Investigating New York City's Cool Roof Program Implementation Using Remote Sensing Through an Environmental Justice Lens

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Abstract: Cities such as New York City expose their residents to artificially elevated temperatures, known as the urban heat island effect (UHI). The UHI is a designed phenomenon where daytime and night-time temperatures are higher in cities than in outlying areas. As a result, UHI causes a range of socio-economic, public health, and ecological issues. Additionally, the UHI is unequally distributed among lower-income communities of colour, with fewer means to respond to the UHI and extreme heat events. Research has shown that increasing urban trees and cool roofs are two of the most effective strategies for mitigating UHI. This paper explores the effects and equitable implementation of New York City's cool roof program. Results show that cool roofs are an integral UHI mitigation strategy.

Keywords: Cool roof, remote sensing, urban heat island, environmental justice

1 Introduction

This paper explores the results of a remote sensing approach to assess cool roof implementation in New York City, USA, through an environmental justice lens. The length of this paper does not allow for an in-depth discussion of the remote sensing and programming methods used to create the dataset itself. Instead, the focus is on the results and their application to design and planning. This paper examines the observable results of New York City's (NYC) efforts to implement its Cool Roof Urban Heat Island (UHI) Mitigation Program. Specifically, we evaluated the following two questions:

1) To what degree are cool roofs providing land surface temperature mitigation?
2) To what degree are cool roofs implemented in the most heat-vulnerable neighborhoods?

Like most highly urbanized cities, New York City struggles with the UHI. The UHI is a designed phenomenon where daytime temperatures are 0.5 – 3.9 °C (1 – 7 °F) higher than temperatures in outlying areas, and night-time temperatures are about 1.1 – 2.8 °C (2 – 5 °F) higher (UNITED STATES ENVIRONMENTAL PROTECTION AGENCY 2014). The cause of the UHI is removal of predominantly vegetated land covers which are replaced by designed and constructed urban surfaces. Replacing woody and herbaceous vegetation with impervious surfaces dramatically reduces the natural cooling effects of shading and evaporation of water from soil and leaves (LEAL FILHO et al. 2017). Additionally, building density and building materials with large thermal admittance materials and narrow streets trap heat while reducing the natural cooling effects of wind (UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH 2022). Finally, cities have larger thermal mass and heat-storing surface areas than vegetated rural areas. Heat storage allows the UHI to build throughout the day and then reradiates the heat throughout the night, providing little to no cooling relief during extreme heat

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events, while worsening the health impact of extreme heat events by disrupting the restorative effects of sleep (CHAKRABORTY et al. 2019, LI et al. 2022).

The combination of UHI and extreme heat events lead to significant health concerns and a negative climate-energy feedback loop that exacerbates socio-economic problems. Specifically, heat waves are the deadliest weather-related disaster in various countries across continents (BORDEN & CUTTER 2008, SALLIS 2018). Additional health and social effects of combined heat waves and UHI include increased crime, decreased productivity, depression, alcohol consumption, and poor sleep (SAVERINO et al. 2021). These events increase energy consumption as residents attempt to keep cool, creating a negative energy demand-climate change feedback loop, further exacerbating the urban climate (TZEMPELIKOS & LEE 2021).

Rising heat is a significant concern, as not all people have equal capacity to respond to increasing UHI and heat wave events. SAVERINO et al. (2021) and HOFFMAN et al. (2020), among many others, have shown that many cities' historic zoning and redlining practices created hotter urban environments that low-income people of colour predominantly inhabit. This pattern is due to intentional, systematic disinvestment and design choices that have left fewer trees and more heat-absorbing, storing, and radiating materials in these neighbourhoods (WILSON 2020). As a result, the UHI has become a significant problem associated with urbanization and one that many researchers, practitioners, and communities are working to address.

