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LETTER

Potential impacts of cool and green roofs on temperature-related mortality in the Greater Boston region

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Abstract

Many cities are developing mitigation plans in an effort to reduce the population health impacts from expected future increases in the frequency and intensity of heat waves. To inform heat mitigation and adaptation planning, information is needed on the extent to which available mitigation strategies, such as reflective and green roofs, could result in significant reductions in heat exposure. Using the Weather Research and Forecasting (WRF) model, we analysed the impact of green and cool (reflective) roofs on the urban heat island (UHI) and temperature-related deaths in the Greater Boston area (GBA) and New England area (NEA) in summer and winter. In the GBA, green and cool roofs reduced summertime population-weighted temperature by 0.35\(^\circ\)C and 0.40\(^\circ\)C, respectively. In winter, green roofs did not affect temperature, whereas cool roofs caused a temperature reduction of 0.40\(^\circ\)C. In the NEA, the cooler summers induced by green and cool roofs were estimated to reduce the heat-related mortality rates by 0.21\% and 0.17\%, respectively, compared to baseline. Cool-roof-induced temperature reduction in winter could increase the cold-related mortality rate by 0.096\% compared to baseline. These results suggest that both green and cool roofing strategies have the potential to reduce the impact of heat on premature deaths. Additionally, the differing effects in winter suggest the need for a careful consideration of health trade-offs in choosing heat island mitigation strategies.

1. Introduction

Both extreme heat and cold weather conditions can have negative impacts on human health through a variety of mechanisms \([1, 2]\), and global warming could lead to greater impacts \([3–5]\). Research suggests that more than 70,000 deaths were attributable to extreme heat conditions over Europe in August 2003 \([6]\). More than 50,000 people died during the 2010 heatwave in Russia \([7]\). Future projections suggest that summertime warming of over 2\(^\circ\)C may occur across the north-eastern part of the US by the 2090s \([8]\). Furthermore, the US population will increase by 81.4\% from 2020 to 2060 and will be mostly concentrated in urban areas and the over-65 age group \([9, 10]\), which will further increase the potential for adverse health outcomes in urban areas \([11]\). Mitigation strategies are urgently needed to reduce the health impacts of warming.

Several mitigation strategies to reduce extreme heat exposure have been proposed \([8, 12, 13]\). Roofing strategies are the most studied measures, considering roofs receive large amounts of solar radiation in urban areas, as a result of which roofs have great potential for regulating urban temperature \([14]\). In general, roofing strategies include both green roofs and cool roofs (which in this study represent reflective roofs) \([14, 15]\). Many studies have confirmed that both roofing strategies can effectively reduce localized outdoor warming to protect people from overheating and reduce heat-related mortality, offering a considerable public health benefit for urban residents \([16–18]\). While the functional processes of green and cool roofs are different \([19]\), cool roofs...
increase the amount of incoming solar radiation that is reflected back to space (and thus not absorbed as heat) by increasing the albedo of roofs; in contrast, green roofs increase the evaporation of water by soil and vegetation on rooftops [15]. These different mechanisms may change the relative impacts of these strategies on climate conditions despite summertime cooling. Regarding cool roofs, in Athens, research shows that the application of cool roofs resulted in a 0.5 °C reduction in winter [20]. Additionally, in Italy, research found that the proposed cool roof produced maximum winter overcooling by up to 1.2 °C [21]. Regarding green roofs, an observational study in Hong Kong found that green roofs offer passive and effective warming of indoor space in winter [22]. Additionally, a field experiment in Pennsylvania found that green roofs reduce the heat flow through the roof and keep the indoor temperature at a certain level during the winter [23]. All these studies confirm that cool/green roofs will impact not only extreme heat in summer but also other seasonal temperature conditions, such as cold in winter.

To propose a better strategy, many studies have tried to compare the various climate impacts between cool roofs and green roofs [8, 24]. Major studies have focused on comparing the cooling efficiency of cool roofs and green roofs during summer or extreme heat days [9, 14, 25]. However, as mentioned above, roofing strategies will not only cool extreme heat but also affect winter temperature. That is, they may not only reduce heat-related mortality but also impact cold-related mortality. In particular, recent evidence suggests that cold-related mortality does not decline significantly with warmer weather backgrounds during winter [26–28], especially in areas located in mid-high latitudes, such as the New England area (NEA) [29]. Therefore, we should extend our focus beyond making cooling comparisons.

