48.2	(26.7)	21.5
Stand-Alone Retail	31.3	14.7	(512)	7.33	5.63	10.13	7.41	1,640	(405)	1,230
All (combined)	798	119	(2,930)	66.4	55.0	83.4	68.1	13,800	(2,890)	10,900

Table 17. Regional annual site energy, energy cost, and emission savings by building type from the installation of shade trees (scenario CS-1 in Leidos 2015c) reported to three significant figures.

Building category	Tree count [k]	Annual electricity savings [GWh]	Annual gas savings [ktherm]	CO_2 emission reductions [kt]	NO_x emission reductions [t]	SO_2 emission reductions [t]	CO_2e emission reductions [kt]	2016 electricity cost savings [US$K]	2016 gas cost savings [US$K]	Annual HVAC energy cost savings [US$K]
Single Family	821	155	(6,310)	72.0	52.4	106	72.1	18,800	(6370)	12,400
Multi Family	57.9	25	(1,370)	9.69	5.85	16.8	9.41	3,060	(1,390)	1,680
Large Office	10.2	1.88	127	2.08	2.23	1.55	2.26	229	101	330
Medium Office	106	48.9	1,080	40.8	40.5	37.4	43.5	5,930	850	6,780
Mid Rise Apartment	1.42	0.315	(21.3)	0.097	0.04	0.204	0.090	38.2	(16.8)	21.5
Stand-Alone Retail	21.3	2.37	(101)	1.08	0.77	1.61	1.07	287	(79.5)	208
All (combined)	1,020	234	(6,600)	126	102	163	128	28,400	(6,900)	21,500

3.3 Simple payback times

1.1.8 Cool roofs

The regional simple payback time for the installation of cool roofs in lieu of conventional roofs was 0 to 15.3 years for residential buildings and 0.6 to 3.3 years for non-residential buildings. The regional simple payback time was 0.4 to 8.0 years Table 18

We further report the simple payback times for medium office and single-family home building prototypes Table 19 and Table 20, respectively.

We found a range of cost premiums for cool roof material types. Cool options for built-up roofing products had the highest premium per unit roof area (0.10 to 0.20 $\$/ft^2$). At the regional scale, these premiums were responsible for 100% of the region's low cost-premium estimate and ~40% of the region's high cost premium estimate for non-residential buildings. However, these products only covered 19% of the region's non-residential roof area.

Asphalt shingle premiums ranged from \$0.00 to \$0.13 per ft^2 of roof area. Since residential buildings experienced only modest annual HVAC energy cost savings the simple payback time was 15 years (regional cool roof cost premium / regional annual HVAC energy cost savings).

Table 18. Regional simple payback times for cool roofs on residential buildings, non-residential buildings, and all buildings.

Building use*	Regional cool roof material cost premium—LOW [US$M]	Regional cool roof material cost premium—HIGH [US$M]	Regional annual HVAC energy cost savings [US$M]	Simple payback time—LOW [y]	Simple payback time—HIGH [y]
Residential	0	65.1	4.24	0.0	15.3
Non-residential	4.33	22.1	6.67	0.6	3.3
All (combined)	4.33	87.1	10.9	0.4	8.0

*Refer to Table 5 for a list of the building categories included in each building type.

Table 19. Regional simple payback times by vintage for cool roofs on medium office building prototypes.

Medium office building prototype	Regional cool roof material cost premium—LOW [US$M]	Regional cool roof material cost premium—HIGH [US$M]	Regional annual HVAC energy cost savings [US$M]	Simple payback time—LOW [y]	Simple payback time—HIGH [y]
Pre-1980	1.90	9.68	3.32	0.6	2.9
Post-1980	1.41	7.21	1.72	0.8	4.2
New Construction	0.184	0.938	0.079	2.3	11.9

Table 20. Regional simple payback times by vintage for cool roofs on single-family building prototypes.

Single family building prototype	Regional cool roof material cost premium—LOW [US$M]	Regional cool roof material cost premium—HIGH [US$M]	Regional annual HVAC energy cost savings [US$M]	Simple payback time—LOW [y]	Simple payback time—HIGH [y]
Pre-1980	0	34.8	3.14	0.0	11.1
Post-1980	0	15.0	0.694	0.0	21.6
IECC 2006	0	7.93	0.119	0.0	66.6
IECC 2012	0	2.02	0.023	0.0	89.1

1.1.9 Shade trees

Simple payback times for shade trees ranged from 1.7 years for medium office buildings to 11.5 years for stand-alone retail buildings (Table 21). Across the region, the combined simple payback time was 4.9 years (Table 21).

Table 21. The regional simple payback time estimates for shade trees per building category and combined for all buildings.