Research has identified several best practices to mitigate UHI, but the two most effective are reducing heat-absorbing surfaces, such as roofs and asphalt paving, and increasing tree canopy cover (BARTESAGHI-KOC et al. 2021, PARK et al. 2021, TAMASKANI ESFEHANKALATEH et al. 2021). As a result, cities have launched tree planting and cool roof campaigns to mitigate UHI and extreme weather events, such as the MillionTrees NYC and NYC CoolRoofs campaigns. While the authors support an integrated approach to UHI mitigation and acknowledge the additional benefits urban trees provide, this paper focuses exclusively on cool roofs because they are cheaper than planting and maintaining trees and provide immediate UHI mitigation. Indeed, LI et al. (2014) demonstrated cool roofs with an albedo value of 0.7 could reduce the near-surface temperature by 3° C at the building scale.

To increase cool roof adoption, NYC adopted two laws, Local Law Number 33 of 2007 (section 1504.8) (1968 BUILDING CODE OF THE CITY OF NEW YORK 2007) requiring that all new buildings' roofs are white in color or EnergyStar rated as highly reflective for at least 75 percent of the area of the roof and Local Law Number 21 (LOCAL LAW 21 2011) which required any roof repairs or replacements to comply with section 1504.8 of Local Law Number 33 of 2007. Despite being 15 years into the cool roof program, NYC does not comprehensively understand to what degree cool roofs have been implemented outside of specific sub-initiatives, such as NYC °CoolRoofs program. As a result, the NYC Mayor's Office of Resiliency (MOR) wishes to evaluate the area of cool roofs implemented to date and its policies' effectiveness in reducing the city's UHI effect by increasing the albedo of the city's rooftops. To assist in identifying the most heat vulnerable communities the city created a Heat Vulnerability Index, consisting of temperature, amount of green space, households with air conditioning, percent of people in poverty, percent of black population, and heat related illness hospitalization rates. To achieve equitable heat mitigation cool roofs should be implemented in lower income black communities with high heat related hospitalization rates, high temperatures, little greenspace, and lack of air conditioning. Additionally, the New York City Housing Authority (NYCHA) should play a key role in adapting public housing to cool roofs. This paper seeks to fill this gap, while understanding the degree to which the implementation of the cool roof program is equitably distributed throughout the city and addressing the most heat-vulnerable communities.

2 Methods

To create a cool roof dataset, a combination of earth observation products was used to create roof albedo measurements using Python, r, and combined them with New York City geospatial data for analyses for the year 2020. The data and processing steps are outlined below.

2.1 Remote Sensing Data and Processing

The earth observation products consisted of cloud-free Landsat OLI Level 2 Science Products images from 2018 and 2016 (UNITED STATES GEOLOGICAL SURVEY 2022) and New York State ortho imagery from 2020 (HART et al. 1999). Landsat images were used to train an algorithm to measure reflectivity using ortho images, which are captured in early spring each year. First, we used the reflectance of Landsat images to measure the narrow band surface albedo using the method developed by LIANG (2001) for Landsat 5 images. To use similar wavelengths for Landsat 8 bands we modified Liang's Landsat formula to calculate Landsat shortwave albedo using SMITH's (2010) normalization method below:

$$\alpha_{short} = \frac{0.356\rho_1 + 0.130\rho_3 + 0.373\rho_4 + 0.085\rho_5 + 0.072\rho_7 - 0.0018}{0.356 + 0.130 + 0.373 + 0.085 + 0.072}$$

The narrow band Albedo data was used to train a linear regression to calculate roof reflectivity using the four bands from the New York State orthoimages (blue, green, red, and near-infrared).

