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Massachusetts Institute of Technology

An integrated model for quantifying the impacts of pavement albedo and urban morphology on building energy demand

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ABSTRACT

This contribution details a high-resolution approach to estimate the net greenhouse gas (GHG) impact of changing pavement albedo in urban areas by accounting for both changes in air temperature and building energy demand (BED) caused by the albedo change. The approach uses machine-learning-based meta-models that allow stakeholders to estimate the impact of pavement albedo modification for specific, detailed neighborhoods in a rapid, computationally efficient manner. This method is applied to a case study involving all buildings and the adjacent pavements in Boston, MA. Results from the case study indicate that increasing pavement albedo reduces average temperature and usually reduces carbon emissions from BED for densely-built and medium-density neighborhoods while results from low-density neighborhoods were mixed. Model results suggest that increasing pavement albedo would lead to BED GHG benefits in 88% of Boston neighborhoods. Increasing the albedo of the 1,100 miles of roads in those communities would yield nearly 91,720 metric tons of reduced carbon emissions over the next fifty years.

Keywords: pavement albedo, building energy demand, urban morphology

1 INTRODUCTION

Urban surfaces, including roofs and pavements, play an important role in shaping the urban microclimate, altering its energy balance and contributing to the so-called urban heat island (UHI) effect [1]. UHIs have been associated with both increased energy demand from buildings and deleterious health outcomes [2]. As global average temperatures rise, the magnitude of these effects is only expected to grow. To address these concerns, public and private stakeholders have begun to implement mitigation strategies. Ideally, each UHI mitigation strategy would not reduce urban warming by creating other types of environmental burdens; if it did, decision-makers should have quantitative information about the tradeoffs they would make.

Much has been written about the net environmental benefit for the most commonly cited mitigation strategies including both "cool" roofs and additional greenspace [3-5]. One mitigation strategy that has not been extensively studied is "cool" pavements. Cool pavements alter the energy balance of the surrounding environment, typically through surface characteristics that reflect more solar energy. This characteristic is referred to as albedo, with higher values representing higher reflectance. Generally, there are two categories of climate-related effects related to pavement albedo [6]. The first is a direct radiative forcing (RF) that results from the reflectance of energy from the surface and back out of the atmosphere. The second effect is the change in energy demand from nearby buildings (subsequently referred to as building energy demand or BED) and the associated greenhouse gas (GHG) emissions from energy generation. We aim to fill a key gap in understanding this second effect of cool pavements. Specifically, we explore how the impact of cool pavements changes with urban form (i.e., morphology), using both a coupled physical-simulation model and a novel, machine-learning model developed from thousands of physical simulations. We then explore the net BED effects in the context of a case study of Boston, Massachusetts. Results from the case study suggest that increasing pavement albedo usually reduces carbon emissions from BED for densely-built and medium-density neighborhoods while results from low-density neighborhoods were mixed. Model results suggest that increasing the albedo would lead to BED GHG benefits in 88% of Boston neighborhoods. Increasing the albedo of the 1,770 km of roads in those communities would yield more than 90,000 metric tons of reduced carbon emissions over the next fifty years.

Recent research trends in building energy consumption entail models that consider a building in the context of surrounding buildings in a neighborhood [7]. These models have been effective for evaluating different building-level energy efficiency strategies. For large-scale energy modeling, on the other hand, urban energy balance models such as urban canopy models (UCM) have been widely adopted in the meteorological community. To reduce the computational cost, these models usually consider the simplest neighborhood context. Usually UCMs represent an urban region as a 1-D or 2-D canopy consisting of a single building and canyon floor, which is an oversimplified representation of urban morphology [8]. In reality, the components of the outdoor environment (buildings, streets, vegetation, etc.) have complex interactions with each other.

As computational power has become less costly, several research efforts have modeled the interactions between buildings and the surrounding environment, accounting for the outdoor energy balance and the indoor-outdoor energy exchanges [9-14]. Most of the modeling frameworks require a co-simulation environment between building energy simulation engines and urban-scale simulation engines, which capture effects at multiple scales. The earliest example of this type of modeling is from Kikegawa et al. who coupled a one-dimensional urban canopy meteorological model with a simple sub-model for building energy analysis [9]. Salamanca et al. developed a building energy model (BEM) within an urban canopy parameterization for mesoscale models [11]. Mauree et al. recently coupled the Canopy Interface Model (CIM) with CitySim, an urban energy modeling tool to simulate the energy performance of buildings with different urban forms and local climate [14]. While these coupled models were successfully implemented and validated against measured data, they were limited to a few variations of urban form and context within the investigated cities. Therefore, it’s difficult to generalize the results to other contexts. One exception is Quan et al. who conducted a parametric study of the density-energy relationship to explore how building density, building shape, and building typology jointly influence building energy performance. This work demonstrates the importance of urban morphology to energy questions but did not explore its impact on urban microclimate or the impact of surface characteristics [15].

Several studies have explored the climate implications of large-scale albedo modification related to agriculture [16–19]. We are aware of only two studies that have addressed the specific issue of how ground surface energy balance would affect BED. Yaghoobian et al. found a cooling load savings of 17% in buildings due to a reduction in shortwave radiation transfer from the ground to nearby buildings by using low-albedo ground surfaces [20]. In a later study, they found that increasing pavement albedo from 0.1 to 0.5 near a four-story office building in Phoenix would increase annual cooling loads up to 11% (33.1 kWh/m^2), while the annual heating load was not sensitive to such a modification [21]. Li et al. reported that the cooling effect of pavements has a positive correlation with the peak value of solar radiation intensity [22]. In another study, Vox et al. showed that the albedo of higher than 0.22 can result in a significant reduction of the surface temperature mainly in the warmest hours [23]. During the night-time hours, no change in the temperature was observed. These results indicate the potential of reflective pavements to have significant impacts on adjacent buildings. Haley et al. used results from a regional climate simulation and the EnergyPlus building energy simulation program [24] to assess the energy and environmental consequences of cool pavements in Los Angeles and Fresno, California. Their work also reinforces the fact that the net effect of increased incident radiation and reduced ambient temperature on building energy due to pavement albedo increase is not intuitive [25].

These studies were critical in identifying the potential implications of surface albedo change. However, because the required coupled physical simulation models are time-consuming to set up and run, they have only been applied to a few urban forms. It would be valuable to better understand the role of urban form on the implications of albedo change and to be able to rapidly scan an urban area to identify neighborhoods where albedo change is likely to bring benefit. The most promising areas can be studied in more detail.

In order to begin to fill that gap and guide future urban planning or design decisions, this study investigates the impact of pavement albedo modification strategies on effective GHG emissions and how that impact changes with urban form or morphology, as it is more formally known. The hope is that this provides a more comprehensive picture of the role of pavement albedo modification in the urban planner's toolkit.