Building category	Total regional shade tree first costs [US$M]	Regional annual HVAC energy cost savings [US$M]	Simple payback time [y]
Single Family	82.1	12.4	6.6
Multi Family	5.79	1.68	3.5
Large office	1.02	0.311	3.3
Medium office	10.6	6.31	1.7
Stand-alone retail	2.13	0.185	11.5
Mid-rise apartment	0.142	0.018	7.7
All (combined)	102	21.0	4.9

4 Discussion

4.1 Building vintage matters

More than half of the residential and commercial buildings in the region were constructed before 1980. The use of high albedo roofs and shade trees to cool the surface of the building will reduce the amount of heat transferred into the occupied space and decrease HVAC energy consumption. This effect is greater for older, less-insulated buildings. For example, the cool roof annual HVAC cost savings for medium offices built before 1980 was four times greater than that for medium offices constructed after 2008. The difference is even greater for single-family homes where a residence built before 1980 had annual HVAC cost savings eight times greater than that of newly constructed home (constructed after 2010).

This is important when we weigh the costs and benefits of cool roofs. Older vintages of medium offices and single-family homes had much shorter simple payback times than the newly constructed buildings. The high estimate for the payback time for pre-1980 single-family homes was about 11 years compared to a newly constructed home with a payback of about 89 years.

4.2 Cool roof cost premiums

Most cool roof products were available at no cost premium, but some cool roof products incurred premiums up to \$0.20 per ft^2 of roof area. The regional roofing market is dominated by asphalt shingle products—close to 70% of the roof area. This is good and bad news since the cost premiums for such products range from \$0/ft^2 to \$0.13/ft^2. Installing cool asphalt shingles when replacing existing asphalt shingles could be an opportunity to increase adoption of cool roof products since they cover 68% of total roof area. To keep the adoption of cool asphalt roofs affordable, the low-cost cool asphalt shingles should be the preferred choice. Unfortunately, what we found is that the lower-priced cool shingles were "light" colored (Figure 2), which might not meet the aesthetic requirements of all building/homeowners.

4.3 Policy implications

This study has demonstrated that cool roofs and shade trees could reduce the region's building site energy use, energy costs, and emissions. From cool roofs alone, the region could save up to 113 GWh of electricity and \$10M in energy costs annually. Since there are some cost premiums with the adoption of cool roofs and installation of shade trees, the region could consider a few policy directions to strengthen the case for their adoption.

1. <u>Prioritize adoption of strategies in older building stock</u>

   It was clear from the analysis that the benefits of cool roofs and shade trees are greater for the region's older building stock. A regional policy therefore could prioritize adoption of these UHI countermeasures for buildings constructed before 1980. That might include distributing leaflets in older neighborhoods or new resources for roofing contractors, which would communicate the benefits of cool roofs for older buildings.

2. <u>Offer rebates for cool roof products and shade trees</u>

   We found cost premiums for some cool roof products and first costs for shade trees. While there were cool roof products available at no additional cost, some of the more popular roofing products, such as asphalt shingles, incurred cost premiums when featuring "cool" dark colors (Figure 2). The region could work with the local utility to introduce cool roof and shade tree rebates which would help offset the cost premium and first costs. Since utilities with energy efficiency mandates are interested in reducing energy consumption, the energy-saving benefits we presented in the report make cool roofs and shade trees attractive measures for a utility to incentivize. For example, in Los Angeles, California, the local municipal utility offers up to \$0.30/ft² for cool roof products (LADBS 2015). This would be more than enough incentive to cover the cool roof cost premium for each product we assessed.

This could also work in combination with efforts to prioritize older buildings. The rebate could be targeted to older neighborhoods or distributed by the utility to owners of older buildings to maximize building energy and emission savings.

3. Combine UHI countermeasure benefits

We report on the direct annual site energy, energy cost, and emission saving benefits associated with these two UHI countermeasure strategies. It would strengthen the case for their adoption if these benefits were combined with other co-benefits that would result from their implementation. For example, shade trees provide storm water management benefits, and cool roofs can improve the health and comfort of building occupants during heat events who are without AC from a power failure or lack of cooling equipment.

5 Conclusions

We evaluated the regional building site energy, energy cost, and emission benefits that result from cooling the surface of the building with tree shade or high-albedo roofing. We also calculated simple payback times based on the cool roof cost premiums and shade tree first costs.

From the regional adoption of shade trees, we found annual savings of 234 GWh for electricity and \$21.5M for HVAC energy costs. For cool roofs, the region could save up to 119 GWh of electricity and \$10.9M in energy costs per year. However, we found some cost premiums for cool roof products so simple payback times ranged from 0 to 15.3 years for residential buildings and 0.6 to 3.3 years for non-residential buildings. We were unable to investigate other important co-benefits of cool roofs, such as peak power reduction and improved reliability of the electrical grid during the warm season. If these were included in the analysis, the simple payback times would have been reduced. In addition to the range in cost premiums, we found that the simple payback times were affected by the building vintage. Older buildings accrued larger HVAC energy cost savings than new construction from installation of cool roofs and shade trees. This resulted in shorter simple payback times for older vintages in all building categories.

