GREEN ROOFS AND COOL MATERIALS AS RETROFITTING STRATEGIES FOR URBAN HEAT ISLAND MITIGATION
Case Study in Belgrade, Serbia

by

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The effect of extensive and intensive green roofs on improving outdoor microclimate parameters of urban built environments is currently a worldwide focus of research. Due to the lack of reliable data for Belgrade, the impact of extensive and intensive green roof systems on mitigating the effects of urban heat islands and improving microclimatic conditions by utilizing high albedo materials in public spaces were studied. Research was conducted on four chosen urban units within existing residential blocks in the city that were representative of typical urban planning and construction within the Belgrade metropolitan area. Five different models (baseline model and four potential models of retrofitting) were designed, for which the temperature changes at pedestrian and roof levels at 07:00, 13:00, 19:00 h, on a typical summer day, and at 01:00 h, the following night in Belgrade were investigated. The ENVI-met software was used to model the simulations. The results of numerical modeling showed that utilizing green roofs in the Belgrade climatic area could reduce air temperatures in the surroundings up to 0.47, 1.51, 1.60, 1.80 ºC at pedestrian level and up to 0.53, 1.45, 0.90, 1.45 ºC at roof level for four potential retrofitting strategies, respectively.

Key words: *green roof, urban heat island, urban microclimate, microclimate mitigation, ENVI-met*

Introduction

Climate conscious urban design comprises a group of elements and strategies that can be applied in modern cities. This study investigates retrofitting design scenarios – the influence of green roofs installed onto existing residential buildings in Belgrade on the urban microclimate and the influence of exchanging the existing low albedo materials in public spaces (roads, pavements, squares, playgrounds) for higher albedo materials.

Vegetative roofs, often termed green roofs, living roofs or roof gardens in the literature, are roofs with vegetation on the uppermost layer [1]. Depending on the substrate depth, type of vegetation, complexity of the irrigation and drainage system, accessibility, and extent of maintenance requirements, vegetative roofs are divided into extensive and intensive roofs. They offer multiple benefits. Green roofs contribute reducing the energy consumption and to more efficient stormwater management. They reduce CO_2 emissions. In addition, they have a significant role in

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the strategies for adapting to high temperatures and reducing the effect of heat islands in urban environments. Also, green roofs expand the lifetime of roofing membranes. They also contribute to increasing urban biodiversity, reducing noise, increasing the market value of the buildings, increasing the amounts of open space utilized, absorbing atmospheric pollutants, offering the possibility for development of urban agriculture, and having positive effects on human health. They also were marked as a component which contributes to raising the esthetics of the city. Reviews of the main environmental benefits of green roofs are available [2, 3].

The role of green roofs in mitigating the effects of urban heat islands has been previously discussed [4-13]. The greatest contributors to urban heat islands are large asphalt or concert areas with low albedo values, the reduced percentage of vegetation in urban environments, high buildings and narrow streets that modify the direction and speed of winds and create urban canyons, or any combination of these factors, as well as activities in urban environments that generate heat (HVAC systems, transport and other anthropogenic processes and factors). Green roofs increase the albedo of urban areas and are considered a key approach for moderating the effect of urban heat islands. Vegetative roofs can reduce the ambient temperature by 0.3 to 3 °C at city level and can efficiently reduce the effect of urban heat islands [4].

The use of green roofs is one of the strategies to climate change adaptation in cities, as described previously [5, 14, 15]. Vegetative roofs are one part of the system of green infrastructure in cities. Green infrastructure has been studied as a strategic approach and part of the solution for reducing heat and pollution in urban environments [5, 6, 10, 15, 16]. With regard to the natural cooling effect through the process of evapotranspiration, it was concluded that green infrastructure should be strategically implemented in urban environments and utilized in urban and architectural design. Green infrastructure is the most effective tool in the fight against climate change [3, 7, 14].