2 METHODOLOGY

Albedo is defined as the proportion of reflected shortwave radiation (wavelength from 0.2μm-3.0μm) to the total incoming shortwave radiation at the top of the atmosphere. In this study, we considered the weighted mean value of albedo in an urban neighborhood (network level). To address the limitations of existing building modeling frameworks, we developed machine-learning-based meta-models that allow stakeholders to estimate the impact of pavement albedo modification for specific, detailed neighborhoods in a rapid, computationally efficient manner. The meta-models were developed from a large synthetic dataset of analyses executed in coupled-physics models of energy exchange and use within a neighborhood. A hybrid modeling framework was developed to create those analyses. This hybrid model combines the capabilities of several existing tools, including the geometry generation tools Rhinoceros® (Rhino) and Grasshopper® [26], the energy and radiation simulation plugin for Grasshopper®, Ladybug and Honeybee [27], and the urban climate simulator, Urban Weather Generator (UWG) [28]. The validation and accuracy of these models have been studied by several researchers and have been validated individually. Nevertheless, there is an opportunity for further studies to evaluate the uncertainty related to using these tools together. Because the models are computationally expensive and because urban morphology ranges over a broad multidimensional space, a parametric design of experiments (DOE) was developed to efficiently map the impacts of urban morphology. The workflow shown in Figure 1 can be summarized in four steps.

First, key urban morphological parameters were selected that influence building energy consumption and a range of urban geometries, each with different combinations of morphological parameters, were created using Rhino and Grasshopper [26]. The second step simulated the energy flows and use in each neighborhood instance using the Urban Weather Generator (UWG) [28], Ladybug, and Honeybee models. These two steps generated a synthetic dataset comprising the morphological parameters for each neighborhood instance and four modeled temperature and energy responses $\Delta T, \Delta E^C, \Delta E^H, and\ \Delta E = \Delta E^C + \Delta E^H$ that represent temperature, cooling BED, heating BED and total BED change, respectively. It should be noted that both cooling and heating changes are estimated based on their thermal energy values. Third, using this dataset, statistical meta-models were developed to relate responses to the descriptive parameters. Finally, in order to demonstrate the methodology in a realistic urban setting, detailed information related to the morphology of real neighborhoods was extracted from a geographic information system (GIS) database at the building level. The meta-models were then applied to predict changes in BED for every building considering realistic urban context, based on the extracted morphological parameters. The next sections explain an overview of each of these steps.

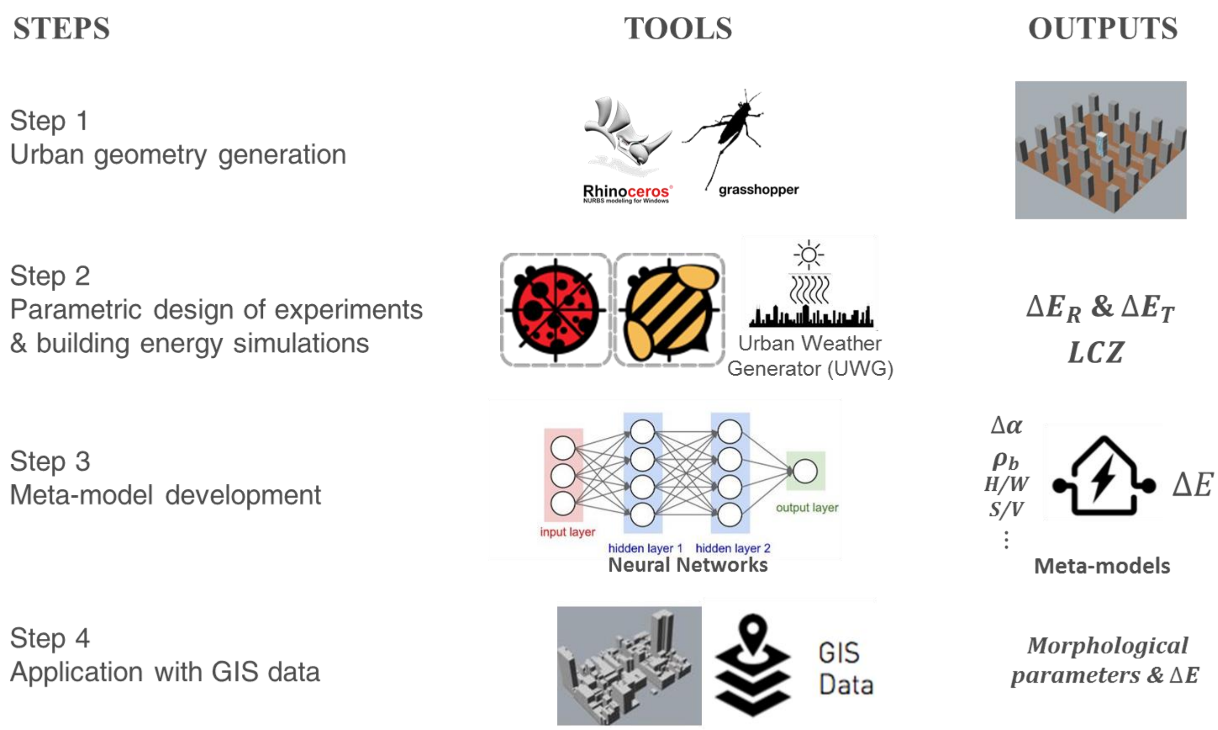

Figure 1. Modeling framework for studying the impact of pavement albedo ($\Delta\alpha$ is pavement albedo change; ΔE_R is the change in BED due to incident radiation; ΔE_T is the change in BED due to ambient temperature)

2.1 Urban Geometry Generation

Generating various urban geometries and assigning each building to one of the defined geometries enable one to capture the details of neighborhood characteristics. In addition, the generated geometries provide references for the meta-models to facilitate the BED change estimation of individual buildings in a rapid and computationally efficient way. Hence, this step should be conducted in a careful manner to take into account the important morphology parameters that can influence the BED response to the albedo change.

2.1.1 Selection of urban morphological parameters

A list of morphological parameters that may influence energy use and heat island effects was extracted from the literature and presented in the Supporting Information (SI1). Based on initial single-variable sensitivity analyses, we identified four key morphological parameters that significantly influence the impact of pavement albedo modification on BED: *building height* (*H*), *canyon aspect ratio* (*H/W*), *building density* (ρ_b), and *building length* (L).

We organized and bounded our exploration of morphology based on a taxonomy developed by Stewart & Oke [29]. To better understand the drivers of urban microclimate, Stewart & Oke categorized neighborhoods into what they called local climate zones (LCZs) and identified ten different urban and sub-urban LCZs. For each neighborhood characteristic (*H, H/W*, ρ_b and *L*), we defined five evenly spaced levels to cover the ranges for each LCZ identified by Stewart & Oke from empirical studies [29]. The specific values used in this study are shown in Table 1.

To construct a fully dimensionless meta-model, two dimensionless parameters, i.e., shape factor (*S/V*) and façade density (ρ_f), were derived for each neighborhood geometry based on the four known parameters. Shape factor was defined as the ratio of the surface area (*S*) to volume (*V*) for a given building and was approximated as the ratio of the building's perimeter (*r*) to its footprint area (*fa*). Formally, this is stated as:

$$S/V = \frac{S}{V} \approx \frac{r}{fa} \tag{1}$$

Façade density (ρ_f) was defined as the ratio of the street-facing surface area (*H* x *L*) to the building footprint area (*fa*).

