ON THE USE OF 'COOL ROOFS' TO REDUCE RESIDENTIAL HEAT EXPOSURE DISPARITIES IN BOSTON, MA

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A "cool roofs" program targeted to the hottest, most vulnerable neighborhoods in Boston has the potential to significantly reduce urban heat islands and heat exposure disparities. Boston's hottest neighborhoods have the highest proportion of flat black roofs, such as those on our famous triple deckers, which absorb rather than reflect heat. Because of the proportion of this type of roof and housing stock in Boston, a targeted program to whiten or lighten residential rooftops would have a measurable impact on reducing extreme heat, improving thermal comfort, and reducing energy use in summer. A similar program has recently been piloted in Louisville, KY, offering lessons for potential implementation in Boston. While Boston's recent Heat Resilience Plan (City of Boston 2022) already highlights the need for a cool roof program, the focus is on commercial or city-owned property such as schools, and the intervention calls for grants to nonprofits rather than integration with Boston's existing residential programs. Boston has an opportunity to invest in a more focused program targeting the hottest, most vulnerable residential blocks.

BACKGROUND

Heat exposure represents a growing threat to Boston's public health, contributing to increases in morbidity and mortality, along with decreased academic achievement, adverse pregnancy outcomes, and a loss of labor productivity. Heat disproportionately impacts vulnerable populations such as older adults, people of color, and residents of low-income households leading to disparities in residential cooling demand across Boston (Figure 1; Tieskens et al. 2022). We use data from a scientifically peer-reviewed, statistical quantification of the impact of landcover composition/characteristics on temperatures across Boston (Smith et al. 2022) to quantify the reduction in heat exposure associated with landscape modifications such as tree planting and installation of highly reflective surfaces (e.g. cool roofs) and to consider how heat solutions could be implemented as part of (re)development initiatives to create a more equitable, sustainable, and resilient city for all Bostonians.

While cool roof and urban greening initiatives are both well-founded adaptation strategies for mitigating heat exposure, the existing landcover composition of a neighborhood often precludes opportunities for tree planting, especially within the most vulnerable communities which are characterized by high fractions of building and pavement cover. Our analysis points to the conversion of flat, dark residential rooftops across the city to cool roofs as a highly effective pathway towards reducing heat exposure disparities and improving the thermal comfort of Boston's most vulnerable residents.

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APPROACH

We conducted an analysis that combines data on all rooftops in Boston with temperature, social vulnerability (based on age, poverty rate, language barriers, living situation, and racial composition), and tree canopy to the individual city blocks where targeted rooftop interventions can be most effective in cooling the city. We stratified the residential population of Boston into 10 equal size groups based on their "cooling demand" (a metric that accounts for average temperature, population density, and population vulnerability) to 1) characterize existing trends in landcover composition and building structure across the groups and 2) to estimate the temperature impacts of realistic tree planting and cool roof scenarios across groups. Full methodological details are provided in the appendix.

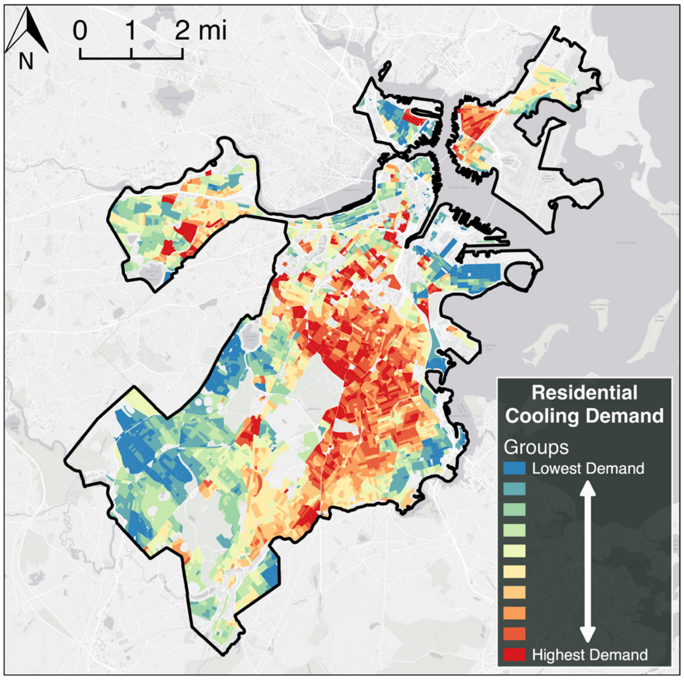


Figure 1. *Map of residential cooling demand at the city block scale, where residential cooling demand represents a metric that accounts for average temperature exposure, population density, and population vulnerability (Tieskens et al. 2022) High demand blocks are the hottest, most dense areas of Boston with the most vulnerable residents.*