We have found these UHI countermeasures beneficial to reduce the region’s building site energy use, energy costs, and emissions. To increase the adoption of these measures, the region could prioritize adoption of strategies in older building stock, offer rebates offset cool-roof cost premiums and shade-tree first costs, and combine UHI countermeasure co-benefits in support of other local government priorities and plans (e.g., storm water management) to strengthen the case for their use.

References

EIA. (2012). Commercial Building Energy Consumption Survey (CBECS) – public use microdata. US Energy Information Administration, Washington, DC. Accessed 2018-09-24 from http://www.eia.gov/consumption/commercial/data/2012/

EIA. (2015). Residential energy consumption survey (RECS) – public use microdata. US Energy Information Administration Washington, DC. Accessed 2018-09-24 from http://www.eia.gov/consumption/residential/data/2015/

IECC. (2018). Overview of the International Energy Conservation Code. International Code Council Washington, DC. Accessed 2018-10-16 from https://www.iccsafe.org/codes-tech-support/codes/2018-i-codes/iecc/

LADBS. (2015). Cool roof fact sheet and FAQ. City of Los Angeles Department of Building and Safety and Loa Angeles Department of Water and Power Los Angeles, CA March 2015. Accessed 2018-09-25 at https://www.ladbs.org/docs/default-source/publications/ordinances/cool-roof-fact-sheet-and-faq.pdf?sfvrsn=10

Leidos. (2015a). Energy savings of heat-island reduction strategies for the Kansas City Area. Leidos report commissioned by the Mid-America Regional Council. September 2015.

Leidos. (2015b). Energy savings of high albedo roofs for the Kansas City Area. Leidos report commissioned by the Mid-America Regional Council. September 2015.

Leidos. (2015c). Energy savings of shade trees for the Kansas City Area. Leidos report commissioned by the Mid-America Regional Council. September 2015.

Levinson, R., Akbari, H., Konopacki, S., & Bretz, S. (2002). Inclusion of cool roofs in nonresidential Title 24 prescriptive requirements. Report LBNL-50451, Lawrence Berkeley National Laboratory, Berkeley, CA. https://doi.org/10.2172/813562

Lowes. (2018). Lowe's Southern Kansas City location website, Building Supplies, Roofing. Accessed 2018-08-29 at https://www.lowes.com/c/Roofing-Building-supplies

SEEAT. (2018). Carbon Management Information Center Source Energy and Emissions Analysis Tool (SEEAT), Version 7.3, Copyright 2017 Gas Technology Institute. Accessed 2018-09-24 at http://seeatcalc.gastechnology.org

Appendix D

Task 5: Existing plans for metropolitan Kansas City to incorporate Urban Heat Island countermeasures

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Urban heat island (UHI) countermeasures and cool city strategies figure prominently across a range of regional planning efforts at the Mid-America Regional Council (MARC). Regional plans associated with transportation, air quality, green infrastructure, hazard mitigation and climate resilience all consider related problems and solutions. Increasingly, regional plans are being more fully integrated, with an emphasis on cross-cutting solutions transcending sectors and jurisdictions. Heat island reduction strategies and benefits provide a perfect example of measures that complement multiple plans and provide additional co-benefits to those efforts.

1 The Regional Transportation Plan (Transportation Outlook 2040)

The plan includes policy goals related to alternative transportation, air and water quality, natural resource protection, energy and climate resilience and public health. Many modes of transportation release heat during use and transportation infrastructure replaces vegetation with dark, impervious surfaces which both contribute to the regions urban heat island effect (UHIE) and hinder the region's ability to achieve its transportation-related goals. The Kansas City region has an urbanized area of about 802 square miles, with one-third of that total being impervious buildings, roads and parking lots. Impervious roads constitute 6.3% of the total area, or 51 square miles. Parking lots and driveways make up 17.8%, or 143 square miles.

The current plan under development will consider heat island mitigation measures like complete green streets, urban forestry, native landscaping, and storm water best management practices. Each of these measures would help achieve multiple community goals.

2 Clean Air Action Plan

The Kansas City Regional Clean Air Action Plan (CAAP) is a comprehensive, community-based, voluntary plan for reducing ground level ozone and, consequently, protecting public health in the Kansas City metro area. The plan update in 2011 included a focus on native and sustainable landscaping, streetscaping and green infrastructure for governments and residences, implementation of the latest building energy codes, and best practices for commercial landscaping.

Native landscaping reduces emissions from mowing and cools the city from increased shade and infiltration and complements complete street, stormwater, and green infrastructure goals. The current plan update continues to focus on previously identified heat island reduction strategies.

Regional Green Infrastructure Framework seeks to link, conserve and restore natural areas and hydrologically-connected green spaces in service of multiple environmental, public health and social equity goals. The framework offers a community and systems-based, integrated planning approach to protecting open space, and optimizing ecosystem services like cooling the city. The regional Ecological Value map serves as a basis for understanding the relationship between the built and natural environments, and for prioritizing green infrastructure investments to achieve multiple benefits, including urban heat mitigation.