These two parameters, plus the *canyon aspect ratio* (*H/W*) and *building density (ρ_b)*, were then used to build the meta-models. These were chosen as the model predictors because each impacts pavement albedo-induced BED from different perspectives. Building density (ρ_b) and façade density (ρ_f) directly determine the area of buildings and building walls affected by changes in the amount of incident radiation received and reflected from the pavements. They also impact the changes in canyon temperature. Canyon aspect ratio (*H/W*) affects the amount of solar radiation incident on the canyon floor, as higher buildings and narrower canyons result in more shading and less incident radiation. Finally, shape factor (*S/V*), defined as the surface area to volume ratio, influences the effect of ambient temperature change on BED.

Because of the computational intensity of the models, we applied a fractional factorial design method for an analysis comprising ten LCZs. We specifically used a design comprising 2,960 neighborhood configurations – about half of a full factorial design. To select this fraction, we executed a full factorial analysis of one LCZ and found this fraction to lead to less than a 5% decrease in model performance (as measured by R-squared). Changes in BED (ΔE) due to a 0.2 increase in pavement albedo ($\Delta\alpha = 0.2$) were simulated and recorded for each neighborhood configuration in the experimental design. A change of 0.2 was modeled because this is a widely used value for the difference in albedo between asphalt and concrete pavements and the potential increase in pavement albedo due to the use of a reflective coating [30].

2.1.2 Urban geometry generation: Rhino with Grasshopper

Three-dimensional urban geometries used for this research were generated within Rhino, a CAD-based modeling environment used by urban designers and architects [31]. Grasshopper is a plugin for Rhino that allows algorithmic modeling and parametric simulations. Using Grasshopper, we defined a parametric representation of a reference neighborhood that contains buildings with identical structural and thermal characteristics and a street network in between. The building dimensions and spacing, and therefore the scale of the neighborhood, were defined by the four morphological parameters – shape factor (*S/V*), façade density (ρ_f), canyon aspect ratio (*H/W*), and building density (ρ_b).

A key question concerning the definition of these reference neighborhoods is their size. The area of the modeled neighborhood should not be so small that it is not representative of the urban fabric. For the purposes of our study, a very small neighborhood would not allow for the possibility of multiple reflections of radiation among buildings and street. At the same time, the reference neighborhood should not be too large, because it increases computational expense. According to Stewart & Oke [29], an LCZ typically spans from 400 meters to 1 kilometer in length of any side.

To align with this scale, our reference neighborhood comprised three blocks of buildings, each with two sets of five buildings, separated by two pavements in between, as shown in Figure 2. The building in the center of the middle row (indicated with a white roof, used only for emphasis in the figure; all buildings were modeled with the same roof characteristics) is the reference building (RB) for energy or radiation simulations. To support the DOE, 2,960 3D urban geometries were created.

Table 1. Physical characteristics for the 10 local climate zones (Source: Stewart & Oke [29]*).*

Local climate zone (LCZ)	Canyon aspect ratio	Building density	Average building height (m)	Sky view factor
LCZ 1 **Compact high-rise**	>2	0.4-0.6	>25	0.2-0.4
LCZ 2 **Compact mid-rise**	0.75-1.5	0.4-0.7	8-20	0.3-0.6
LCZ 3 **Compact low-rise**	0.75-1.5	0.4-0.7	3-8	0.2-0.6
LCZ 4 **Open high-rise**	0.75-1.25	0.2-0.4	>25	0.5-0.7
LCZ 5 **Open mid-rise**	0.3-0.75	0.2-0.4	8-20	0.5-0.8
LCZ 6 **Open low-rise**	0.3-0.75	0.2-0.4	3-8	0.6-0.9
LCZ 7 **Lightweight low-rise**	1-2	0.6-0.9	2-4	0.2-0.5
LCZ 8 **Large low-rise**	0.1-0.3	0.3-0.5	3-10	>0.7
LCZ 9 **Sparsely built**	0.1-0.25	0.1-0.2	3-8	>0.8
LCZ 10 **Heavy industry**	0.2-0.5	0.2-0.3	5-15	0.6-0.9

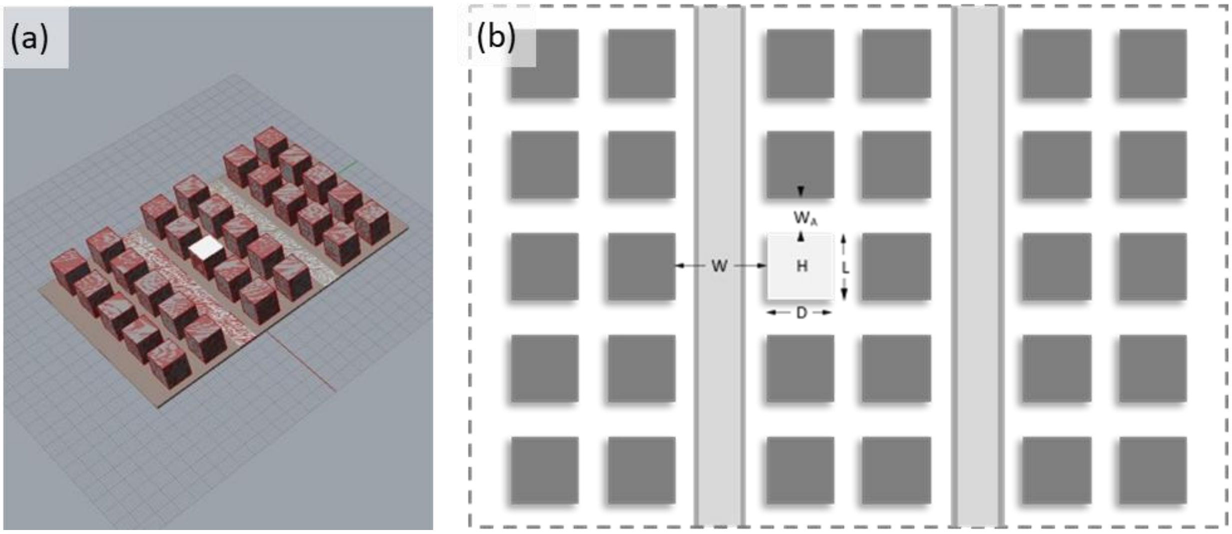

Figure 2. A generic urban neighborhood for the parametric analysis in the Rhinoceros interface. (a) perspective view; (b) top view. The building in the center of the middle row (indicated with white roof) is the reference building of interest for energy or radiation simulations. White is only used for emphasis. All buildings were modeled with the same roof characteristics.

