# CITY-SCALE ANALYSIS OF GREEN ROOF EFFECTIVENESS IN REDUCING LOCAL SURFACE TEMPERATURES

*Natasha Stamler*[1,2*]

[1] Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA
[2] Building Physics and Services, Department of the Built Environment, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

* Email: stamlern@mit.edu

## ABSTRACT

Intensifying urban heat poses a significant threat to public health. To combat this danger, cities are increasingly implementing vegetated green roofs on buildings. This study develops an open-source, quasi-experimental method to evaluate the cooling impacts of green roofs across a city relative to nearby unvegetated roofs. This method, combined with publicly available data across a 14-year period, is applied to quantify the reduction in land surface temperatures (LST) due to green roofs in Washington, D.C. The results show significant variation in cooling performance among green roofs, indicating that not all green roofs reduce rooftop temperatures. The method developed in this study provides a low-cost approach for policymakers and planners to assess the cooling capacity of green roofs in their communities. It can aid in evaluating the effectiveness of green roof programs in mitigating urban heat, especially in resource-constrained situations or for large cities with numerous green roofs.

***Index Terms***— Green roof, urban heat, Landsat 5 TM, land surface temperature, quasi-experimental analysis

## 1. INTRODUCTION

In the coming decades, millions of people will increasingly be exposed to deadly urban heat [1]. To mitigate these rising temperatures, many cities have begun to install vegetated “green” roofs on buildings [2]. While research has demonstrated the potential cooling impact of individual roofs, little research has been done to evaluate the cooling impacts of many green roofs throughout a city. Utilizing publicly available satellite imagery and open-source software, this study develops a quasi-experimental approach to quantify the extent to which green roofs across a city reduce local land surface temperatures (LST). While near-ground air temperature is the key metric to assess human-level heat impacts, quantifying LST variability between green roofs and nearby non-green roofs is an important step in understanding how vegetation affects urban heat. This study builds on the work of McConnell et al. (2021), who developed a quasi-experimental research design to quantify the cooling effects of three green roofs in Chicago, Illinois [3]. The method developed in this study is applied to Washington, D.C., the city with the greatest square footage of green roof installations in North America [4]. By using publicly available and open-source data and software, this method is reproducible and can be extended to other cities in future studies.

## 2. DATA AND METHODS

Landsat 5 TM imagery from 1999 to 2011 was used to calculate LSTs. Only scenes from hot days, defined as those with a NOAA-reported maximum air temperature above 80°F (26.7°C), were sampled, to quantify cooling impacts only on the days with dangers for heat-related health impacts. Quality assurance was performed to exclude all pixels containing clouds and/or cloud shadows.

Roofs were identified using the building footprints from the publicly available Open Data DC Building Footprints dataset. Only buildings in both the 1999 and 2013 captures were included in this analysis to exclude temperature changes due to building demolition or construction, which are both major building modifications unrelated to green roof installation. Green roofs were identified using the Open Data DC Best Management Practices (BMPs), a publicly available dataset of structural controls used to reduce the effects of stormwater runoff, including green roofs, released by the City of Washington, D.C. To expand this method to other cities lacking green roof data, green roofs could be identified using the supervised image classification developed by Treglia et al. (2022), which has been tested in New York City [5].

The causal effect of green roof installation on rooftop LST relative to that of nearby non-vegetated control roofs was analyzed to avoid accounting for temperature changes unrelated to the green roofs, such as regional climate variations. A control roof was identified for each green roof using criteria similar to that used by McConnell et al. (2021) [3]. The corresponding control roof for each green roof was the building with a non-vegetated roof within a 90-270-meter buffer around each green roof with the largest area and the closest elevation to that of the green roof. The buffer was used to avoid spatial spillover effects from a green roof's vegetation onto its control roof based on previous research quantifying the thermal influence of large green spaces on hot urban environments [6, 7]. Selecting proper control roofs ensures that the noninterference assumption in the statistical model holds, meaning that installing a green roof does not affect its control site [3]. All green roofs without corresponding control roofs were removed from the study. In addition, due to the 30 m x 30 m spatial resolution of Landsat 5 TM imagery [8], all buildings with areas less than 900 $m^2$ (9688 $ft^2$) were removed. Band 6, the Landsat 5 TM thermal infrared band, has a 120 m x 120 m spatial resolution, but is resampled to 30-meter pixels [8]. Landsat data was downloaded from the USGS EROS Science Processing Architecture (ESPA) On Demand Interface, a free platform that enables bulk downloading of NASA satellite data, including Landsat TM Level-2 Products. Of the 668 buildings with currently installed green roofs in Washington, D.C., a total of 337 met all necessary criteria and were studied on the 84 hot days between 1999 and 2011 on which a Landsat 5 TM scene with less than 10% cloud cover captured the entire city. All scenes were taken from path 15 and row 33.