Adopting vegetative roofs leads to reducing GHG emissions [17-21]. The use of vegetative roofs has been identified as an ecological approach and suitable technique for reducing air pollution, which is a product of direct (directly linked with external emissions polluters) or indirect processes (modifying the microclimate by the use of vegetative roofs reduces the amount of energy utilized for HVAC, and consequently, the amount of pollutants emitted). The performance of green roofs is dependent on the status of the vegetation, the roof position, and the ambient air-flow conditions. Altogether, 1675 kg of air pollutants were quantifiably removed by 19.8 ha of green roofs annually [19]. One square meter of vegetative roof could offset the annual particulate matter emissions of one passenger car [18]. On sunny days, green roofs could reduce the CO_2 concentration by 2% in urban neighborhoods [17]. Where there is luck of areas in densely built urban environments that can be greened, installing vegetative roofs would increase the percentage of area under vegetation. Bearing in mind that trees and shrubs can be planted on intensive green roofs, they make a greater contribution to reducing air pollution than extensive roofs having grasses and low-growing plants.

The effects of utilizing green roofs on city microclimates and reductions in energy requirements have been investigated in different climatic areas: Toronto [5, 6], Chicago [19], Portland, Chicago, Atlanta, Huston [22], London [23], Lisbon [24], Athens [25, 26], cities in the Netherlands [27], cities in Northern Spain [28], Rome [29], Palermo [30], Teramo [31], Catania [32], Hong Kong [33], Kuala Lumpur, Singapore, and Hong Kong [8], Kawasaki [20], Hangzhou [34], Adelaide [10], Melbourne [11], Guangzhou and Frankfurt [35], *etc*. Vegetative roofs contribute differently to microclimate modification in different climatic zones. Findings show green roofs have the greatest impact in the hottest and driest climates [3]. Green roofs are often pointed to as efficient technologies for reducing indoor temperatures and energy consumption of buildings in both warm and cold climates [36, 37].

The building sector expends 40% of the total energy in the EU [38] and in Serbia [39]. In Serbia, 70% of that energy is consumed by the residential sector, mostly for space heating [40]. Therefore, any effort made towards reconstruction of existing buildings would be significant, considering the great potential for improving the environmental impact and reducing the energy expenditure of such buildings.

Unfortunately, regulations, guidelines, standards or codes in regard to the installation of green roofs in Serbia do not exist. In Serbia some municipalities provide a certain percentage of non-refundable participation in the renovation, thus stimulating the owners of the facilities to invest in the reconstruction of buildings. Also, banks provide more favorable loans for renovation projects for raising energy efficiency. Loans are mainly used for the renovation of family houses. In Europe, the situation is very different. Some countries and cities have adopted bylaws and municipal regulations that prescribe the obligation to use green roofs in certain buildings or zones. The assistance is also provided to help finance the construction of green roofs at various stages of their construction and life cycle. Also, there are examples of permitted construction area increase, tax deduction for green roof investors, and the reduction of the fees for construction contributions. As a result of the adoption of laws, bylaws and regulations, as well as financial incentives, investing in the construction of green roofs is more represented in France, Austria, Norway, Switzerland, Great Britain, and Germany than in other European countries in which such initiatives are missing. Moreover, the politics of both states and cities, and the legislature linked with the goals of reconstruction of the existing building stocks are changing and continually improving. Changes and improvements in building renovation policies have been reported for France, Germany, Denmark, and Sweden [41].

Research on the reconstruction and revitalization of existing buildings by implementing green roofs was reported previously in other countries [28, 30, 37, 42]. Research has been conducted in Belgrade and Serbia on potential models of energy reconstruction and on optimization of measures for renewing residential buildings, with the aim of improving the energy efficiency and influencing the environment [43-45]. These studies critically analyzed key elements of the thermal envelope and proposed a set of measures and potential models for energy optimization [43-45], without focusing on the impact of green roof systems. Additionally, other published research on this topic from Serbia was based on individual buildings [40, 46]. The impacts of installing green roof systems on improvements in microclimate conditions on the neighborhood scale and on urban units were not investigated, which is the subject of this research.

To our knowledge, reliable data from the scientific literature are lacking on the impact of green roofs in Belgrade, on the basis of which the effects of their use could be determined. Therefore, for this research, the impact of vegetative roof systems on the urban environment in the Belgrade climatic zone was studied using the software tool, ENVI-met. For research purposes, four scenarios of green roof systems utilized on existing buildings were used and compared with a basic, realistic model on four selected locations, in order to explore the improvement of micro climate conditions, on typical urban structures located in Belgrade.