2.2 Parametric Design of Experiments and Building Energy Simulations

Modifying the albedo of pavements has at least two effects that alter energy use in the reference building (RB): it alters the ambient temperature near the RB and the intensity of radiation incident on that building. To capture both of these effects, we made use of two modeling platforms that are described in more detail in the next two subsections. Here we give an overview of how their results were used to arrive at a final estimate of energy impact.

First, for the reference building in each neighborhood instance (i), we estimated the ambient temperatures when albedo is low (baseline temperature: $T_i\big|_{\alpha_{Low}} = T_{iL}$) and when albedo is high ($T_i\big|_{\alpha_{High}} = T_{iH}$). Second, we used a neighborhood energy simulation platform to model annual energy use (E_i) for the RB. Formally, we evaluated heating $\left(E_i^H\right)$ and cooling energy $\left(E_i^C\right)$ use separately.

Specifically, we used the neighborhood energy simulation to estimate the change in energy use, ΔE_i , as the difference in energy use when albedo is high (α_H) and temperature is as expected for high albedo, $E_{i,\alpha_H,T_{iH}}^H$ and $E_{i,\alpha_H,T_{iH}}^C$, and when albedo is low (α_L) temperature is baseline, $E_{i,\alpha_L,T_{iL}}^H$ and $E_{i,\alpha_L,T_{iL}}^C$. For these analyses, both incident radiation and ambient temperature differ. Mathematically, this is stated as

$$\Delta E_i^{\xi} = \left(E_{i,\alpha_H,T_{iH}}^{\xi} - E_{i,\alpha_L,T_{iL}}^{\xi}\right) \quad (2)$$

where ξ is either H or C.

2.2.1 Radiation and building energy simulation with Ladybug & Honeybee

Ladybug and Honeybee (LaH) connect Grasshopper to several validated physics simulation engines, such as EnergyPlus™, Radiance, DAYSIM, and OpenStudio® for building energy, comfort, daylighting, and lighting simulation [27]. Using this tool, it is possible to simulate both multiply-reflected transfers of shortwave radiation (using the Radiance engine) and building energy consumption (using the EnergyPlus™ engine). EnergyPlus™ performs a full yearly thermal dynamic simulation. As a result, annual energy consumption for heating $\left(E_i^H\right)$ and cooling

$\left(E_i^C\right)$ were modeled. The procedure of radiation and building energy simulation is detailed in the Supporting Information section SI3.

2.2.2 Microclimate/ambient temperature simulation with UWG

UWG is an urban design simulation tool that provides climate-specific temperatures for cityscape geometry and land-use change [32]. It estimates the hourly urban canyon air temperature and humidity based on weather data from a rural weather station. The model takes as input the weather file for a nearby rural weather station and parameters that describe urban morphology and surface materials (this latter point makes it suitable for studying the impact of changing surface albedo). The output from UWG is a modified weather file (.epw) that captures UHI effects and is compatible with many building performance simulation programs, including EnergyPlus. The tool has been tested for several urban areas and can satisfactorily estimate urban temperatures in different climates, weather conditions, and urban configurations [28]; its performance is comparable to a more computationally expensive mesoscale atmospheric model [33]. It should be noted that meteorological parameters, such as global irradiations used in the weather file, were implemented as input parameters in UWG for temperature simulation as well as Radiance for daylight calculations. Details related to the weather file modification are presented in the Supporting Information section SI4.

2.2.3 Simulations to develop synthetic dataset

The LaH and UWG models were executed for a set of 2,960 urban geometries assuming the weather conditions for Boston, MA (case study described in a subsequent section). For each simulation, the RB was assumed to meet ASHRAE standards 90.1-2010 [34] for climate zone 5A as defined in LaH.

Previous studies have shown that the albedo of pavements changes as a function of time and use. Generally, the albedo of new asphalt pavements increases and the albedo of new concrete pavements declines. However, a robust model reflecting such dynamics has not been reported in the literature [3,33]. In addition, a simulation of the time-dependent albedo for multiple cities shows that the average albedo of the network may not change during a period of 50 years due to periodic maintenance and repair of the pavement surface [36]. As such, in this study, we considered albedo values that represent an average of aged and new pavements as reported in different studies [37]. This is analogous to the approaches taken by Rosado and Levinson [38] and Guo et al. [39] in evaluating changes in roof albedo and wall albedo, respectively. Hence, we estimate the impact of albedo change by comparing the simulated result from a baseline scenario where albedo is low (α_L=0.1) with that from an increased-albedo scenario (α_H=0.3).

2.3 Meta-models for predicting BED due to Pavement Albedo Modification

Using the results of the 2,960 simulations, meta-models with response variables of changes in heating BED (ΔE_i^H) and cooling BED (ΔE_i^C) for the reference building in an LCZ were developed. To identify the best model form, we evaluated various machine-learning models to fit the data, including multiple regression, random forest regression, support vector machine, and neural networks. For each LCZ, these model forms were tested and evaluated using 10-fold cross-validation to avoid overfitting of the model. Neural networks were found to best predict ΔE due to $\Delta\alpha$. The root mean square error (RMSE) and R-squared of the meta-models for the 10 LCZs in the case of Boston (case study described in the next section) are summarized in the Supporting Information section SI5.

2.4 Application to realistic neighborhoods with GIS data

GIS data is widely used in spatial analysis and urban planning to support decision-making. For the case study developed here, shapefiles containing building information of Boston were obtained from MassGIS (Bureau of Geographic Information) [40]. These shapefiles provide data on building footprints, building heights, building types, etc. for 129,370 buildings in Boston. In addition, vector data containing primary road networks for Boston was found in TIGER/Line® shapefiles from the U.S. Census Bureau [41]. The procedure of applying the proposed method to the Boston case study are presented in the Supporting Information section SI6.

2.4.1 Computing overall global warming potential results

Applying the meta-models, changes in BED (ΔE_i^H and ΔE_i^C) due to a 0.2 increase in pavement albedo were estimated for every building described in the Boston shapefile. To estimate the impact of increasing pavement albedo at a neighborhood scale or even at a city scale, the results for individual buildings were then aggregated for each census tract. Whether at the building level or for the census tract, the global warming potential (GWP) impact of increasing pavement albedo was calculated from changes in cooling and heating BED, multiplied by the corresponding CO_2 emission factors for cooling and heating, respectively. The procedure for calculating the emission factors for different environmental modeling scenarios is detailed in SI7 of the Supporting Information.

3 RESULTS AND DISCUSSION

3.1 DOE results and discussion

Results from the DOE for Boston show that canyon aspect ratio (*H/W*), building density (ρ_b), façade density (ρ_f), and surface-area-to-volume ratio (*S/V*) can all alter BED due to changes in pavement albedo, but their influence on cooling demand and heating demand is different.