The temperature impact of each green roof was calculated using a statistical method at the intersection of social and physical sciences called difference-in-differences (DiD) analysis or before–after control-impact (BACI). It compares changes over time between treatment and control groups using longitudinal data and the following linear mixed model:

$$Y_t = \beta_0 + \beta_1 P_t + \beta_2 G_t + \beta_3 (P_t \cdot G_t) + \epsilon_t$$

Where $Y_t$ is the LST outcome; $P_t$ is a temporal indicator for green roof installation where 0 is pre-treatment (before green roof installation) and 1 is post-treatment (after green roof installation); $G_t$ indicates the treatment status of the site, where 1 is a green roof and 0 is a nearby control roof; $\beta_3$, the coefficient on the interaction term $P_t \cdot G_t$, is the difference-in-differences estimator of interest, which measures the average treatment effect of green roof installation on LST; and $\epsilon_t$ is the residual errors. Year fixed effects were included to control for any background temporal trends that may influence outcome variables across all sites.

## 3. RESULTS

Descriptive density plots illustrating the distribution of pre- and post-green roof installation mean LST values for each green roof and control roof site are shown in Figure 1. While the mean LST of the green roofs was higher than that of the control roofs both before and after green roof installation, the difference between the means was lower after the installation (1.04°C before and 0.29°C after), indicating a relative cooling effect due to the green roof installation.

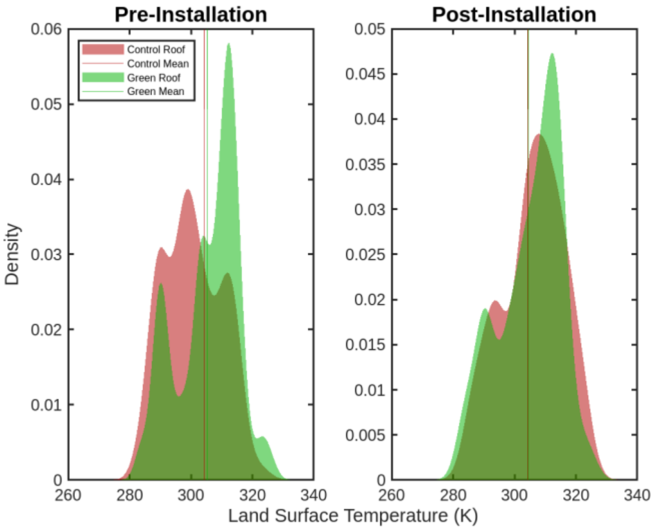

**Figure 1**. Density plots of land surface temperature (LST) for each green roof and paired control site. Vertical lines indicate mean values. The mean green roof LST was higher than that of the control roofs both before and after green roof installation, but the difference decreased after installation.

Parallel trends plots for 8 example green roofs and their corresponding control roofs are shown in Figure 2. The presence of parallel curves for all plots prior to green roof installation indicates that the green and control roofs respond similarly to environmental conditions, making them an appropriate match. The left column shows 4 examples of green roofs that successfully decreased roof LST relative to their corresponding green roofs, while the right column shows 4 example green roofs that did not. These examples demonstrate that green roof installation did not universally decrease LST for all rooftops studied.

The DiD regression results show the causal effects of the green roof installations on LST. The intercept term ($\beta_0$) was estimated to be 300.68. The coefficient for the time variable $P_t$ ($\beta_1$) was estimated to be 5.21. This indicates that, on average, there is an increase in LST in Washington, D.C., over time, regardless of the roof treatment status. The coefficient for the treatment variable $G_t$ ($\beta_2$) was estimated to be 4.93. This suggests that, on average, the green roofs had a higher LST compared to the control roofs, after accounting for other factors in the model. The coefficient for the interaction term $P_t \cdot G_t$ ($\beta_3$) was estimated to be -5.71. This implies that green roof installation has a moderating effect on the relationship between time and LST. The negative coefficient suggests that the green roofs experienced a smaller increase in LST over time compared to the control roofs. On average, the green roofs had a 0.14°C increase in LST after installation, while the control roofs had a much higher 5.16°C increase in LST over the same period.