Territory and data

Four locations in existing urban neighborhoods within the Belgrade metropolitan area with differing urban structures, number of stories, and percentage of green and asphalt surfaces were studied. Locations were representative of typical urban forms of the Belgrade metropolitan area. The locations were:

- location BGD01 – part of the territory of the municipality of New Belgrade – Block 70,
- location BGD02 – part of the territory of the municipality of Stari Grad – Donji Dorcol, the block encompassed by Visokog Stevana, Cara Urosa, Dunavska, and Panciceva streets,
- location BGD03 – part of the territory of the municipality of Vracar, the block encompassed by Makenzijeva, Baba Visnjina, Njegoseva, and Nevesinjska streets,
- location BGD04 – part of the territory of the municipality of Zemun – the urban neighborhood of Galenika.

Satellite images of the investigated locations with their boundaries marked are shown in fig. 1. Views of the modeled structures in the four locations, BGD01, BGD02, BGD03, and BGD04 are given in fig. 2. The models fully complied with the actual conditions in the locations. The average building height was 15 m (BGD01), 35 m (BGD02), 20 m (BGD03), and 8 m (BGD04). Belgrade is located in a moderate continental climate zone, with warm summers, mean summer air temperature from 21-25 ºC, 30 to 55 tropical days and up to 26 tropical nights annually, with heat waves in July and August [47]. In the current research, statistical data and parameters for a typical summer day in Belgrade were used, see tab. 2.

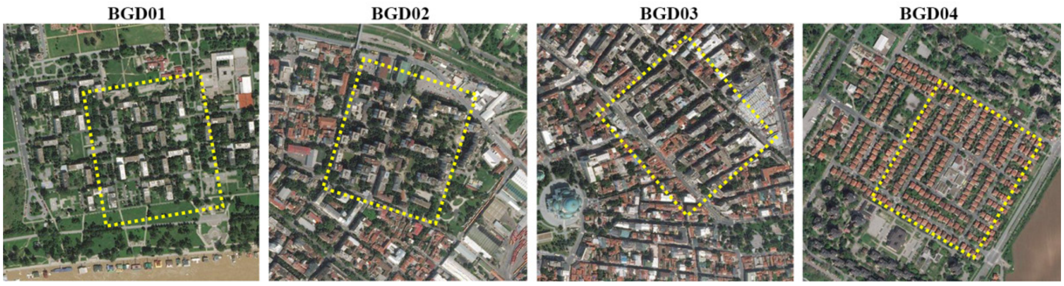

Figure 1. Satellite images of the locations with the boundaries of the investigation marked
(*for color image see journal web site*)

Methodology

The ENVI-met software is one of the most commonly used programs for investigating the influence of green roofs [5, 6, 9, 27, 29, 31, 34, 48]. When the characteristics of the thermal envelopes of buildings are investigated in detail, combined software is often used, *e. g.* ENVI-met and EnergyPlus [30, 35, 49], or Eco Roof simulation model and EnergyPlus [32]. For more complex individual buildings, TRNSYS is used [50]. Software simulations are used in urban planning of new urban neighborhoods and for investigating different urban forms [27, 34, 51, 52].

The ENVI-met is a scientifically established prognostic, 3-D, high resolution urban microclimate model [53, 54], which considers physical fundamentals based on the principles of fluid mechanics, thermodynamics and atmospheric physics to calculate 3-D wind fields, turbulence, air temperature and humidity, radiative fluxes, and pollutant dispersion. The typical spatial and temporal resolution is 0.5-10 meters and 1-5 seconds, respectively, and the simulation time is usually between 24 h, and 5 days. The model can simulate: flow around and between buildings, heat and vapor exchange processes at urban surfaces, turbulence, exchanges of energy and mass between vegetation and its surroundings, particle dispersion, and simple chemical reactions. The main input parameters for an ENVI-met simulation include weather conditions, initial temperature profiles, geometry and physical properties of urban surfaces, and plants. The full equation system and further details about the ENVI-met model are given in other studies

[53-56]. The ENVI-met has been applied to urban microclimate studies in different climatic regions [6, 9, 31, 34, 48, 57, 58] and verified with field experimental data by some researchers [5, 10, 27, 59-61].