3.1.1 Influence of canyon aspect ratio *(H/W*), building density (ρ_b), and façade density (ρ_f)

Figure 3 plots the observed change in cooling and heating energy for various levels of *H/W,* ρ_b, and ρ_f for the DOE results of reference buildings in LCZ 2 neighborhoods. Because several variables were changed for each neighborhood configuration within the experimental design, significant scatter is observed in Figure 3. Nevertheless, some key trends are observable. Figure 3a shows that the change in cooling demand first increases slightly, but decreases quickly after *H/W* approaches 1. When the aspect ratio is small (<0.94), the context resembles a wide canyon, where buildings are far apart and/or the average building height is small. In this case, modifications to pavements exert only a small impact on surrounding buildings. Nevertheless, as *H/W* grows, one of two effects occurs: 1) *H* grows so that the cross-section of the building receiving incident radiation grows, or 2) *W* shrinks so that incident radiation dissipates less before it impacts the building (The change in delta incident radiation as a function of aspect ratio is presented in SI3).

In either case, ΔE_c first increases as H/W grows. However, as the canyon aspect ratio continues to increase beyond around 1.0, the amount of shading from buildings to pavement or to other buildings increases and ΔE_c begins to decline. As shown in Figure 3b, ΔE_h follows a somewhat muted, inverse pattern – first becoming more negative then approaching zero as H/W increases.

Based on the results of this experimental design, the impact of ρ_b is less pronounced than that of H/W. As shown in Figure 3c and d, ΔE_c due to pavement albedo change becomes slightly more negative with ρ_b, while ΔE_h approaches zero as ρ_b increases. Figure 3e and f indicate that ΔE_h changes more with changes to façade density (ρ_f) than does ΔE_c. Generally, ΔE_h becomes more negative as ρ_f increases, while ΔE_c becomes slightly less negative as ρ_f increases.

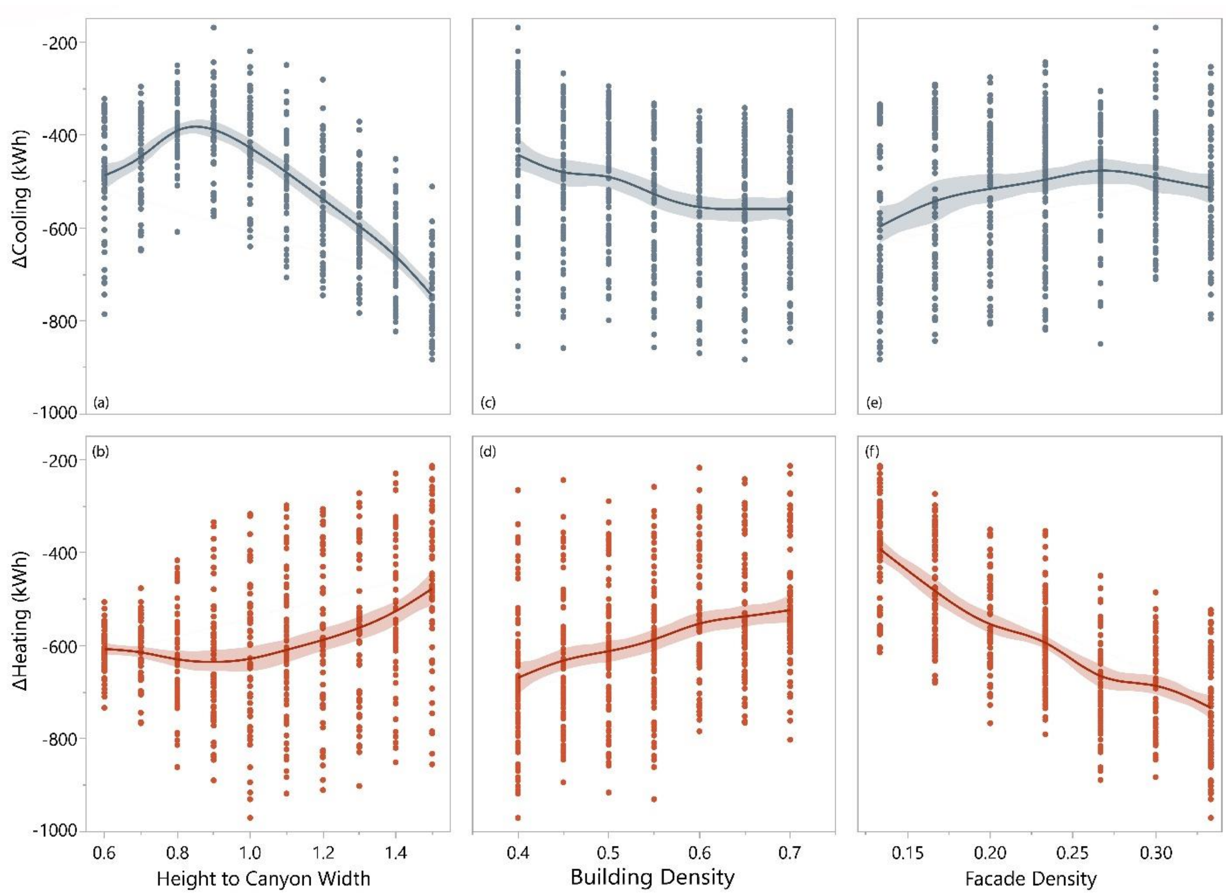

Figure 3. Changes in annual values of (thermal) cooling demand (a, c, and e) and (thermal) heating demand (b, d, and f) for Boston LCZ 2 due to 0.2 increase in pavement albedo for samples with different values of canyon aspect ratio (H/W) and building density (ρ_b) and façade density (ρ_f). Each point represents one neighborhood configuration modeled as part of the design of experiments. Lines represent the mean of observed responses. Shaded region represents a 95% confidence interval of mean.

3.1.2 Influence of shape factor (*S/V*)

Surface-to-volume ratio (*S/V*) is a measure of building compactness that is considered to play a significant role in building thermal exchanges [42]. Generally, for a constant building volume, increasing surface-to-volume ratio increases the energy demand in buildings. In this analysis, a strong change in ΔE due to pavement albedo as *S/V* changes is evident. In fact, as shown in Figure 4, we observe that that for LCZ 2, change in cooling demand, change in heating demand and net GHG all increase asymptotically as *S/V* increases. As a result, considering the net thermal changes, the impact of changing pavement albedo is more significant for buildings with lower shape factors.