KEY FINDINGS

❶ **Dark roofs are strong absorbers of sunlight and therefore tend to drive warmer temperatures in and around the building, increasing the health risks of extreme heat exposure.** Rooftops account for 20% of the total land area of Boston and have a large influence on local microclimates due to their direct exposure to the sun and sky. Dark roofing materials tend to absorb sunlight and subsequently release the absorbed energy as thermal emissions inter the lower atmosphere. In contrast, lighter colored roofing materials absorb a much smaller fraction of incident sunlight and instead reflect most of the incoming sunlight away from the surface. Long-term observations of surface temperature in Boston show that at the city block scale, an increase in solar reflectivity of 10% will reduce average daytime summer surface temperatures[1] by more than 3 °F within the block.

❷ **Boston residents in the hottest, densest, most vulnerable neighborhoods tend to live in buildings with flat, darker roofs.** We found a high concentration of buildings characterized by flat, dark roofs, such as triple deckers, in the most vulnerable neighborhoods. Flat, dark roofs account for over 50% of the roof area within the most vulnerable communities, compared to just 23% of roof area within the least vulnerable communities, highlighting the role of building structure in observed heat exposure disparities (Figure 2).

❸ **As has been widely reported, these hottest and most vulnerable neighborhoods also have considerably less tree canopy. Perhaps less well known is that they also have less plantable area, more buildings, and hence more rooftop area.** Landcover composition is a primary driver of temperature variability across Boston, where neighborhoods with a high amount of greenspace receive cooling benefits from the shade and activity of vegetation. Urban greening initiatives are incredibly important to improving quality of life, improving air, and creating attractive spaces. But our analysis shows they are less viable as a cooling intervention in the hottest places, as the amount of immediately plantable area (defined as the sum of grass and bare soil cover) in these areas is 20% lower than the citywide average.[2] In contrast, residential communities with the highest "demand" for cooling have on average 14% more building roof area than the citywide average, pointing to modification of rooftop reflectivity as a high impact intervention (Figure 2).

1 Measured by satellites, daytime land surface temperature is typically warmer than air temperature as surfaces absorb heat during the daytime and release it back at night.

2 We note, of course, that the city has an opportunity to convert areas that are currently not plantable, such as parking lots, into greenspace.

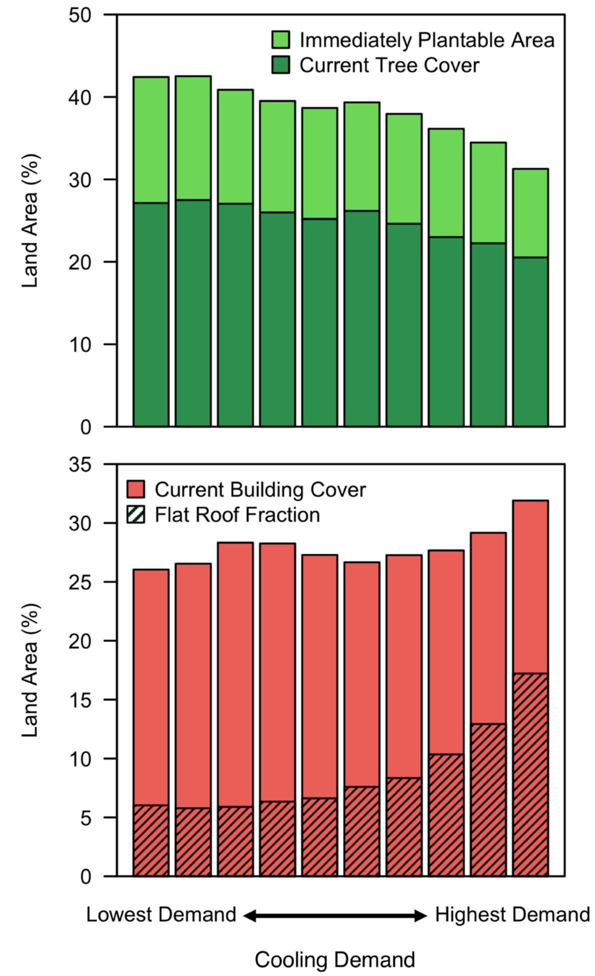


Figure 2. *Comparison of greenspace (top) and building area (bottom) trends across ten equal size groups of residential cooling demand in Boston. Groups correspond to the ten groups defined in Figure 1.*