3 Regional Climate Resilience Strategy

The strategy is based on a meso-scale climate projection for the year 2060. Assuming the current emissions trajectory remains unchanged, the region will experience an increase of the number of days per year in which the temperature exceeds 105˚F, from 0.7 to 21.9. Increased temperatures would exacerbate area heat islands posing numerous threats to public and environmental health, walking and biking, economic productivity and public safety. The strategy highlights heat island reduction strategies—trees and green infrastructure—as among the most promising mitigation measures for temperature change as well as mitigating the projected increases in flooding. The strategy also highlights energy efficiency investments in efforts to bolster indoor health and safety during periods of extreme heat, especially among vulnerable populations. The disproportionately high energy burden among vulnerable communities in the metro area reinforces the relationship between social equity, energy affordability, and public health.

4 Regional Hazard Mitigation Plan

The plan focuses on multiple natural and anthropogenic hazards confronting the metropolitan area. Heat waves and flooding are each highlighted in the plan. Other plans also note these hazards along with a set of promising, multi-benefit mitigation measures. The 2020 plan update process will seek to prioritize and operationalize green infrastructure, cool roof and other HI mitigation measures through heightened levels of collaboration between the emergency management and infrastructure design communities.

4.1 Links to regional plans for metropolitan Kansas City

- Transportation Outlook 2040, http://www.to2040.org/
- Clean Air Action Plan, http://www.marc.org/Environment/Air-Quality/Reports/Clean-Air-Action-Plan

- Green Infrastructure Framework, http://www.marc.org/Environment/MetroGreen-Parks/Current-Projects/Green-Infrastructure-Framework
- Regional Climate Resilience Strategy, http://www.marc.org/Environment/Plans-Studies
- Regional Hazard Mitigation Plan, http://www.marc.org/Emergency-Services-9-1-1/MEMC/Activities/Regional-Hazard-Mitigation-Plan

Appendix E

Task 7: Evaluating the benefits of vegetation and cool roofs: A step-by-step guide developed from a case study of the Kansas City region

BERKELEY LAB

MARC
MID-AMERICA REGIONAL COUNCIL

Steps for Urban Heat Island (UHI) countermeasure evaluation

1. Review past research and policies/programs of other local governments
2. Outline objectives of investigation
3. Model the air temperature reduction potential from cool community strategies
4. Quantify the relationship between electric power demand and ambient air temperature
5. Calculate the city-wide energy and emission benefits from air cooling strategies ("indirect" savings)
6. Calculate the city-wide energy and emission benefits from surface cooling strategies ("direct" savings)
7. Evaluate the cost and cost-effectiveness of each UHI countermeasure
8. Assess the results to understand how they can be used to inform policies, plans, or policy frameworks

STEP 1: Review previous related research and other local government policies / programs

Goal: Learn from other research and implementation efforts.

- Keep in mind when reviewing research from other areas that the benefits of UHI countermeasures vary with
  - Climate
  - Building stock
  - Urban development patterns (e.g., density, city layout)
  - Land use / land cover
  - Scale of implementation
  - Preexisting conditions

- Review existing research for your study area, region, and nation.
  - What UHI countermeasures did the previous research evaluate or implement?
  - What were their methods of evaluation and/or implementation?
  - What were the outcomes and results of these studies?
  - What lessons learned can be applied to your planning?

- Search for other local governments that have implemented programs or policies related to UHI countermeasures, such as
  - Solar reflective ("cool") roofs, walls, or pavements
  - Pervious (a.k.a. permeable) pavements
  - Shade trees
  - Garden (a.k.a. green, or vegetative) roofs
  - Green infrastructure (landscape elements, such as bioswales)
  - Green open spaces (e.g., parks)
  - Water elements

- Programs or policies might be found in building codes, storm water management plans, climate adaptation plans, and other government guidance.

- Look for this information in general audience resources, such as web pages, program brochures, presentations, and case studies that summarize an organization's process and results. Also search for academic resources in conference papers, conference presentation, and journal publications.

- Reach out to staff involved in the implementation or research efforts to inquire about processes, barriers, and critical steps for success.
  - What lessons learned can be taken into consideration for your planning?

STEP 2: Outline the objectives of the investigation

Goal: Identify where, how, and why the study is being undertaken.

- Define the scope and objectives of your study.
  - What problem(s) are you trying to resolve with UHI countermeasures?
  - What benefits are you seeking?
  - What is the city/community of interest? Can it be clearly defined?

- What is the scale of implementation and study?
  - What UHI countermeasures are of interest for the study?
  - Are the benefits also important for other policy priorities?