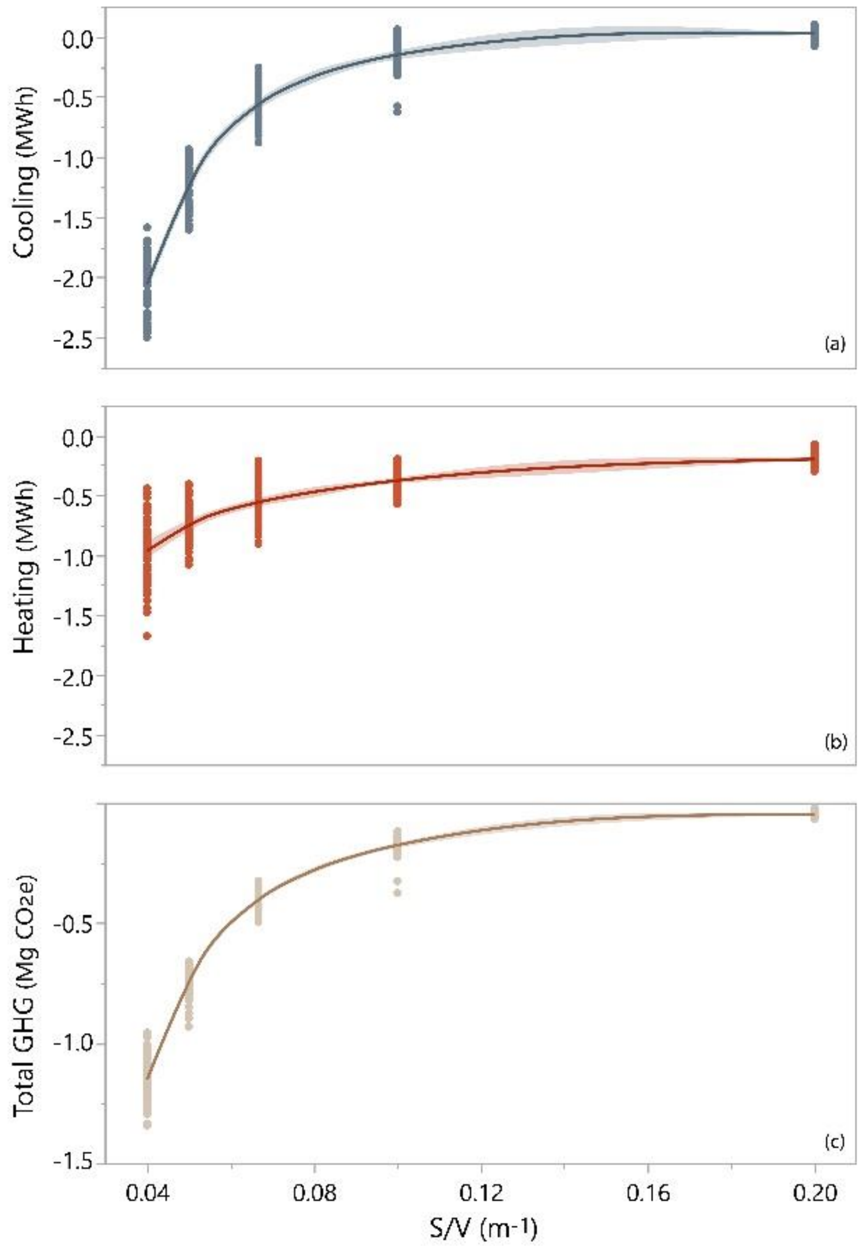

Figure 4. Changes in cooling demand (a), heating demand (b), and total GHG emissions (c) for Boston LCZ2 neighborhoods due to a 0.2 increase in pavement albedo for reference buildings with different shape factors.

3.1.3 Incident radiation vs. ambient temperature

It should be noted from Figure 3a that the changes in cooling BED due to increased pavement albedo are slightly negative (cooling energy savings) when *H/W* is small. As *H/W* grows, energy-saving first shrinks (becomes a smaller negative number) but then grows (becomes more negative) as *H/W* grows or the neighborhood becomes denser. The switch in the direction of this trend reveals a trade-off between the two mechanisms: incident radiation and ambient temperature, which can be explained by the underlying physics. In EnergyPlus, energy demand is calculated by solving a series of heat balance equations on building surfaces and on indoor air [43].

On the building external wall, the heat balance can be written as:

$$q_{sw} + q_{lw} + q_{cv} - q_{cd} = 0$$

where q_{sw} is the shortwave radiation, including direct, reflected and diffused solar radiation
q_{lw} is the longwave radiation from the environment, including sky, air, and the ground
q_{cv} is the convective flux from the environment
q_{cd} is the conductive flux through the wall

Increasing pavement albedo has a direct effect on q_{sw}; more solar radiation is reflected from the pavement. It also causes the ambient air temperature to reduce, as does the ground temperature. As a result, both the longwave radiation q_{lw} and the convective flux q_{cv} from the environment decrease. The net balance of the increased q_{sw} and decreased $(q_{lw} + q_{cv})$ determines the direction of conductive flux q_{cd} through the wall, ultimately affecting the heat gain and energy demand indoor. The relative magnitude of the shortwave q_{sw} and the longwave radiation q_{lw} depends on urban morphology, which is why the slope change is observed for changes in cooling BED in Figure 3a. Figure 5 shows the schematic view of the heat balance on the building wall that faces the pavement. One should note that EnergyPlus does not automatically take into account the temperature changes at different altitudes and therefore, in this sense, the energy consumption on different floors is not captured. Further studies are required to add this feature to the BED simulation and a model evolved from the UWG, the Vertical City Weather Generator, estimates a vertical profile of ambient air temperature [44].

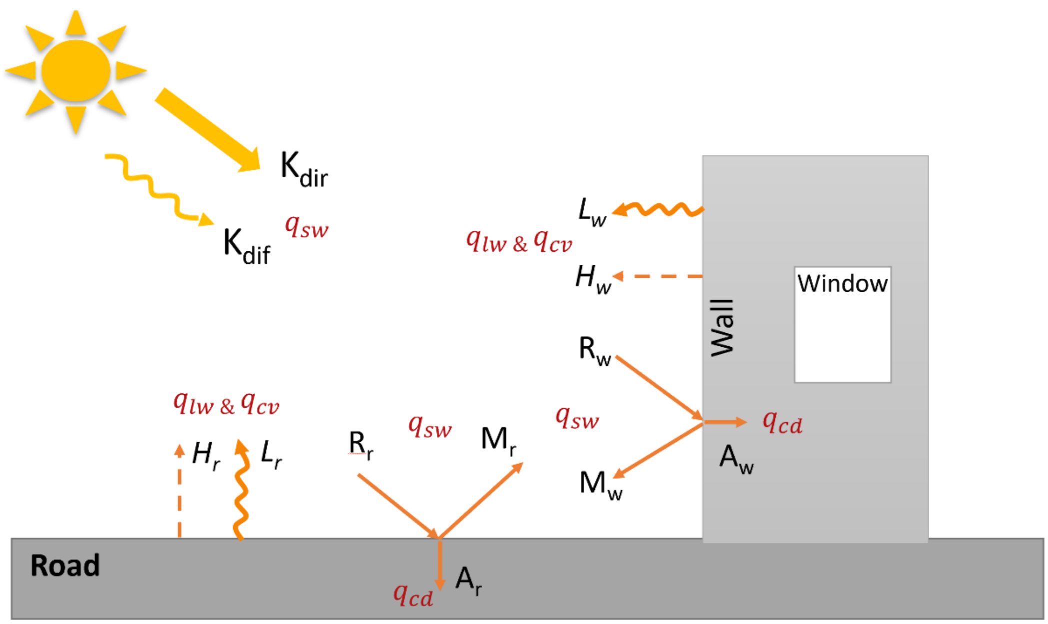

Figure 5. schematic view of heat balance on the building wall exposed to the pavement side (H = convective heat transfer, L= longwave radiation, K_{dir} = direct radiation, K_{dif} = diffused radiation, R = incoming shortwave radiation M = Outgoing shortwave radiation, A = absorbed radiation, r = road, w = wall)

3.2 Citywide case study results and discussion

Each of the more than 100,000 buildings in Boston was evaluated to estimate the prevailing local morphology including the canyon aspect ratio (*H/W*), shape factor (*S/V*), areal density (ρ_b) and façade density (ρ_f). This information was used to assign each building a local climate zone based on the characteristics of its neighborhood. Simulation-based meta-models were developed and applied to predict changes in BED due to a 0.2 increase in pavement albedo for each of these buildings for its LCZ neighborhood.