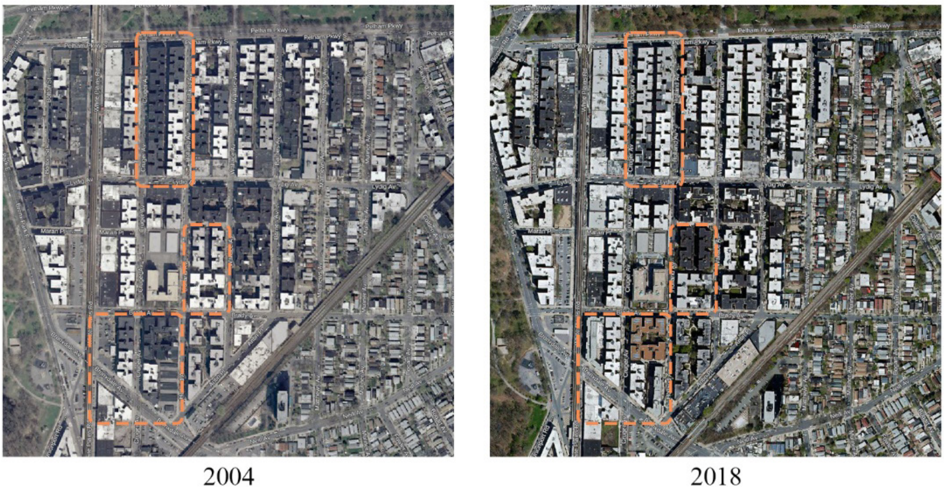

Fig. 1: Remotely sensed cool roof example from the Bronx with changes from non-cool roof to cool roof between 2004 and 2018 highlighted

The results provided a 0-1 scale for roof reflectivity, with 1 being a bright roof and 0 being a very dark roof. This scaled data was used to detect the buildings where roof reflectivity changed from a dark roof to a bright (cool roof). This algorithm is based on a query adjusted for the contrast of each image. Roofs with reflectivity values of 0.6 and less are dark roofs, and roofs with higher values were assigned to cool roofs. The data was ground-truthed using a subset of buildings to ensure reflectivity accuracy.

2.2 Vector Data and Processing

Vector datasets consisted of the following geospatial datasets New York City building footprints (Office of Technology and Innovation 2020), New York City borough boundaries (New York City Department of City Planning 2013), and New York City Heat Vulnerability Index (HVI) (NYC Department of Health and Mental Hygiene 2021). The HVI provides neighbourhood scores from 1 (lowest risk) to 5 (highest risk); as a composite of the following heat-vulnerability factors: mean land surface temperature, percent of households with air conditioners, percent of green space (i. e., tree, grass, or shrub cover), percent of people living in poverty, percent black people, and heat stress-related death rates. The remotely sensed roof albedo dataset was spatially joined to its corresponding vector building footprint. Finally, the building and HVI data were spatially joined and summarized at the New York City Borough and neighbourhood level for analysis.

2.3 Analyses

The following statistical analyses were used to answer to what degree cool roofs are providing land surface temperature mitigation: descriptive, correlation, and multiple linear regression statistics. We checked the data, and all assumptions were met. A two-way ANOVA was used to answer the question of to what degree are cool roofs being implemented in the most heat-vulnerable neighbourhoods?

3 Results

In 2020, NYC contained 158,521,974 meters^2 of rooftop of which 38% had cool roofs. NYC boroughs had an unequal distribution of cool roof implementation across boroughs and land uses (Figure 1). NYCHA is the leading residential cool roof installer in Queens and Staten Island boroughs, while non-NYCHA cool roof residential implementations are marginally leading in the Bronx, Brooklyn, and Manhattan (Figure 2). Table 1 contains a complete set of correlations; however, several correlations are noteworthy. The following variables negatively correlated with mean land surface temperature with a $p < 0.01$: percent green space (-0.30), percent cool roof area (-0.26), percent NYCHA cool roof area (-0.27), and percent residential non-NYCHA cool roof area (-0.23). The following variable positively correlated with mean land surface temperatures with a $p < 0.05$, percent black (0.27).