In many recent studies, researchers have tried to assess the effectiveness of green/cool roofs using the Weather Research and Forecasting (WRF) model coupled with the single-layer urban canopy model (UCM). For instance, in Melbourne, increases in the share of green roofs from 30% to 90% would reduce the maximum surface urban heat island (UHI) effect by 1 °C–3.8 °C during heat wave days. At the same time, increases in roof albedo from 0.50 to 0.85 would reduce the UHI effect from 2.2 °C–5.2 °C [30]. In the US, using the WRF/UCM, researchers found that the future UHI can be almost completely offset by adopting cool roofs in Phoenix and New York City and be partially offset by adopting green roofs [25]. Additionally, in Porto, researchers found that the application of cool roofs induced a stronger cooling effect than green roofs under a future heat wave. All of these studies confirm that the WRF/UCM model has the ability to evaluate the climate impact of green roofs and cool roofs in various areas, providing basic model methods for our cross-seasonal research.

In the present study, to summarize, our objective is to quantify the impact of green and cool roofs on temperatures in both summer and winter and to assess the potential health implications of those temperatures. The time periods of this study cover the whole winter (1 December 2015, to 29 February 2016) and summer (1 June 2016, to 31 August 2016) in 2016. We selected the NEA as our study area; the NEA covers the Greater Boston area (GBA), as shown in figure 1(a). The two questions of this study are as follows: 1. What impacts will green and cool roofs have over summer and winter across the GBA and NEA? 2. How might temperature-related mortality be affected in both seasons?

2. Method

2.1. Model description

In this study, we use version 3.8.1 of the WRF model, including a UCM, to investigate the effects of both cool and green roof strategies on the 2 m surface air temperature in the NEA and GBA. The regional distributions are shown in figure 1(a). The WRF model is a state-of-the-art and fully compressible Earth system model developed collaboratively by the National Oceanic and Atmospheric Administration (NOAA), the National Center for Atmospheric Research (NCAR) and other institutes. It has been widely utilized in urban canopy-level modelling [8].

The WRF model provides several parameterizations that can be used to simulate processes that occur at a fine scale. We have chosen several parametrizations based on related research, and they are described in detail in table S1 (in the supplementary material available at https://stacks.iop.org/ERL/15/094042/mmedia). In terms of the urban region, the UCM resolves surface-atmosphere exchanges for three kinds of impervious areas (high-intensity industrial and commercial areas, medium-intensity residential areas and low-intensity residential areas). It takes many important parameterizations of the urban canyon environment into consideration, including the solar azimuth angle, the orientations of an urban canyon and the shadowing effects of buildings [31]. It can reproduce the exchange process between the air temperature at the top of the canopy with that of the lowest level of the atmosphere by incorporating all the factors within the urban canopy, making it possible to further simulate and estimate the impact of roof measures. To establish our UCM simulation, we list some important parameterizations of the urban canyon environment in table S2.

The 2016 National Land Cover Database (NLCD) is used to adjust the land cover classifications in WRF/UCM simulation. We use three kinds of impervious surface data from the NLCD to compute grid cell-specific impervious fractions [32]. The spatial
data of grids dominated by the three kinds of urban land use noted above are shown in figure 2.

In addition, some related studies of Los Angeles found that adjusting some observed land surface properties, such as the green vegetation fraction and leaf area index, can improve model simulations compared to meteorological observation data [33]. Therefore, in this study, we used Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data to modify every grid cell-specific green vegetation fraction and leaf area index to improve the simulation results.

2.2. Simulation domain

Three nested domains are simulated with resolutions of 27 km, 9 km and 3 km. As shown in figure 1(a), the outermost domain (d01) covers most of the north-eastern part of the US, the middle domain (d02) covers the NEA and its surrounding states, and the innermost domain (d03) covers all of the NEA and GBA. As the setting of the WRF model, the inner domain receives boundary conditions from the outer domain. The outermost domain uses operational global final (FNL) data as its boundary conditions. FNL data have a temporal resolution of 6 h with
a spatial resolution of 1°x2°1 and are obtained from the Global Data Assimilation System (GDAS).

2.3. Simulation design
We used WRF to estimate temperatures based on three scenarios: BASELINE, COOL_ROOF and GREEN_ROOF. BASELINE is the scenario in which roof albedo is set to 0.13 and there are no green roofs over the study area. The albedo value of traditional roofs is referenced in related research in the US [8, 32].