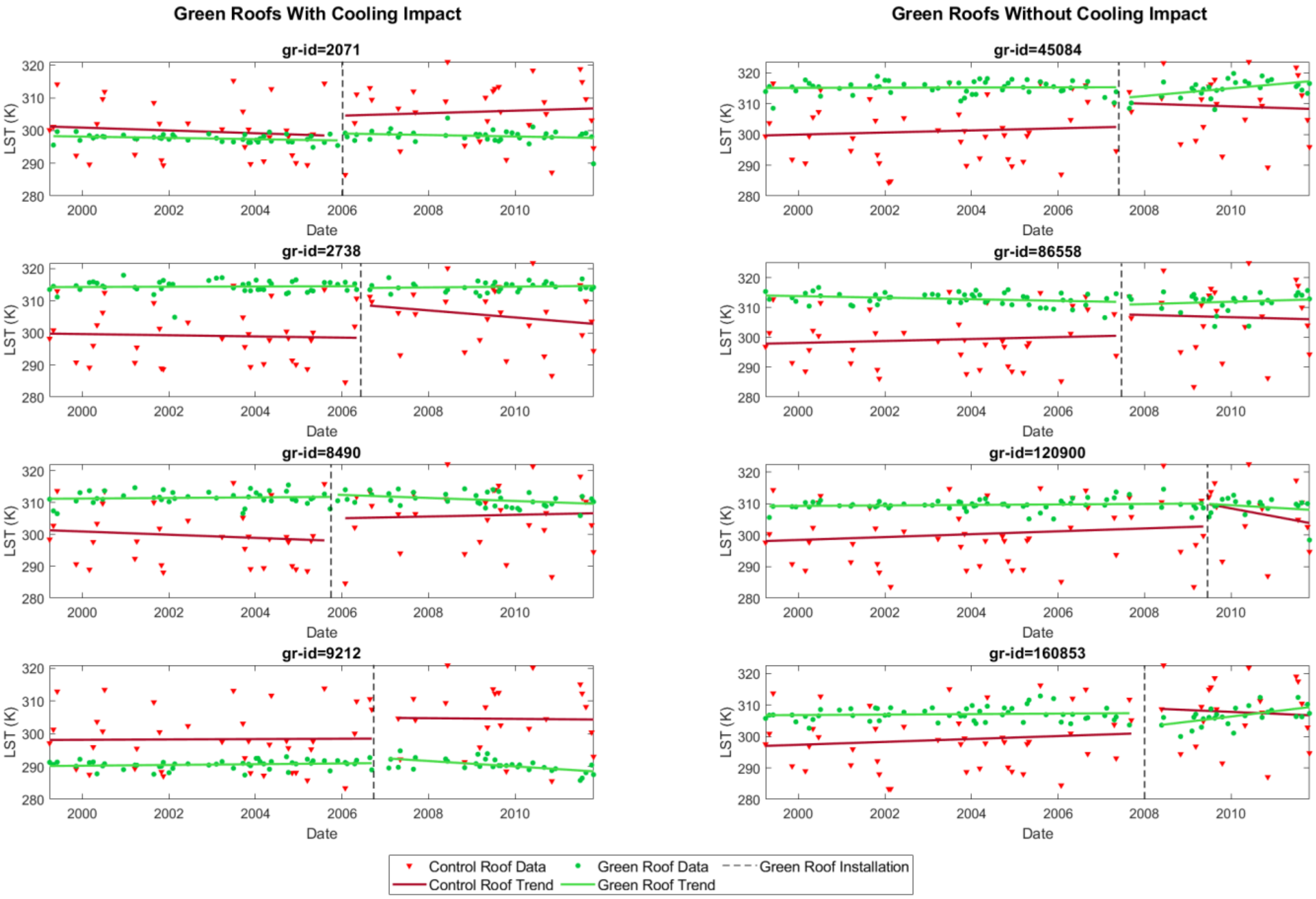

**Figure 2**. Parallel trends plots for 8 green roofs studied in Washington, D.C. The left column shows 4 green roofs that decreased LST relative to their respective control roofs, while the right column shows 4 that did not. Together, these examples demonstrate that not all green roofs in this study successfully cooled their roof surfaces relative to their controls.

However, overall, this model does not explain the variation in LST well. The R-squared value for the DiD regression model was 0.0552, indicating that the model explained only about 5.52% of the variation in LST. Further, the model had a very low F-statistic of 9.83e-51 paired with a very high p-value of 94.74, indicating that the model as a whole was not statistically significant in explaining the variation in LST.