In the current research, data modeling was performed by ENVI-met Version 4 (Summer17 Release). The ENVI-met requires an area input file with 3-dimensional geometry, and a configuration file with the initial parameters.

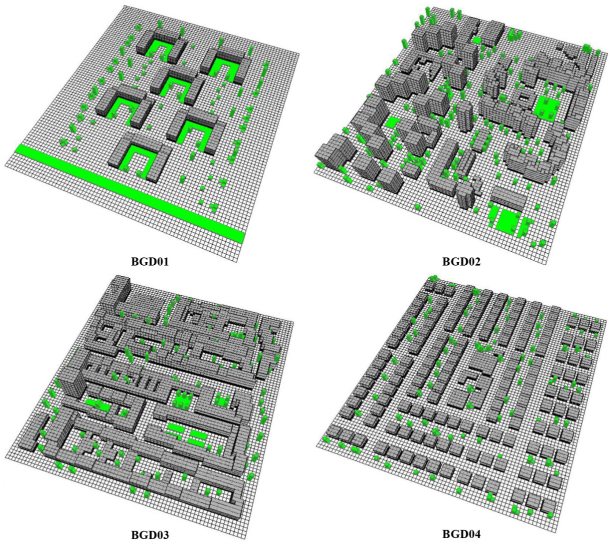

Figure 2. The 3-D models of urban structures in locations BGD01, BGD02, BGD03, and BGD04
(*for color image see journal web site*)

A baseline (real) model was constructed and investigated, as well as four different models of retrofitting strategies for urban heat island mitigation for each of the four chosen urban locations. All four studied locations were 350 × 400 meters, divided into a 3-D grid with 5 m gridline divisions. For all four locations, building heights, the spatial distribution of buildings in the field, position of the vertical greenery, and other spatial elements were modeled on real conditions in the locations, so the ENVI-met models were properly representative of the urban structures in the chosen locations, with spatial relationships reflecting those in real life.

The initial baseline model, termed the realcity (RC) model, contained all the relevant characteristics of the existing condition – the position, size and shape of buildings, position and tipe of plants, distribution of surface materials and soil types – representing the current condition for each urban location. The RC model was used as the baseline for comparison with the green roof retrofitting strategies/models. The second model, RC+extensive green roof (RC+EX), had all the same characteristics as the baseline model, but also contained the added element of extensive green roofs. The third model, RC+intensive green roof (RC+IN), comprised the baseline model with added intensive green roofs. The fourth model, Future model (F), included modeling for extensive green roofs and altered characteristics for roads and pavements, in which the use of cooler materials was modeled, while the fifth model, Futureplus (F+), is a variant with intensive green roofs and cool materials in public spaces. None of the other characteristics of the chosen locations were altered in the research models, so they remained the same as in the baseline model. The green roof structures analyzed in chosen locations are treated as an additional layer of insulation. The vegetation used as an element of green roof is of indigenous (native) variety. Table 1 shows a detailed overview of the elements and their thermal characteristics as defined in the retrofitting models (albedo and emissivity of the roof coverings, roads, pavements, soil and grass, and vegetation). The ratio between the reflected radiation and the incoming radiation (irradiation) is termed the albedo. The albedo values used in ENVI-met, tab. 1, were obtained from research published previously [14, 62, 63]. Emissivity is the ratio of energy radiated by an object and the energy radiated by a black body at the same temperature. For all calculations the emissivity of the materials was considered equal to 0.9. as used in [62-64]. Methods to estimate the emissivity of materials are presented in [65, 66].