The COOL_ROOF scenario assumes uniform application of a 0.88 albedo on all roofs in urban areas. We selected this albedo value based on related research that quantifies the impact of cool roofs on the urban climate in the US [8]. In addition, several roof coatings in the Environmental Protection Agency Energy Star roof product list (https://downloads.energystar.gov/bi/qplist/roofs_pro duct_list.pdf) reach values in this range; for instance, the albedo of the Alpha 8, Energy Seal Coating and Acrylux products is 0.88, 0.89 and 0.87, respectively. This scenario represents an increase of 0.75 relative to the baseline roof albedo. Although the surface albedo in the COOL_ROOF scenario can be set higher, we selected the albedo that is more likely to achieve this aim and would induce an obvious impact.

The GREEN_ROOF scenario assumes that 80% of urban roofs in the study area have an evaporating surface with water availability on the roofs, amounting to a ‘perfect’ green roof scenario in terms of the redirection of available energy towards latent heat instead of sensible heat. Based on related research [30], the green roofs in the UCM consist of three additional layers: a grassland layer, a loam soil with a depth of 15 cm, and a 15 cm growing medium layer. The choice of coverage of green roofs was based on active heat island community actions in the study area. The Boston Green Buildings Zoning Code (BPDA 2017) requires all private developers to adhere to the US Green Building Council’s Leadership in Energy and Environmental Design (LEED) certification standards. One point that counts towards this certification can be obtained by using green or cool roofs. In addition, according to the Annual Green Roof Industry Survey in 2017, the green roof installations in Washington, DC, and New York City are over 1 000 000 and 500 000 square feet, respectively. The coverage of green roofs in US cities is likely to continue rising [34]. Although the coverage of green roofs in the GREEN_ROOF scenario can be set higher for the urban area in this study, we selected the coverage change that is more likely to achieve this aim in the near future.

Temperatures were simulated by WRF for the three scenarios over the entire winter and summer in 2016. Considering the intrinsic uncertainties in the initial part of the simulation, the first 12 h were discarded as the ‘wind-up’ period.

2.4. Health impact calculations
For the changes in the exposure level, we calculated the extreme cold and heat exposure level over the GBA based on daily mean temperature, which is calculated using gridded hourly 2 m air temperature output from the WRF model and population weighting obtained from LandScan’s gridded resident population with a 1 km resolution [35]. For this purpose, we further adjusted the population data to the same resolution as the setting in the WRF output, as shown in figure 1(b). To estimate changes in temperature-related mortality, we used the exposure-response value reported in [29], which is a 1% (95% confidence interval (CI): 0.6%, 1.5%) increase in mortality for every 1 °C increase in the daily mean temperature above the threshold of 16.39 °C in summer and a 0.6% (95% CI: 0.3%, 0.9%) increase in mortality for every 1 °C decrease in the daily mean temperature below the threshold of 2.35 °C in winter.

3. Results
We selected hourly temperature data outputs from the domain of the WRF model. Hourly observation data from four weather stations within the domain were obtained and compared with the simulation results from the nearest grid point. The spatial distributions of these four weather stations are shown in figure S1, and the comparison between the simulated and observed temperatures is shown in table S3. The comparison results show that the modelled 2 m air temperature data are well in line with the observed data, confirming that the results of our model are able to effectively capture diurnal and spatial variations in temperature.

3.1. Spatial patterns of temperature change
Figure 3 shows the spatial distribution of the temperature differences simulated under the two roof intervention scenarios compared to the baseline at 02:00 and 14:00 local standard time (LST) during two seasons.

In summer, the two roofing strategies yielded similar patterns of temperature changes; a higher cooling effect occurred in the urban core of the GBA at 14:00 LST. However, changes in the rural surface temperature are also observed, especially in the downwind area of the city where urban cooling would result in rural cooling under the impact of reduced heat advection from urban areas, as shown in the northern part of the GBA in figure 3. At 02:00 LST, these cooling trends become weaker and transition to a certain warming effect across the southern part of the GBA.

In winter, employing cool roofs consistently reduces the temperature in the urban core, especially.
Figure 3. Summertime and wintertime 2 m temperature changes caused by cool roof and green roof strategies across the GBA.

Figure 4. Seasonal diurnal variations in urban 2 m temperature during summer (a) and winter (b) induced by the COOL_ROOF and GREEN_ROOF strategies compared to the BASELINE strategy. All values are related to urban areas and the seasonal means of the urban air temperature. We accounted only for differences that are virtually certain (greater than a 95% probability) to be significant across the GBA.

at 14:00 LST. However, the temperature impact of green roofs is limited across the study area.