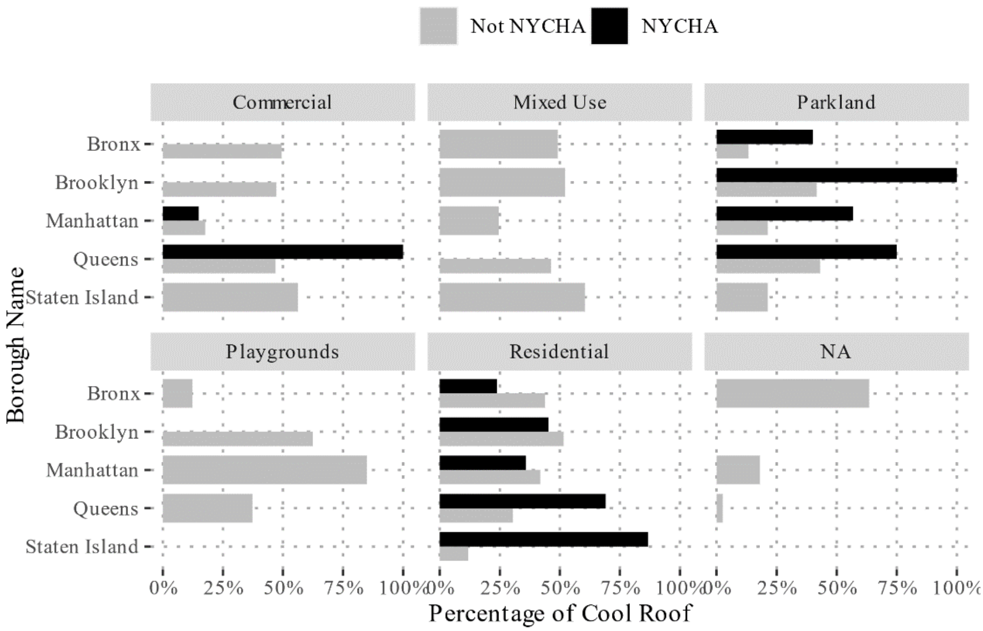

Fig. 2: Percent of non-NYCHA and NYCHA cool roof area per NYC Borough by land use

Table 1: Neighbourhood-level cool roof correlations for study variables for neighbourhoods with NYCHA buildings present

Variables	X1	X2	X3	X4	X5	X6	X7	X8	X9
1. Percent poverty	–								
2. Percent black	0.13	–							
3. Percent green space	-.33**	.21*	–						
4. Percent of households with air conditioning	-.57***	-.53***	0.12	–					
5. Heat-related hospitalization rate	.52***	.49***	0	-.63***	–				
6. Mean land surface temperature	-0.01	.27*	-.30**	-0.18	-0.01	–			
7. Percent cool roof	.50***	0.05	-.52***	-.28**	.35***	-.26*	–		
8. Percent residential NYCHA cool roof area	-0.02	-0.14	0.08	0.16	-0.02	-.27**	0.09	–	

Table 1 (continued)

Variables	X1	X2	X3	X4	X5	X6	X7	X8	X9
9. Percent residential non-NYCHA cool roof area	.52***	-0.01	-.59***	-.27**	.29**	-.23*	.94***	0.01	–
10. Percent commerical non-NYCHA cool roof area	.25*	0.16	-0.04	-0.17	.41***	0	.35**	0.19	.23*
N = 190, n = 95 P-values – * p < 0.05; ** p < 0.01; *** p < 0.001									

Multiple linear regression was conducted to determine the best linear combination of the percentage of cool roofs, green spaces, percentage of households with air conditioning, percent poverty, percentage of people identifying as black, and heat-related hospitalization rates for predicting mean land surface temperatures. Assumptions of linearity, normally distributed errors, and uncorrelated errors were checked and met. This combination of variables significantly predicted land surface temperature $F(6, 84) = 19.38$, $p < 0.001$, with three significantly contributing to the prediction. The adjusted R squared value was 0.5506. This indicates that 55% of the variance in land surface temperature was explained by the model or a large effect (Cohen 2013). Complete regression results are presented in Table 2, which suggests that the percentage of cool roofs and green spaces and the percentage of people identifying as black contribute most to predicting land surface temperatures.