- UHI countermeasures may yield
  - "Direct" benefits that result from cooling building surfaces
    - Building air conditioning energy savings <u>or</u> improved indoor comfort
  - "Indirect" benefits that result from cooling outside air
    - Mitigation of the urban heat island
    - Building air conditioning energy savings <u>or</u> improved indoor comfort
    - Improved outdoor comfort
    - Slowed formation of ozone
  - Resiliency to extreme heat events and future warming
  - Reduced health risks during extreme heat events
  - "Global cooling" benefits that result from increasing reflection of sunlight to space
  - Other local benefits
    - Stormwater runoff control
    - Improved outdoor comfort from shading

- For the Kansas City regional example, our objectives were to
  - Investigate the effects of the deployment of cool roofs and utilization of green infrastructure on Kansas City metropolitan area's outdoor air temperature, indirect building energy savings, and direct building energy savings.
  - Analyze the costs and benefits of the countermeasures to learn if the benefits merited a UHI mitigation policy and/or could be included in other existing policies or planning efforts as co-benefits.

STEP 3: Model the air temperature reduction potential from UHI countermeasures
Goal: Calculate the potential of the UHI countermeasures to reduce air temperatures.

1. Define the community, city, or region of interest. Should be large enough to have influence on its own temperature—think city-scale or larger.

2. Pick a set of episodes (each episode lasting about one week) that will be used to represent the typical summer conditions.

   - The set of episodes for typical conditions may comprise one randomly selected week from each summer month during past year(s).

3. Pick a separate set of episodes that represent the hottest summer weeks.

   - Find the weeklong periods with the highest average temperature that occurred over the past 10 years. Choose at least six episodes.

4. Run the Weather Research and Forecasting (WRF) modeling tool to simulate the meteorological conditions (Skamarock et al. 2008).

5. Prepare the input land cover data for the WRF model.

   - Use land cover data from the USGS National Land Cover Database (NLCD, 16-class land cover classification scheme; see Homer et al. 2011) and National Urban Database and Access Portal Tool (NUDAPT, high-resolution urban morphology; see Ching et al. 2009).
     - If there are gaps between the NUDAPT coverage and your study area, find the median values within the NUDAPT for each development intensity level (i.e., low, medium, and high) and extrapolate those values to the urban areas that are not included within the NUDAPT dataset based on the development intensity level.

6. Download and prepare the input meteorological data.

   - Initial and boundary meteorology conditions can be obtained from the North American Regional Reanalysis (NARR; see Mesinger et al. 2006).

   - Include an 18-hour spin-up period for each episode (average and hot summer episodes).

7. Run the WRF model using the single-layer urban canopy model for each simulation.

   - For each episode, include a control run simulation and a modified simulation with one or more UHI countermeasures.

   - We modeled two countermeasures to assess UHI mitigation in the Kansas City region.
     - Cool roofs: Raised roof albedo to 0.60 from 0.20 (increase 0.40)
     - Green infrastructure: Activated the WRF irrigation scheme to mimic increased soil moisture from vegetation

8. Analyze the differences between the output files from the control and modified simulations to determine the effects of the mitigation strategies.

   - Find the mean air temperature for a certain hour, or set of hours, in the modified simulation and compare that to the same quantity in the control simulation.

   - You can apply same method to also evaluate other climate variables, such as precipitation and wind speeds.

STEP 4: Quantify the relationship between electric power demand and ambient air temperature

Goal: Identify the relationship between power demand and ambient air temperature.

1. From weather records, identify a hot day and a cool (mild) day within the same year that had similar sunlight, weather, and activity. The two test days should be equally spaced about the summer solstice for similar solar exposure. Both should be weekdays because activity and power demands in urban areas are greatest on weekdays. The dominant controller of air conditioning (AC) use is temperature, for which good records are usually available. Preferably the cloud cover/sunlight should be the same, but such detail is often not available,

and is not especially important. The reporting weather station should be as close to the area of interest as possible. Often a good comparable set of days can be found with one in late July and one in early May.

2. From weather records find all hourly values of outside air temperature TT over the course of the year containing the test days—hereafter, the “test year”.

3. Count the number of hours in the test year for which $TT > 18^{\circ}C$ (65˚F). We assume this represents an upper limit to the number of hours during which air conditioning was used in the test year. We denote this “CH18C”, or cooling hours at reference temperature 18 °C. If you prefer a quicker yet sometimes slightly less accurate approach, the U.S. Environmental Protection Agency (US EPA) published a Life Cycle Cost Estimator tool for air conditioning that lists “Full-Load Cooling Hours”, which would be “CH18C”, in their assumptions for many cities across the U.S. (USEPA n.d.). If your city is not listed, find one that has weather similar to that in your city. You might add a safety factor of 20% (multiply by 1.2).

4. Reach out to the electric utility company that services the area of interest; describe your project goals and objectives to seek their support. If it is a municipal utility, the service area of the utility could serve as the boundary for the study.