### 3.2. Diurnal cycle of temperature changes

Figure 4 shows the diurnal cycles of the 2 m air temperature changes associated with the two roof scenarios compared with the baseline result. The results show that the two roofing strategies lead to different diurnal patterns of temperature change. Overall, the adoption of cool roofs caused significant temperature reductions in both winter and summer, while the temperature reductions induced by green roofs occurred only in summer.

During summer, the reduction in the daytime temperature induced by both roofing strategies reaches its maximum around solar noon. The daytime temperature change induced by cool roofs is substantially greater than that induced by green roofs. Nighttime temperatures appear to warm slightly. During winter, green roofs had little impact on temperature changes throughout the day, while the daytime temperature showed an obvious decrease under the COOL_ROOF scenario.

### 3.3. Health impact of the two roofing strategies in the NEA

In this section, we first estimate the population-weighted exposure across the GBA associated with demographic data. Then, we calculate the potential heat- and cold-related mortality across the NEA.
Table 1. Temperature statistics under different scenarios for summer and winter. The values are population-weighted averages across the GBA.

|          | Summer          | Winter          |
|----------|-----------------|-----------------|
| BASELINE | 22.594          | 3.002           |
| GREEN_ROOF | 22.246          | 3.000           |
| COOL_ROOF | 22.190          | 2.604           |

Table 2. Estimated heat- and cold-related mortality rate changes for summer and winter in 2016 across the NEA. The winter numbers represent the growth in the mortality rate caused by temperature decreases due to the adoption of the two roofing strategies. The summer numbers represent the reduction in the mortality rate by temperature decreases due to the adoption of the two roofing strategies. The numbers in parentheses represent the 95% CIs based on the exposure-response coefficients.

| Scenario   | Winter         | Summer         |
|------------|----------------|----------------|
| GREEN_ROOF | 0.002% (0.001%–0.004%) | 0.170% (0.102%–0.255%) |
| COOL_ROOF  | 0.096% (0.048%–0.144%) | 0.210% (0.126%–0.315%) |

Based on the simulation results of the baseline scenario and the two scenarios with roofing strategies using the exposure-response coefficients from related research [29].

As shown in Table 1, under the GREEN_ROOF scenario, changes in the population-weighted average temperature exposure mainly occurred during summer, with the result being 0.34 °C lower than that under the BASELINE scenario. For the COOL_ROOF scenario, the population-weighted results are 0.40 °C lower and 0.39 °C lower than those of the BASELINE scenario during summer and winter, respectively.

The temperature changes induced by the adoption of the two roofing strategies during the two seasons across the NEA are listed in Table S4. As shown in Table 2, in summer, we estimate that 0.210% and 0.170% of the deaths attributed to summer heat could be avoided by implementing cool roofs and green roofs, respectively. However, the wintertime simulation results suggest that 0.096% of the deaths attributed to extreme cold could have been induced by cool roofs, while during this time the health impact of green roofs is not obvious.

Comparing the population-weighted temperature and temperature-related mortality in the COOL_ROOF and GREEN_ROOF simulations, we confirmed that cool roofs may reduce extreme heat exposure and the total number of heat-related deaths more effectively than green roofs under our assumption during summer; however, cool roofs have the potential to increase extreme cold exposure and related deaths during winter. For green roofs, although the cool influence is weaker than that of cool roofs during summer, it had little or no impact on cold-related mortality during winter.

4. Conclusions and discussion

In this study, the effect of green and cool roof strategies on the ambient temperature and related health impacts in summer and winter was investigated using the WRF model. The results confirmed that roofing strategies can play an important role in reducing summer heat exposures and related health risks. While the reductions in the near-surface temperature result in almost the same spatial pattern for the two different roofing strategies in summer, the physical processes that yield these patterns are different across the two roofing strategies. Green roofs reduce the temperatures of urban areas due to the increase in evapotranspiration. With cool roofs, cooling is induced by reflecting more incoming solar radiation. As a result, the two roofing strategies affect the local climate in different seasons in different ways. The daytime cooling under the COOL_ROOF scenario was greater than that under the GREEN_ROOF scenario. This finding is consistent with that of Gaffin [36], who showed that the albedo required on an ordinary roof without any green cover to reproduce the surface temperature change under a roof with green cover is in the range of 0.7 to 0.85 in New York. During winter, it is interesting to observe that the cool roof strategy still partially influences the temperature (no winter cooling was observed under the GREEN_ROOF strategy). This effect occurs because of the constant high reflection of radiation from cool roofs during the daytime in winter, which suggests that the adoption of cool roofs could increase the exposure to wintertime cold since cool roofs absorb less solar energy.