Table 2: Simultaneous multiple regression analysis summary results ($N = 190$)

	Estimate	Std. Error	t value	Pr (>|t|)
(Intercept)	43.097800	2.636983	16.344	< 2e-16 ***
Percent cool roof	-6.504829	0.862647	-7.541	5.00e-11 ***
Percent green space	-0.096726	0.011520	-8.396	9.72e-13 ***
Percent of households with air conditioning	-0.020347	0.026979	-0.754	0.45287
Percent poverty	0.008937	0.013264	0.674	0.50230
Percent black	0.013874	0.004400	3.153	0.00224 **
Heat related hospitalization rate	0.128859	0.170495	0.756	0.45189
Significance codes: 0 *** and 0.001 ** Residual standard error: 0.889 on 84 degrees of freedom Multiple R-squared: 0.5805, Adjusted R-squared: 0.5506 F-statistic: 19.38 on 6 and 84 DF, p-value: 4.696e-14				

The authors found a statistically significant difference in cool roof implementation by heat vulnerability index rank ($F(4) = 2.1196$, $p < 0.01$ and by NYCHA/non-NYCHA ($F(1) = 3.2255$, $p < 0.01$. The interaction between heat vulnerability index rank and NYCHA/non-NYCHA is also statistically significant, $F(4) = 2.4450$, $p < 0.05$. A Tukey post-hoc test did not reveal significant pairwise differences among groups. Figure 3 shows that the percentage of residential cool roof cover tends to decrease as the HVI rank for NYCHA buildings goes up, while the percentage of residential cool roof cover tends to increase as the HVI rank increases for non-NYCHA buildings.

Table 3: Two-way analysis of variance summary results

	Sum Sq	df	F	Pr(>F)
(Intercept)	1.8610	1	23.6676	0.000002573***
Heat Vulnerability Index rank	0.6667	4	2.1196	0.08041(*)
NYCHA/non-NYCHA	0.2536	1	3.2255	0.07426(*)
Heat Vulnerability Index rank: NYCHA/non-NYCHA	0.7690	4	2.4450	0.04839*
Residuals	13.5242	172		
Significance codes: 0 ***, 0.001 **, 0.01 *, 0.05 (*), 0.1				

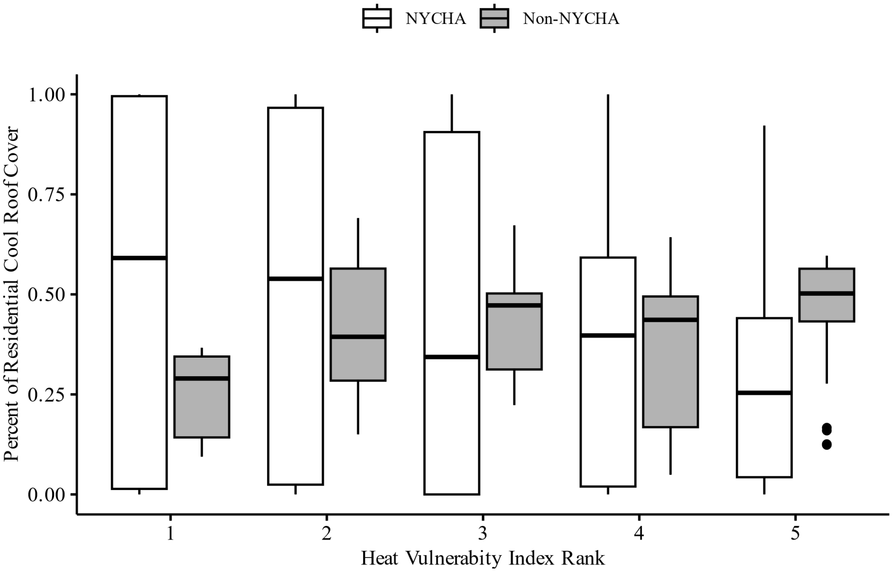

Fig. 3: Box plot comparing the percent of residential cool roof cover, heat vulnerability index rank, and NYCHA/non-NYCHA