Table 1. Characteristics of the baseline model and the four retrofitted models

<table>
<tr><th></th><th>Roof</th><th>Roads</th><th>Pavements</th><th>Soil and grass</th><th>Vegetation</th></tr>
<tr><td>RC model</td><td>Black</td><td>Asphalt road
albedo 0.20
emissivity 0.90</td><td>Concrete pavement
dark albedo 0.20
emissivity 0.90</td><td rowspan="5">Loamy soil
(for all models)
albedo 0.00
emissivity 0.99

Grass
(for all models)
50 cm average
dense
albedo 0.20
plant height
0.63
root zone
depth 0.50</td><td rowspan="5">Real (existing)
vegetation (for
all models)

(Populus alba,
Populus nigra,
Acer sp, Betula
pendula, Plata-
nus orientalis)</td></tr>
<tr><td>RC + extensive
green roof model</td><td>Extensive
green</td><td>Asphalt road
albedo 0.20
emissivity 0.90</td><td>Concrete pavement
dark albedo 0.20
emissivity 0.90</td></tr>
<tr><td>RC + intensive
green roof model</td><td>Intensive
green</td><td>Asphalt road
albedo 0.20
emissivity 0.90</td><td>Concrete pavement
dark albedo 0.20
emissivity 0.90</td></tr>
<tr><td>Future model</td><td>Extensive
green</td><td>Asphalt road
with red coating
albedo 0.50
emissivity 0.90</td><td>Concrete pavement
light albedo 0.80
emissivity 0.90</td></tr>
<tr><td>Futureplus model</td><td>Intensive
green</td><td>Basalt brick road
albedo 0.80
emissivity 0.90</td><td>Concrete pavement
light albedo 0.80
emissivity 0.90</td></tr>
</table>

Table 2 shows an overview of the parameters used in the simulations, as well as the geographic location of Belgrade. Simulations were conducted for a 24 h period, for a typical summer day in Belgrade on 23 June. The simulations commenced at 05:00 h. Three control points (R1, R2, and R3) were positioned at each of the four locations, as shown in fig. 3. Control points show particular results from the numerical simulation.

Results and discussion

Figure 4 shows the external air temperatures at pedestrian level for the baseline model and temperature changes for the four models of retrofitting strategies (RC+EX, RC+IN, F, F+) at 13:00 h in four locations on a typical summer day in Belgrade. Figure 4 clearly shows the temperature reduction trends for the urban heat island mitigation strategies investigated in the study. The models predicted that intensive green roof systems had a greater mitigating effect on urban heat islands than did the extensive vegetative roof systems. High albedo materials additionally improved the microclimate conditions. The best results for mitigating the effects of urban heat islands were obtained by the strategy which involved installing intensive green roof systems and the use of high albedo materials in public spaces (F+) in all chosen locations.

The numeric data in tab. 3 and fig. 5 show the maximum temperature differences predicted by the four models in relation to the baseline model at pedestrian and roof levels for the four studied Belgrade locations on a typical summer day at 07:00, 13:00, and 19:00 h and at 1:00 h the following night. The models showed use of extensive green roof systems in the urban areas would reduce the external air temperature up to 0.47 °C at pedestrian level and up to 0.53 °C at roof level, while intensive green roofs would decrease ambient air temperatures at pedestrian and roof level up to 1.51 °C and 1.45°C, respectively. The models revealed that introduction of cool materials in public areas combined with utilization of extensive green roofs could reduce the temperature up to 1.60 °C and 0.90 °C at pedestrian and roof level, respectively, while cool materials and intensive green roofs would potentially reduce the external air temperature up to 1.80 °C at pedestrian level and up to 1.45 °C at roof level.

Result validation of ENVI-met numerical modelling is done by comparing it with verified data from other researches. In a case study of Rome [29] the study analyses the im-

Table 2. Conditions and details of initial parameters for the simulations used in ENVI-met Version 4 (Summer17 Release)

Start and duration of model run
Start Date (Simulation day): 23.06.2017.
Start Time: 05:00:00
Total Simulation Time [h]: 24

Initial meteorological conditions
Wind speed measured at 10 m height [ms^{-1}]: 1.9
Wind direction: 150 ° (SSE)
Roughness length at measurement site: 0.01
Model rotation out of grid: North was set for each model

Temperature T
Initial air temperature [°C] 16.8
min [°C] 16.8 (05:00 h),
max 30.4 (16:00 h)

Humidity q
Relative humidity [%]
min 34 (16:00 h), max 62% (21:00 h), average 50%

Geographic data for Belgrade, Serbia
Altitude 132 m
Latitude 44°48'N
Longitude 20°28'E