3.2.1 Building Level Results

Figure 6 shows the total 50-year GWP savings for a neighborhood of Boston at the individual building level from increasing pavement albedo by 0.2. It is important to note that there are limitations when directly applying meta-models at the individual building level. It is quite possible that any given building result may be incorrect. However, because of the non-linear response observed (see Figure 3 and Figure 4), aggregating such granular results should provide a useful estimate of the GWP savings or burdens due to the increase in pavement albedo at the neighborhood level. As is apparent from Figure 6, that results can vary significantly even for buildings in close proximity. Three buildings, labeled as A, B, and C in Figure 6, highlight some of these differences. All three buildings experience urban morphology conditions indicative of LCZ 2. We see that building B experiences a cooling burden while building A experiences a cooling benefit. Considering the trends displayed in Figures 3 and 4, this difference appears to emerge due to a larger *S/V* and larger ρ_f but is moderated by a smaller ρ_b. All three buildings experience a heating benefit due to albedo change, but the magnitude varies. Again, comparing A and B, we see that B has a lower heating benefit due primarily to a larger S/V and ρ_b. Similarly, comparing B and C, we see that B has a higher burden due to change in cooling and a lower benefit due to change in heating than C. Both of these effects are primarily driven by the slightly higher *S/V* for building C. The higher ρ_f for building C reinforces the cooling difference while simultaneously muting the difference in heating demand.

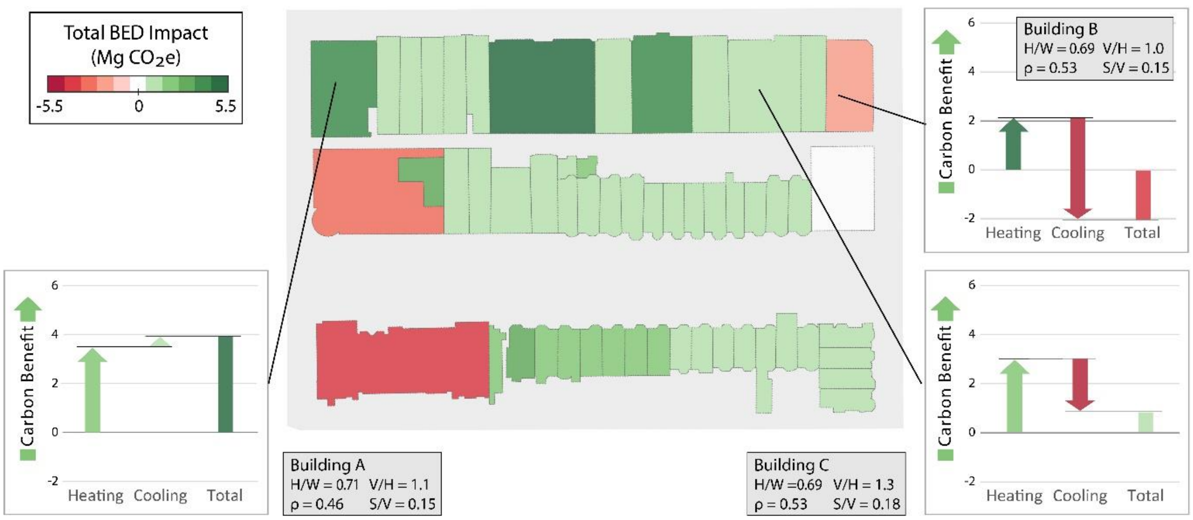

Figure 6. GWP savings from BED at building level due to a 0.2 increase in pavement albedo in Boston over 50 years (a red hue indicates a GWP burden). All results are in terms of Mg CO_2eq for a 50-year analysis period.

3.2.2 Census tract level

Changes in BED at the census tract (CT) level are aggregated by adding up the building-level results in each census tract. These aggregated results are likely more indicative of areas of high potential for detailed study. The aggregated results for a 0.2 increase in pavement albedo are shown in Figure 7. The BED impacts on cooling (Figure 7a), heating (Figure 7b), and the total of the two (Figure 7c) are shown in the panels across the top row of Figure 7. From this figure, we see a broad range of BED impacts ranging from an intense burden (dark red) to an intense saving (dark green). It can be seen from the maps that increasing pavement albedo in Boston tends to increase cooling burdens (see Figure 7a), but generally reduces heating burdens (see Figure 7b). Whether a neighborhood experiences a net GHG benefit depends on the balance of these two effects. To help explore this, Figure 7e shows the most prevalent LCZ for each census tract in Boston. Building density generally decreases from LCZ 1 (compact high-rise – red color) to LCZ 9 (sparsely built – tan color). Generally, we see that neighborhoods are more likely to experience a net benefit when their density is high (LCZs 1-4) than when they are low (LCZs 8 or 9). This pattern of behavior is shown more quantitatively in Figure 7f. In this plot each dot represents the total BED result for one CT. This is the same data that is used to color Figure 7c. CTs are grouped as high density (average density greater than 0.35), medium (0.35 >= ρ_b >=0.25), and low (ρ_b <0.25). Of the 14 high-density LCZs, zero (0) show a net impact. For the 42 medium density CTs, four (4) or 10% show a net impact. Finally, for 121 the low-density CTs, 15% (18) show a net negative impact. Overall, model results indicate that 89% of the Boston CTs (157 out of 177 or 83% of land area) would experience reduced GHG emissions from building energy demand if pavements in that CT had a higher albedo. Within the city of Boston there are nearly 1,300 paved miles (2,080 km) of road. These results suggest that raising the albedo of approximately 1,100 of those miles (1,770 km) would lead to carbon benefits of about 91,720 metric tons over the next fifty years.

Results from two additional scenarios are presented in the Supporting Information section S10. One scenario considers the impact of emissions from the non-baseload grid [45]. The base-load scenario considers the annual average hourly suppliers of energy that operate generally while non-base load suppliers (short-term marginal technology) are those that supply the demand in peak demand hours. For this case, the emission factors for non-baseload cooling and heating were calculated as 0.732 and 0.352 kg CO_2eq/kWh, respectively. With this higher (than the baseload) burden for cooling, we see GHG benefit for changing pavement albedo in only 55% of CTs (49% of urban area). The second additional scenario considers the impact of the long-term marginal generating technology [46]. Under these conditions, emissions factors for cooling and heating fall to 0.309 and 0.303 kg CO_2eq/kWh, respectively, and GHG benefit is observed in all but one CT (>99% of urban area).