4 Discussion

The regression results confirm previous research efforts and demonstrate the significant cooling capacity of vegetation and heat reduction of cool roofs. As stated earlier, the authors advocate for integrated heat mitigation strategies; however, the strength of the relationship between cool roofs and land surface temperature mitigation is worth further discussion. A recent article by TURNER et al. (2022) suggests that institutional actions and plans to address urban heat mention trees 50% more than any other mitigation strategy, with many cities relying on trees alone. These single-strategy approaches are a significant shortcoming in city planning and design. While trees are a critical long-term urban heat mitigation strategy, they often do not offer immediate UHI relief because they need time, space, and good growing conditions to mature. However, cool roofs can be installed relatively quickly, providing an immediate reduction in land surface temperature where it is most needed while trees grow to maturity – as such, planning policy should further integrate multiple short- and long-term mitigation strategies. These results also suggest that landscape architects should explore other uses for highly reflective materials and surfaces where vegetation is low, and the need for UHI mitigation is high; for example, streetscapes, non-vegetated plazas, and parking lots can reduce the UHI.

The results demonstrate that NYC is progressing in implementing its Cool Roof program, but progress is slow, as most boroughs have approximately 50% or less cool roof cover. Additionally, the equitable implementation of the cool roof program in NYC is complex. Previous research (HSU et al. 2021, LI et al. 2022, SAVERINO et al. 2021) demonstrated that UHI disproportionately affected low-income communities of color due to less vegetation and cool roofs. While this is also true in NYC (SOLECKI et al. 2015), the results from this study suggest these relationships are weakening, likely due to two reasons. First, NYCHA provides strong leadership in implementing cool roofs on their affordable and public housing developments, as is evident by the NYCHA and non-NYCHA variability in cool roof implementations between boroughs. NYCHA's efforts offset the income outliers of boroughs like Manhattan. Second, NYC has many policy requirements, building codes, job training programs, and incentives that mandate and encourage cool roof implementation, particularly in vulnerable communities. Cities looking to transform their UHI through cool roofs should identify a community-leading organization and leverage a multi-pronged approach using design guidelines, policies, and incentives. Despite these encouraging results, one concern emerged. NYC created the HVI ranking scheme to guide conversations and UHI mitigation interventions. Yet, results highlight the relationship between increasing HVI ranks and lower NYCHA cool roof implementation.

Meanwhile, non-NYCHA cool roof implementation generally increases as the HVI rank increases. These results suggest that NYCHA is not addressing the most vulnerable identified by higher HVI ranks. However, future research should explore this connection further as other factors, such as roof replacement schedules and a priority placed on non-air conditioned buildings in lower HVI ranked areas, might be given a higher priority.

Future research will explore cool roofs in three ways. First, we will explore the degree to which critical policy interventions, promotional campaigns, incentives, and market implementation have affected the changes in the cool roof area over time. Second, the authors will disentangle the impacts cool roof changes have on neighbourhood aggregated land surface and air temperatures. Third, the research team will explore if current cool roof implementations and benchmarks will adequately mitigate future climate change-exacerbated UHI and extreme heat events.

5 Conclusion

As cities implement UHI mitigation strategies, they must consider cool roof retrofits and installations in combination with urban forest programs. Additionally, designers and planners must consider material choices and their impacts on the UHI, especially in vulnerable communities. Ensuring equitable UHI mitigation, and undoing systemic and historical UHI disparities, requires strong leadership or a guiding organization. As such, cities should provide tangible action plans and enable organizations, such as NYCHA, through a wide range of policy requirements and incentives. Simply put, cool roofs are one of the most affordable and fastest ways to mitigate the UHI.

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