❹ **The conversion of residential flat, dark roofs to cool roofs reduces disparities in average summertime heat exposure.** Currently, residents living in the most vulnerable city blocks experience average daytime summer land surface temperatures that are 3.0 °F warmer than the average temperatures in the least vulnerable city blocks. We simulated the temperature impacts associated with the conversion of all residential buildings with flat, dark roofs to cool roofs, finding that following conversion, the mean summertime temperature disparity between the most vulnerable residents and least vulnerable residents would decrease by 37%, from 3.0 °F to 1.9 °F (Figure 3).

❺ **Louisville, KY implemented a cool roof program, which may offer a starting place for a comparable program in Boston.** The Louisville "Cool Roof Incentive Program" offers $1 per square foot for new or retrofit flat, steep-slope, or low-slope light/white rooftops on residential and commercial buildings. They have varying maximums depending on a variety of factors, with an average incentive of $2,206. Funding is targeted to the hottest districts. The City reports that they worked closely with contractors, who were motivated to advertise the program to prospective customers. They projected that it both lowers temperatures and reduces energy demand, such as from air conditioners. As of September 2022, the program has resulted in the installation of over 1 million square feet of cool roofs across 260 buildings.

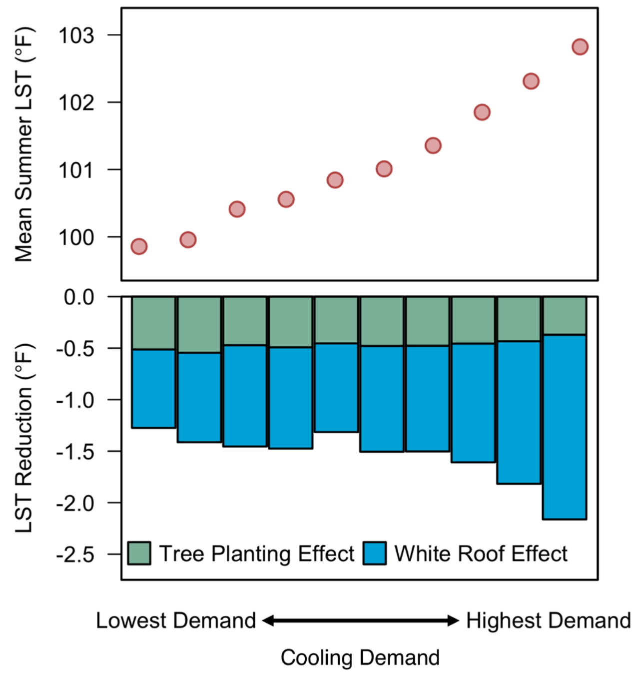


Figure 3. *Top: Long-term average summer daytime land surface temperature (LST) across 10 equal size groups of residential cooling demand in Boston. Bottom: Estimated average summer daytime LST reductions associated with the replacement of all plantable area with canopy cover and the conversion of all flat, dark roofs to cool roofs across 10 equal size groups of residential cooling demand in Boston. Groups correspond to the 10 groups defined in Figure 1.*

OPPORTUNITIES & POTENTIAL NEXT STEPS

Incentivize white/light roof adoption or resurfacing in residential buildings with flat, dark roofs. In line with the cool roof program envisioned in the City of Boston's 2022 Heat Resilience Plan that aims to prioritize buildings in areas with elevated heat exposure and increased prevalence of Bostonians with heat-related health risks, our analysis provides guidance for identifying high-impact regions to target. Rooftops in Residential zoning subdistricts comprise over 60% of rooftop area within the City of Boston,