The results shown in the Figure 7 maps make clear that the net effect of changing pavement albedo depends on urban morphology. Ultimately, to make a final evaluation of the best alternative for each neighborhood, this information will need to be combined with other data on the life cycle impact of pavements. To that end, we also show the total BED impact per area of pavement converted by census tract in Figure 7d. This result trends similarly to the aggregate total savings (Figure 7c).

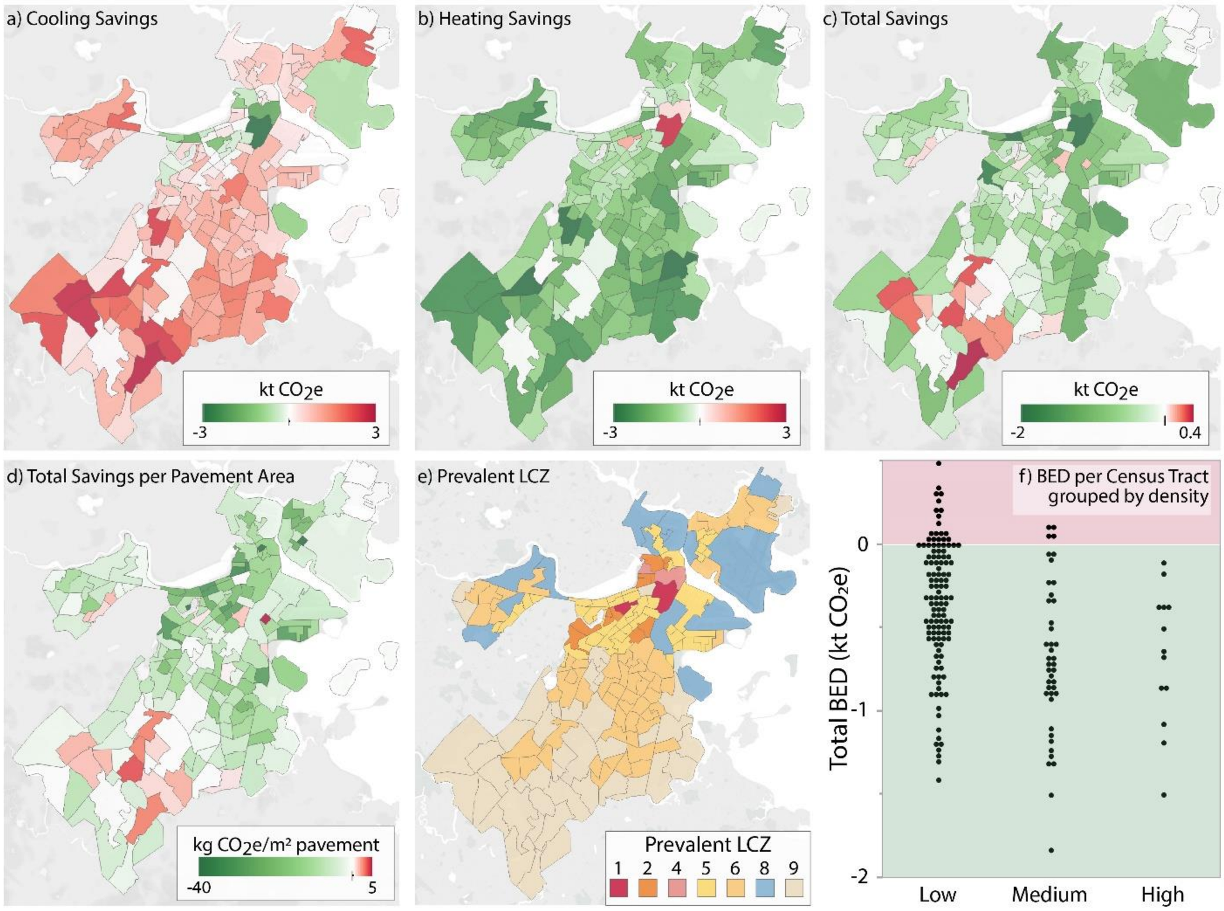

Figure 7. GWP impacts due to a 0.2 increase in pavement albedo in Boston at census-tract level over a 50-year analysis period (red indicates a GWP burden). Impacts due to changes in (a) cooling, (b) heating, and (c) total (i.e. sum of the two) are shown in top row of the figure. The total per area of pavement in the census tract is shown in (d). The prevailing LCZ in each census tract is shown in (e). (f) plots the same information as in (c), but census tracts are grouped by their relative density. Each dot represents on census tract (two highly positive points in the High-density group are not plotted to improve clarity of the other points.) Figures generated in Tableau software. Underlying map images and geographic data © Mapbox © OpenStreetMap.

Overall, the results presented here confirm the hypothesis that urban morphology plays a significant role in shaping the impact of pavement albedo modification on BED. Several morphological parameters are identified as influential factors, including building density, canyon aspect ratio, façade density, and building surface area to volume ratio. Results from the experimental design and the case study of Boston demonstrate that local context can shift the impact of albedo change from benefit to burden.

The Boston case analysis suggests that there are many neighborhoods in which an increase in pavement albedo would create a carbon emissions benefit. Therefore, it is recommended that these strategies be explored in more detail in those contexts, of course using tools that consider urban morphology and microclimate. In addition, a more comprehensive evaluation of the impact of reflective pavements is necessary, considering other phases and components in a pavement's life cycle such as material extraction, construction, vehicle fuel consumption, and end-of-life. Further research on the impact of building properties on BED as well as data collection on the evolution of pavement albedo due to aging and resurfacing would improve the robustness of the model for supporting sustainable pavement designs. Using multiple weather files within a city location will give a more representative condition of the climate in this analysis, particularly for those regions that are adjacent to bodies of water. Further research is required to generate zone-specific climate data for such a high-resolution analysis.

4 CONCLUSIONS

This study proposes a high-resolution approach to quantify the global warming impact changes attributed to cool pavements in an urban vicinity, using both a coupled physical-simulation model and a machine-learning model. The approach was implemented in a case study of the City of Boston to assess the net BED effects of cool pavements. Results from the building-level analysis show that the net GHG saving of changing pavement albedo depends on urban morphology. In addition, the census tract results demonstrate that increasing pavement albedo usually reduces carbon emissions from BED for high and low-density neighborhoods, while results from medium-density neighborhoods were mixed. In fact, increasing the albedo would lead to BED GHG benefits in 88% of neighborhoods in Boston. In addition, the albedo increase would yield more than 90,000 metric tons of reduced carbon emissions over the next fifty years in 1,770 km of urban roads. One should note that the obtained results may not be generalized to other cities located in different climate zones. In fact, in other cities, the heating and cooling degree days as well as urban texture can possibly induce a completely different conclusion. Nevertheless, the proposed model and its outcome open doors for an assessment of the albedo effect on building energy demand as a means of supporting robust decisions on cool pavements while considering the heterogeneity that exists within urban neighborhoods in any city.

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