Number and size of grid and nesting properties
Main model area:
x-Grids:70, y-Grids: 80, z-Grids: 30
Size of grid cell in meters: dx = 5.0, dy = 5.0, dz = 5.0 (base height)
Nesting grids around main area: 3
Soil profiles for nesting grids:
Default = unsealed soil

Figure 3. Urban structures with control points positions, 2-D view

pact of green roofs for the mitigation of the urban heat island effect. The ENVI-met numerical analysis was validated through experimental measurements. The results showed a lowering of the vertical air temperature profile of 0.5°C at morning and about 0.3°C at night with extensive green roofs added on buildings. It was noticed that there is not an air temperature difference from the standard to the green roof scenarios at 2pm when there is the maximum solar radiation. In Belgrade, the values with the implementation of extensive green roofs are similar.

Toronto [5, 6] study evaluates different UHI mitigation strategies in different urban neighbors of Toronto, selected according to their building density. The effects of cool surfaces (on the roofs, on the street pavements or as vegetation areas) are evaluated through numerical simulations using the software ENVI-met. The validation of the ENVI-met model was through a comparison between field measurements and simulation results. The results showed that the temperature in most of the areas are cooler down up to 0.75 °C at 1.8 m above ground at the summer mid-day. Those correspond to our Future model.

Hong Kong case study [67]. Firstly, the building-scale field measurement found that the 484 m^2 experimental extensive green roof can significantly ameliorate rooftop microclimate and cut building energy consumption. Secondly, the neighborhood-scale ENVI-met modeling