## 4. DISCUSSION AND CONCLUSIONS

This study evaluated the cooling impacts of 337 green roofs in Washington, D.C., on 84 hot days between 1999 and 2011. The results suggest that there is significant variation in cooling performance between green roofs and further suggests that not all green roofs can fully mitigate warming trends associated with urban heat, in line with the findings of McConnell et al. (2021) [3]. There are several possible explanations for these results. Certain aspects of a green roof may make it a more effective cooling surface, such as its size, maintenance, plant type, growing medium depth, indoor energy consumption, rooftop structure, and location, as has been discussed in previous studies [3]. Additionally, certain environmental factors, such as time since last rainfall, may affect green roof performance. Certain aspects of the control roofs may also impact their ability to retain or reflect heat, such as albedo. For example, high-albedo white roofs can be cooler than green roofs [9]. Further work is necessary to identify the extent to which these factors affect rooftop LST and if their impacts are consistent among different kinds of green roofs in different cities and climates. Future studies could apply the method developed in this study with Landsat 8 LST data to evaluate the effectiveness of green roofs installed after 2013.

This paper successfully demonstrated an open-source method to apply publicly available data to evaluate the effectiveness of green roofs across a city in reducing rooftop surface temperatures. This low-cost method can aid policymakers and planners in empirically evaluating the cooling capacity of green roofs in their own communities. Using such a remote sensing method to evaluate the cooling impacts of green roofs at the city scale is especially useful in resource-constrained situations or for large cities with many green roofs, where deploying sensors is unfeasible.

Specifically for Washington, D.C., as the City implements policies such as the RiverSmart Rooftops Green Roof Rebate Program, data on the cooling impacts of green roofs are key to informing its efforts. This is especially important as this study's results support previous results that suggest that green roofs may not be as effective a solution for urban heat as some might hope [3]. As more cities around the world, including major cities like Chicago, IL, USA and Hamburg, Germany, continue to incentivize green roof installation, this method will be a valuable tool for planners and policymakers in assessing the effectiveness of their programs in mitigating urban heat.

## 5. REFERENCES

[1] O. Hoegh-Guldberg, D. Jacob, M. Taylor, M. Bindi, S. Brown, I. Camilloni, et al., "Impacts of 1.5°C of global warming on natural and human systems," *Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, 2018.

[2] B.A. Norton, A. M. Coutts, S. J. Livesley, R. J. Harris, A. M. Hunter, and N. S. G. Williams, "Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes," *Landscape and Urban Planning*, vol. 134, pp. 127–138, 2015, https://doi.org/10.1016/j.landurbplan.2014.10.018

[3] K. McConnell, C. V. Braneon, E. Glenn, N. Stamler, E. Mallen, D. P. Johnson, R. Pandya, J. Abramowitz, G. Fernandez, and C. Rosenzweig, "A quasi-experimental approach for evaluating the heat mitigation effects of green roofs in Chicago, Illinois," Sustain. Cities Soc., vol. 76, no. 103376, 2022, https://doi.org/10.1016/j.scs.2021.103376

[4] B. Stand, "GRHC Releases Green Roof Market Survey Results," *Living Architecture* Monitor, vol. 20, no. 3, pp. 2, 2018, https://static1.squarespace.com/static/5feb6d2cab06677bba637eba/t/60d0cad686744c03f87c1e80/1624296164200/greenroofs_lam_2018Fall.pdf

[5] M. L. Treglia, T. McPhearson, E. W. Sanderson, G. Yetman, and E. N. Maxwell. "Examining the distribution of green roofs in New York City through a lens of social, ecological, and technological filters," Ecol. Soc., vol. 27, no. 3, 20, 2022, https://doi.org/10.5751/ES-13303-270320

[6] S. Parison, M. Hendel, and L. Royon, "A statistical method for quantifying the field effects of urban heat island mitigation techniques," *Urban Climate*, vol. 33, no. 100651, 2020, https://doi.org/10.1016/j.uclim.2020.100651

[7] H. Sugawara, S. Shimizu, H. Takahashi, S. Hagiwara, K. Narita, T. Mikami, and T. Hirano, "Thermal Influence of a Large Green Space on a Hot Urban Environment," *Journal of Environmetnal Quality*, vol. 45, no. 1, pp. 125-133, 2016, https://doi.org/10.2134/jeq2015.01.0049

[8] "What are the band designations for the Landsat satellites?" U.S. Geological Survey (USGS), n.d., accessed May 30, 2023 from https://www.usgs.gov/faqs/what-are-band-designations-landsat-satellites

[9] A. M. Coutts, E. Daly, J. Beringer, and N. J. Tapper, "Assessing practical measures to reduce urban heat: Green and cool roofs," *Building and Environment*, vol. 70, pp. 266-276, 2013, https://doi.org/10.1016/j.buildenv.2013.08.021