   - Obtain and process local utility data for analysis, as follows:
     - Ask the utility to provide hourly electrical power demand records for each test day, and for one day before and after each test day (six days in total). Request hourly power demand values either aggregated for your study area or for each customer meter within every ZIP code in your study area. Ask for clearly and unambiguously labeled units, dates, and times, as well as a brief guide explaining how to interpret each value of hour and power.
       - Hourly power demand records on the days preceding and following each test day can be helpful to adjust for timing differences between the power data and the weather data (e.g., sometimes it is not clear whether records are labeled with clock, daylight, or standard time).
       - Verify that power demand records received are chronologically and geographically complete, and clearly labeled. If there are gaps, follow-up with the utility to understand the reason for the incomplete dataset. If a meter’s record is not complete it should not be counted in the daily total, but keep track how many meters are being ignored so that the completeness of the tally can be estimated.

5. Use mesoscale meteorological simulation or other methodology to estimate the maximum reduction in hourly air temperature, $(\Delta TT)_{max}$, attainable by cooler surfaces (see Step 3).

6. Relate power demand to ambient air temperature.

   - Subtract the hourly power demand on the cool day from that on the hot day to estimate hourly AC power demand on the hot day.

- Regress hourly AC power demand P against hourly temperature on the hot day to estimate the maximum rate of change of the AC demand vs. temperature, $(dP/dT)_{max}$.

- Approximate the maximum annual city-wide AC energy saving as

$$\Delta E_{a,max} = (dP/dT)_{max} \cdot (\Delta T)_{max} \cdot \text{CH18C}$$

STEP 5: Calculate the city-wide monetary and emission benefits from air cooling strategies ("indirect" savings)

Goal: Assess potential cost savings and environmental co-benefits from cooling the outside air.

1. To find the maximum annual AC cost savings from reduction in city-wide air temperatures, multiply the maximum annual cooling energy savings ($\Delta E_{a,max}$) by the highest summer price of electricity charged by the local utility.

    - The rate for commercial buildings is often less than the residential rate. In our analysis for Kansas City we used the higher residential rate to bound maximum cooling energy savings.

2. To find the maximum reduction in CO_2 emissions, multiply the maximum annual cooling energy savings ($\Delta E_{a,max}$) by the CO_2 emission factor, *e*, defined as the mass of CO_2 emitted at the power plant per unit electricity consumed at the building site.

    - The Source Energy and Emissions Analysis Tool, or SEEAT (GTI 2018) provides suitable CO_2 emission factors.

    - The US EPA's Emissions & Generation Resource Integrated Database (eGRID, US EPA 2017) reports CO_2 emission factors based on electricity leaving the power plant. If using an eGRID factor, convert its basis to site energy use by dividing by 0.9. This step accounts for losses in transmission and distribution.

3. To find the maximum reduction in peak-power demand, multiply $(dP/dT)_{max}$ by the maximum reduction in temperature, $(\Delta T)_{max}$.

STEP 6: Calculate the city-wide monetary and emission benefits from surface cooling strategies ("direct" savings)

Goal: Assess potential cost savings and environmental co-benefits from cooling building surfaces.

1. Cool roofs and shade trees can decrease annual energy use, energy cost, and emissions by reducing the solar heat gain and surface temperature of building envelope surfaces.

2. To compute these savings, use a whole building energy simulation program such as EnergyPlus (DOE 2018b) to calculate the annual energy uses of residential and commercial building prototypes before and after applying the measure (cool roof or shade tree).

- A prototype typically represents a specific building vintage and category (e.g., pre-1980 single-family home with gas furnace). Residential and commercial building prototypes conforming to various years of building energy efficiency standards are available from the U.S. Department of Energy (DOE 2018c, 2018a).
- For each form of site energy consumed—typically electricity for cooling and natural gas for heating—calculate cool roof site energy savings (potentially negative) by subtracting annual site energy use of the prototype with a cool roof from that of the same prototype with a conventional roof. Apply the same procedure for prototypes with and without shade trees.
- Compute energy cost savings by applying residential or commercial sector site energy prices to the site energy savings.
- Compute emission savings by applying site energy emission factors to the site energy savings.
- Normalize cool roof savings to roof area to obtain cool roof savings intensity, and normalize shade tree savings to number of shade trees to calculate shade tree savings intensity.
- Leidos (2015a, 2015b, 2015c) computed cool roof savings intensity and shade tree savings intensities for prototype buildings in the Kansas City region.

3. Compute potential regional cool roof savings for each prototype by multiplying its cool roof savings intensity by the regional conventional (non-cool) roof area corresponding to that prototype.
4. Calculate regional shade tree savings for each prototype by multiplying its shade tree savings intensity by the number of shade trees that can be planted for regional buildings corresponding to that prototype. Make sure that the regional shade tree planting scenario agrees with that used in the simulation of shade tree savings intensity. For example, if the simulations assume one shade tree on each side of the building, its regional shade tree planting scenario should do the same.
5. Compute regional savings for the entire building stock by summing regional savings per prototype.