In addition, we explored the health effects of the green and cool roofing strategies. In summer, we estimated that cool roofs would reduce the population-weighted temperature by 0.40 °C over the GBA and reduce the overall number of heat-related deaths by 219 across the NEA. Additionally, green roofs could reduce the population-weighted temperature by 0.35 °C and prevent 177 heat-related deaths. Our assessment results are comparable to those of previous studies. Such studies show that, for example, increasing the roof albedo by a value of 0.62 in New York City would prevent 45 deaths during a heatwave [37]; a reduction in temperature due to a higher reflective coating could alter heat conditions to reduce heat-related mortality by 38% in Greece [38]; increasing the roof albedo by a value of 0.45 could save 32
lives in Baltimore and 22 lives in Los Angeles during a heatwave event [39]. However, these studies did not observe the health impact of the cool roofs in winter. In our analysis, during winter, cool roofs substantially reduced the population-weighted temperature by 0.40 °C over the GBA and increased cold-related deaths by 100 across the NEA. In contrast, green roofs had little impact on winter mortality due to the limited temperature changes induced.

Regarding the distribution of temperature-related mortality over the two seasons, the results of this study suggest that widely adopting green/cool roofing strategies across urban areas could effectively reduce heat-related morality, whereas adopting cool roofs could increase the amount of cold exposure during winter. This finding could be important for increasing the importance of health-related considerations in urban planning to adapt to future climate change.

We should also be aware of some implications and limitations of our study results. First, the performances of the green and cool roofs studied here are affected by coverage and albedo conditions. For green roofs, when the coverage area is modified, the performance of green roofs will change accordingly [30]. In addition, the green roof discussed here represents only a certain type of roof covered by grassland, which is modelled by the WRF/UCM model. As relevant research has pointed out [40], the climate impact of green roofs is affected by the species of vegetation, soil moisture, and other factors. For cool roofs, we emphasize that the influence of cool roofs discussed here is specific to a roof albedo of 0.88. As indicated by Li’s research [14], if the roof albedo changes over time due to, for example, dirt accumulation, its influence will also change. We chose to apply an albedo of 0.88 across all roofs in the COOL_ROOF scenario and assumed an 80% adoption rate of green roofs in the GREEN_ROOF scenario based on our goal of demonstrating the potential impact of a feasible near-future scenario of maximum weather effects and associated impacts on temperature-related health effects based on existing policies.

Second, temperature-related health effects are determined by the exposure level, which is more likely to be related to the indoor temperature. Currently, the amount of indoor heat exposure of individuals is sparsely observed, although a few studies have examined this issue, finding that in the eastern US, individual exposure is generally lower than that predicted by weather stations [41, 42]. Other studies show that some urban residents are exposed indoors to higher than ambient temperatures during heat events in summer [43]. However, the epidemiological research in this study is based on outdoor temperatures, as indoor temperature is beyond the scope of what can be simulated with a regional weather model.

Moreover, the effectiveness of these roofing strategies is impacted by other local climate conditions. One phenomenon observed from our results confirmed this hypothesis. During summer, the lower heat flux or weaker UHI effect over urban surfaces caused by cool/green roof adoption will weaken atmospheric instability and vertical mixing. At the same given boundary layer height, it will leave more area to the air from upwind. That is, the atmosphere is less affected by the surface conditions from urban areas, while it is more affected by advection from upwind areas, which for the GBA are warmer and more humid sea surfaces. Therefore, during summer, the stronger advection of moist and warm air from sea surfaces leads to an obvious increase in temperature across the southern part of the GBA. This increase is especially apparent at night, as shown in figure 3, when the heat island effect is supposed to be most pronounced. Thus, when the summer monsoon from the Atlantic Ocean intensifies in the future, the effectiveness of roof adaptation across the study area may be affected.

Future projections of temperature-related health effects are challenging due to the uncertainties of future infrastructure as well as demographic and socioeconomic changes in the future, which could alter the exposure-response function between temperature and mortality. In our study, we assumed a constant function. It will be helpful for future urban planning initiatives to consider more of these factors based on emerging research. Analyses of this kind can provide useful input to urban planners concerned with heat island adaptation in a changing climate.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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