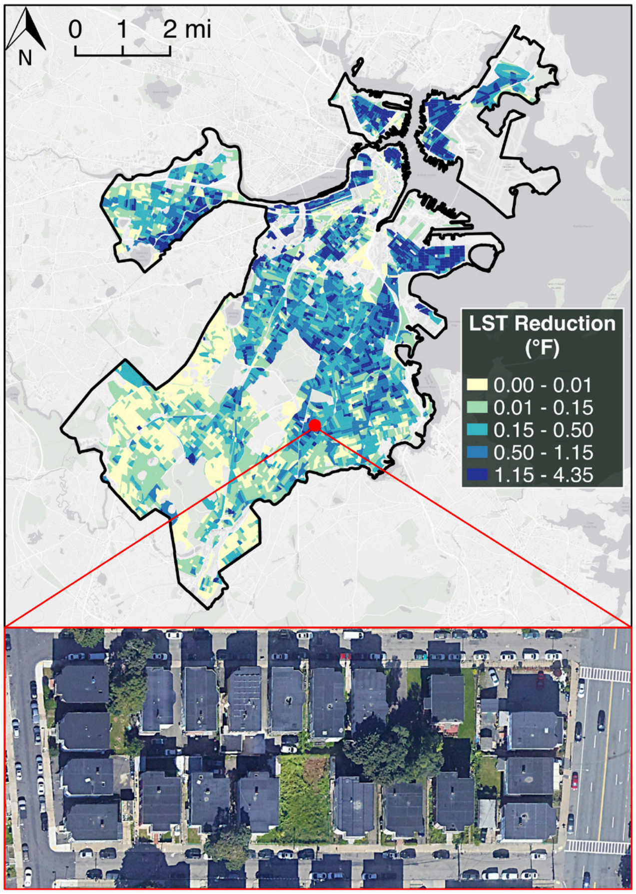


Figure 4. *Top: Mean summer land surface temperature reduction associated with the conversion of flat, dark roofs to cool roofs at the city block level. Bottom: Example of a block composed entirely of triple deckers with flat, dark roofs in Mattapan. City blocks similar to the block highlighted here represent blocks with a high potential for reduced heat exposure from the implementation of cool roofs. We estimate an average summer land surface temperature reduction of 2.1 °F in this particular block.*

highlighting residential buildings as a priority for climate-sensitive design interventions. Furthermore, the city blocks with the highest residential demand for cooling are characterized by a high proportion of buildings with flat, dark roofs (Figure 2; Figure 4).

> *"Our analysis supports the heat benefits of cool roofs and proposes an actionable pathway for Boston to equitably and optimally target local areas for intervention."*

The notion of maximizing rooftop solar reflectivity for climate resiliency is a well-established concept, but has heretofore been limited in implementation by a lack of research on optimal deployment. In 2009, United States Secretary of Energy and Nobel-prize winning physicist Steven Chu touted the benefits of cool roofs, stating that the adoption of cool roofs and cool pavements could result in the "equivalent of reducing the carbon emissions due to all the cars on the road for 11 years." Our analysis supports the heat benefits of cool roofs and proposes an actionable pathway for Boston to equitably and optimally target local areas for intervention (Figure 4).

Our analysis produced a spatially explicit dataset that the city could use in identifying priority blocks, within Boston's hottest neighborhoods, where a focused residential cool roofs program could yield the greatest benefits for residents. Table 1 shows city blocks highlighted by our analysis as potential targets based on a range of example objectives, including identification of the largest overall temperature impact, the largest temperature impact within the highest residential cooling demand group, and largest temperature impact across triple decker-dominated blocks.

The 2022 Heat Resilience Plan found that heat is experienced in a variety of ways across the city and emphasized solutions that address the underlying factors that result in a greater heat burden for some residents. A pilot program aimed at converting the rooftops of high-priority city blocks from flat, dark roofs to cool roofs provides opportunities for Boston to not only implement cool roof technology in the hottest and most vulnerable neighborhoods in a cost-effective manner, but also to install temperature sensors to monitor the local temperature changes and survey residents on perceived changes as part of the heat sensor network proposed in the Heat Resilience Plan. A targeted, residential cool roof incentive program in Boston offers a solution towards a more just, equitable, and resilient city. ■