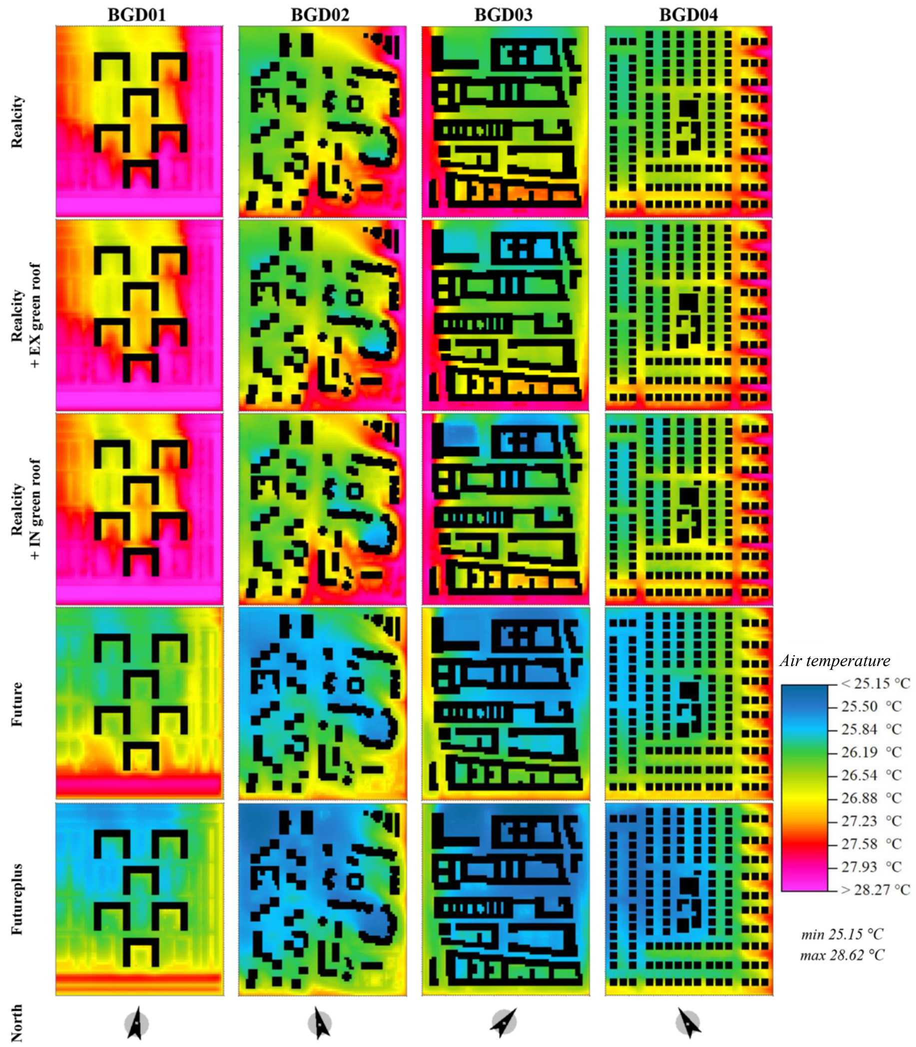

Figure 4. Detailed maps of potential temperature changes at pedestrian level (1.5 m) for the baseline model and the four retrofitted models at four locations on June 23 2017 at 13:00 h (*for color image see journal web site*)

revealed that greening all roofs in residential communities can extend the cooling effects from the rooftop to the entire neighborhood. For typical summer day, five different urban locations with different urban forms have maximum air temperature variation at pedestrian level is 2.7, 1.5, 1.8, 0.5, 1.4 °C in the daytime, 1.4, 0.5, 0.7, 0.3, 0.4 °C at night, respectively. Urban design factors such as building height, distance, site coverage and orientation can affect the diurnal, horizontal and vertical pattern of the *cool-islands* created by green roofs. Green roof can also enhance the rooftop thermal comfort by alleviating the intensity and duration of heat stress. The findings suggest that compact cities can green the roof space to provide thermally comfortable and recreational venues for urban residents.

Table 3. Comparison of the maximum temperature differences ΔT [ºC] at pedestrian and roof levels predicted by the four models in relation to the baseline model at four locations in Belgrade at 07:00 h, 13:00 h, and 19:00 h on June 23 and at 01:00 h on June 24

Time of day on June 23 or 24	Realcity+EX green roof comparison with RC (1 on x-axis)	Realcity+IN green roof comparison with RC (2 on x-axis)	Future comparison with RC (3 on x-axis)	Futureplus comparison with RC (4 on x-axis)
BGD01				
Pedestrian level (1.5 m) ΔT [ºC]				
07:00	– 0.21	– 0.69	– 0.93	– 1.21
13:00	– 0.13	– 0.26	– 1.60	– 1.80
19:00	– 0.13	– 0.28	– 0.59	– 0.71
01:00	– 0.19	– 0.40	– 0.31	– 0.54
Roof level (17.5 m) ΔT [ºC]				
07:00	– 0.33	– 0.92	– 0.52	– 1.10
13:00	– 0.17	– 0.28	– 0.90	– 1.14
19:00	– 0.19	– 0.39	– 0.39	– 0.66
01:00	– 0.28	– 0.65	– 0.36	– 0.73
BGD02				
Pedestrian level (1.5 m) ΔT [ºC]				
07:00	– 0.23	– 0.65	– 0.66	– 1.10
13:00	– 0.37	– 0.91	– 1.33	– 1.62
19:00	– 0.29	– 0.68	– 0.53	– 0.85
01:00	– 0.17	– 0.44	– 0.26	– 0.51
roof level (37.5 m)				
07:00	– 0.21	– 0.79	– 0.25	– 0.79
13:00	– 0.16	– 0.42	– 0.48	– 0.72
19:00	– 0.14	– 0.44	– 0.28	– 0.59
01:00	– 0.14	– 0.54	– 0.19	– 0.59
BGD03				
Pedestrian level (1.5 m) ΔT [ºC]				
07:00	– 0.47	– 1.51	– 0.69	– 1.57
13:00	– 0.33	– 0.72	– 1.39	– 1.54
19:00	– 0.31	– 0.95	– 0.53	– 1.01
01:00	– 0.35	– 1.28	– 0.39	– 1.29
Roof level (22.5 m) ΔT [ºC]				
07:00	– 0.53	– 1.45	– 0.56	– 1.45
13:00	– 0.29	– 0.62	– 0.61	– 0.93
19:00	– 0.26	– 0.71	– 0.37	– 0.82
01:00	– 0.30	– 0.99	– 0.35	– 1.01
BGD04				
Pedestrian level (1.5 m) ΔT [ºC]				
07:00	– 0.23	– 0.76	– 0.51	– 1.00
13:00	– 0.09	– 0.34	– 0.90	– 1.21
19:00	– 0.19	– 0.39	– 0.37	– 0.57
01:00	– 0.30	– 0.53	– 0.37	– 0.59
Roof level (12.5 m) ΔT [ºC]				
07:00	– 0.19	– 0.84	– 0.32	– 0.94
13:00	– 0.14	– 0.41	– 0.54	– 0.87
19:00	– 0.21	– 0.45	– 0.33	– 0.58
01:00	– 0.33	– 0.66	– 0.39	– 0.72