NOTE: We have calculated the direct and indirect building site energy, energy cost, and emission saving benefits resulting from the adoption of the UHI countermeasures. However, there are other benefits that could be assessed to help inform your results, such as improvements to public health and reductions in storm water run-off.

STEP 7: Evaluate the costs of the UHI countermeasures

Goal: Calculate the costs and/or cost premiums from adopting the UHI countermeasures.

1. For UHI countermeasures of interest, determine whether they are (a) used in lieu of an existing conventional product/practice, such as cool roofs; or (b) require new installation, such as increased vegetation.

   - For option (a) calculate the cost premium for selecting the UHI countermeasure product instead of the conventional product.
   - For option (b) calculate the first (installation and material) costs of adopting the UHI countermeasures.

2. Quantify the potential extent of each UHI countermeasure. For example, for cool roofs, calculate for each building category the regional roof area, which is close to the building footprint area that is often available via County Assessor data or within local planning departments/organizations. (You may need to subtract the areas of roof that are already cool.) For shade trees, assess the number of new trees that could be planted.

3. Use existing resources and contact local stakeholders, manufacturers, organizations, and companies to learn the local cost premiums and unit (or unit area) installation costs.

   - For the regional Kansas City study, we found that the local south Kansas City Lowe's online store was a good resource to learn about cool roof cost premiums. We also worked with our partner, MARC, to estimate shade tree installation costs.

4. Combine the cost information per unit or per unit area with the extent of each countermeasure to calculate regional costs. For example, the unit cost to install one new shade tree will be multiplied by the number of new shade trees that will be planted throughout your study area.

   - For cool roofs, you could go into more detail to investigate specific cool roof material costs. For example, you could estimate the regional cool-roof premium by summing the products of each material's unit-area cost premium and regional total area. Therefore, you could evaluate more than one cool roof option for your study area (e.g., pitched roof vs. flat roof products). Please refer to our *Costs and Benefits of Cool Roofs and Shade Trees in Kansas City Metropolitan Area* report for more information.

STEP 8: Assess the results to understand how they can be used to inform policies, plans, or policy frameworks

Goal: Evaluate whether UHI countermeasures should be incorporated into local policy.

- Assess the results from each of the steps to evaluate all the benefits and costs of the UHI countermeasures together. In addition, review the cost-effectiveness of adopting the UHI countermeasures.
  - Do the UHI countermeasures achieve your intended benefits?

  - Are some more cost-effective than others?
  - Would you be able to achieve the scale of adoption to achieve the benefits?

- Revisit your study objectives.
  - Have you achieved your objectives?
  - If not, has that changed how you should assess the results or implement the findings?

- Based on the study objectives and the findings, evaluate policy and planning options.
  - Develop a new independent UHI countermeasure policy or plan to increase adoption of the selected UHI countermeasures.
    - Example: New York City launched the NYC °Cool Roofs program (City of New York 2014) which supports local jobseekers through a paid and transitional work-based learning experience to apply white coatings to NYC rooftops. The program works with building owners to apply the white coatings with a goal of one million square feet of new white rooftops each year.
  - Include a UHI countermeasure target or goal in an existing policy or plan.
    - Example: The City of Los Angeles' *Sustainability City Plan* (City of Los Angeles 2017) has a goal to reduce their urban/rural air temperature difference by 3.0 °F by 2030. To meet this goal, they included a target to install 10,000 new cool roofs by 2017 when they developed the plan in 2015.
  - Use the findings to support the use of UHI countermeasures in existing policies to achieve multi-benefits.
    - Kansas City example: The findings will be used to support the inclusion of complete green streets and urban forestry practices in the Regional Transportation Plan (MARC 2015b). The plan includes policy goals related to alternative transportation, air and water quality, natural resource protection, energy and climate resilience, and public health.
    - Kansas City example: The Regional Hazard Mitigation Plan (MARC 2015a), which focuses on multiple natural and anthropogenic hazards like heat waves and flooding, will prioritize and operationalize green infrastructure, cool roofs, and other UHI mitigation measures in its 2020 plan update.

- Share your ideas and findings with diverse stakeholder groups to build support and refine policy or plan.
  - Stakeholder groups could represent (among others):
    - Local businesses
    - Real estate and development
    - Construction & trades
    - Community development
    - Workforce development
    - Emergency management
    - Utilities
    - Local non-profits
    - Faith-based groups
    - Manufacturers of cool products
    - Park departments
    - Homeowner associations

        - Building code development and enforcement
        - Public health
        - Transportation

- Outline the next steps in implementing the plan or policy.
    - Who needs to approve the plan or policy? What are the steps for that approval process?
    - What information is still needed to implement the plan or policy?
    - What is the timeline to implement the plan or policy?

- These things take time—be prepared and patient. Allow your ideas to evolve as you build support. You will discover a lot from early adoption efforts. Approach all policy or planning efforts as circular processes, where early lessons inform future roll-out efforts.