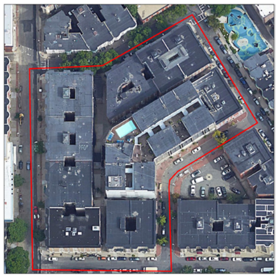
Priority	Neighborhood	Bounded By	Building Cover (%)	Tree Canopy Cover (%)	Estimated LST Reduction (°F)	Aerial View
Largest LST Reduction Overall	Fenway	Stoneholm St., Edgerly Rd., Hemenway St., Norway St.	68.7	5.9	-4.4	
Largest LST Reduction in Highest Residential Cooling Demand Group	Roxbury	Waldren Rd., Westminster Ave., Wardman Rd., Walnut Pk.	56.6	6.5	-3.7	
Largest LST Reduction in Majority Triple Decker Block	South Boston	Winfield St., E 7th St., Sanger St., E 8th St.	55.3	1.8	-3.9	

Table 1. *Description of example city blocks that could be selected for cooling interventions based on three different example priority criteria.*

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APPENDIX

1. Calculation of Residential Cooling Demand

Residential cooling demand is calculated at 30-meter spatial resolution based on a heat risk exposure index defined in Tieskens et al. (2022) as:

$$HRI = HVI_i \times P(hwday)_i \times POP_i$$

where the heat risk exposure index (HRI) at 30-meter pixel i is calculated by multiplying the heat vulnerability index (HVI; derived from American Community Survey data on age (percentage of people over 65 years), poverty (percentage of people with income below the poverty line minus percentage of people enrolled in higher education to account for students), language barriers (percentage of people speaking English less than well), vulnerable living situation (percentage of people older than 65 living alone), and racial composition (percentage of non-white people)) by the probability for local heatwave conditions ($hwday_i$) by the residential population (POPi) to account for heat exposure. 30-meter pixels were aggregated to the census block level by computing the mean HRI for all pixels with a pixel centroid falling within the boundaries of each census block across the city. The 10 equal size residential demand groups were then determined by computing the deciles associated with the aggregated HRI values.

2. Calculation of Landcover Composition and Building Characteristics

The landcover composition of each census block across the city was calculated with the 2019 high-resolution landcover product for the City of Boston produced by the University of Vermont Spatial Analysis Laboratory. The landcover product maps the spatial distribution of seven landcover classes including tree canopy, shrubs/grass, bare earth, water, buildings, roads, and other paved surfaces. Immediately plantable area was defined as the sum of shrubs/grass and bare earth. The percent of tree canopy, plantable area, and building cover was computed for each census block by dividing the land area of each landcover type by the total land area of the census block. Land cover percentages were then averaged across the 10 residential cooling demand groups described above to characterize the landcover trends within each group. Flat roof fraction was determined using roof structure information provided by fiscal year 2022 property assessment data.

3. Estimation of tree planting and cool roof temperature impacts

The sensitivity of daytime summer land surface temperature in Boston to landcover composition and reflectivity (or albedo) was determined with a spatial regression analysis at the census block scale in Smith et al. (2022). We use the values reported in Smith et al. (2022) to estimate the expected temperature reductions associated with tree planting and increases in albedo at the census block scale. To determine the temperature impacts of tree planting, we determine the potential increase in tree canopy cover for each census block based on the amount of immediately plantable area. We assume a temperature reduction of -0.14 °F for each percent of bare earth replaced with tree cover and a temperature reduction of -0.04 °F for each percent of grass cover replaced with tree cover (Smith et al. 2022).

To determine the temperature impacts associated with the conversion of flat, dark roofs to cool roofs, we assign an albedo of 0.5, which represents the minimum solar reflectance for flat roofs required to qualify for the City of Louisville's Cool Roof Incentive Program, to each flat, dark roof within each census block and subsequently recalculate the theoretical albedo of the land surface at 30-meter spatial resolution based on the area-weighted mean albedo of each 30-meter pixel, accounting for the increased building albedo. We validate this methodology by comparing the theoretical increase in albedo at 30-meter spatial resolution in Boston with observed increases in albedo due to the implementation of white roofs in Louisville, KY. The theoretical cool roof albedo at 30-meter spatial resolution is then aggregated to the census block scale by computing the average albedo at 30-meter spatial resolution within the census block. We assume a temperature reduction of -0.34 °F for each albedo increase of 0.01 at the census block scale (Smith et al. 2022).