REFERENCES

Ching, J., Brown, M., Burian, S., Chen, F., Cionco, R., Hanna, A., … Williams, D. (2009). National urban database and access portal tool. *Bulletin of the American Meteorological Society*, 90(8), 1157–1168. https://doi.org/10.1175/2009BAMS2675.1

City of Los Angeles. 2017. Sustainability City Plan. Accessed 2018-10-01 http://plan.lamayor.org/wp-content/uploads/2017/03/the-plan.pdf

City of New York. 2014. NYC ˚Cool Roofs. Accessed 2018-10-01 https://www1.nyc.gov/nycbusiness/article/nyc-coolroofs and https://www1.nyc.gov/site/sbs/careers/industrial-training.page

DOE. (2018a). Commercial Prototype Building Models. Building Energy Codes Program, U.S. Department of Energy. Accessed 2018-10-01 https://www.energycodes.gov/development/commercial/prototype_models

DOE. (2018b). EnergyPlus whole building energy simulation program. Building Technologies Office, U.S. Department of Energy. Accessed 2018-10-01 https://energyplus.net

DOE. (2018c). Residential Prototype Building Models. Building Energy Codes Program, U.S. Department of Energy. Accessed 2018-10-01 https://www.energycodes.gov/development/residential/iecc_models

Fry, J., Xian, G. Z., Jin, S., Dewitz, J., Homer, C. G., Yang, L., … Wickham, J. D. (2011). Completion of the 2006 national land cover database for the conterminous United States. *Photogrammetric Engineering and Remote Sensing*, 77(9), 7. https://pubs.er.usgs.gov/publication/70034549

Gilbert, H., & Levinson, R. (2018). Heat island mitigation assessment and policy development for the Kansas City region. Task 4 report: Costs and Benefits of Cool Roofs and Shade Trees in Kansas City Metropolitan Area for metro Kansas City region. Report XXX, Lawrence Berkeley National Laboratory, Berkeley CA.

GTI. 2017. Carbon Management Information Center Source Energy and Emissions Analysis Tool (SEEAT), Version 7.3, Gas Technology Institute. Accessed 2018-10-01 http://www.cmictools.com/cmicec/default.aspx

Homer, C.G., Dewitz, J.A., Yang, L., Jin, S., Danielson, P., Xian, G., Coulston, J., …Megown, K., (2015). Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing, 81(5), 9. http://bit.ly/1K7WjO3

Jeong, S., Millstein, D., & Levinson, R. (2018). Heat island mitigation assessment and policy development for the Kansas City region. Task 3 report: Evaluation of urban heat island mitigation strategies for the Kansas City Metropolitan Area. Report XXX, Lawrence Berkeley National Laboratory, Berkeley CA.

Leidos. (2015a) Energy savings of heat-island reduction strategies for the Kansas City Area. Leidos report commissioned by the Mid-America Regional Council. September 2015.

Leidos. (2015b) Energy savings of high albedo roofs for the Kansas City Area. Leidos report commissioned by the Mid-America Regional Council. September 2015.

Leidos. (2015c) Energy savings of shade trees for the Kansas City Area. Leidos report commissioned by the Mid-America Regional Council. September 2015.

MARC. (2015a). Regional Hazard Mitigation Plan. Mid-America Regional Council. Accessed 2018-10-01 http://www.marc.org/Emergency-Services-9-1-1/MEMC/Activities/Regional-Hazard-Mitigation-Plan

MARC. (2015b). Transportation Outlook 2040. Mid-America Regional Council. Accessed 2018-10-01 http://www.to2040.org

Mesinger, F., Di Mego, G., Kalnay, E., Mitchell, K., Shafran, P. C., Ebisuzaki, W., … Shi, W. (2006). North American regional reanalysis. *Bulletin of the American Meteorological Society*, 87(3), 343–360. https://doi.org/10.1175/BAMS-87-3-343

Pomerantz, M., Rosado, P., & Levinson, R. (2018). Heat island mitigation assessment and policy development for the Kansas City region. Task 2 report: Quantifying the relationship between ambient air temperatures and electric power demand for metro Kansas City region. Report XXX, Lawrence Berkeley National Laboratory, Berkeley CA.

Skamarock, W., Klemp, J., Dudhia, J., Gill, D., Barker, D., Wang, W., … Duda, M. (2008). A description of the advanced research WRF version 3. UCAR/NCAR. https://doi.org/10.5065/D68S4MVH

US EPA. (n.d.) Life Cycle Cost Estimate for 1 ENERGY STAR Qualified Central Air Conditioner(s). U.S. Environmental Protection Agency and U.S. Department of Energy. Accessed 2018-10-01 https://www.energystar.gov/sites/default/files/asset/document/CentralAC_Calculator.xls

US EPA. (2017). Emissions & generation resource grid integrated database (eGRID) 2014 v2 [Summary Tables]. Accessed 2018-10-01 http://www.epa.gov/cleanenergy/egrid