The models predict the temperature reductions at pedestrian level achieved by utilizing a system of green roofs on lower-level urban structures (BGD04) would be greater than on the other buildings studied, which had more stories (BGD01, BGD02, BGD03). This might be explained by the fact that the distance between the roof and the pedestrian level is less in BGD04 than in the medium-rise buildings (BGD01 and BGD03) or the high-rise structures in BGD02. Therefore, the influence of green roofs, both extensive and intensive, was more pronounced in BGD04 at pedestrian level.

Results were more pronounced at roof rather than at pedestrian level for both extensive and intensive green roofs. Exceptionally low buildings were an exception, *e. g.* an underground storehouse in BGD03 with a height reaching just 1 m above ground level, where the effect of implementing an intensive green roof was felt more at pedestrian level rather than 2.5 m above the green roof level.

The data show that for the climatic zone of Belgrade, it should be possible to lower the external air temperature for all types of buildings by installing green roofs, with a significant improvement felt at pedestrian level in locations with low-story urban structures, particularly in urban neighbourhoods with family houses, as well as in areas with one- or two-story buildings (warehouses, workshops, schools, kindergartens, underground garages). Less improvement (smaller temperature reductions) would occur in areas with high-rise buildings and in densely populated areas.

The models predicted installation of green roofs would produce reductions in the external air temperature by similar amounts at roof level, *i. e.* at the level of the uppermost story or the penultimate story, for all building types in the Belgrade climatic zone, which indicates the importance of utilizing green roofs on all types and heights of buildings.

This research showed the use of intensive green roofs would produce greater reductions of the outdoor air temperatures at pedestrian level than did extensive green roofs.

The use of high albedo materials for surfaces in public spaces in combination with green roofs produced the most significant results, particularly at pedestrian level (1.5 m).

In densely populated urban units and built-up zones such as BGD03, roof surfaces are almost the only surfaces which could be planted and provide the only chance for some parts of the city to become green oases. Installing green roofs on existing buildings would increase the percentage of planted green surfaces by 11, 21, 43, and 28% at locations BGD01, BGD02, BGD03, and BGD04, respectively.

The results show the impact of green roofs in Belgrade's climatic zone would be felt throughout the entire 24 h period, but the least impact would occur during the night, while the use of high albedo materials would be felt the most during those periods when solar radiation has direct impact.

The effect of exchanging low albedo materials for high albedo ones in public spaces would be more significant around low-level buildings, since shadows formed by high-rise buildings in narrow streets prevent direct exposure to solar radiation and direct heating of the surfaces.

Figure 6 shows temperature changes registered in control points, placed to monitor the temperature reduction trends for the investigated strategies. Control points confirmed the temperature reduction trends described above for the implementation of extensive and intensive green roofs, and the exchange of low for high albedo materials in public spaces.

A noticeable temperature reduction was observed at pedestrian level in the interior of compact blocks of traditional buildings in the center of Belgrade, as studied in BGD03, fig. 6, and also in the interior courtyard (atrium) of a double-story (height = 10 m) kindergarten in

Figure 5. Maximum temperature differences Δ*T* [ºC] at pedestrian and roof levels predicted by four models in relation to the baseline model at four locations (BGD01, BGD02, BGD03, BGD04) in Belgrade on June 23 at 07:00 h, 13:00 h, and 19:00 h and at 01:00 h on June 24; *Legend: y-axis: ΔT [ºC], x-axis: (1) RC+EX green roof comparison with RC, (2) RC+IN green roof comparison with RC, (3) Future comparison with RC, (4) Futureplus comparison with RC*

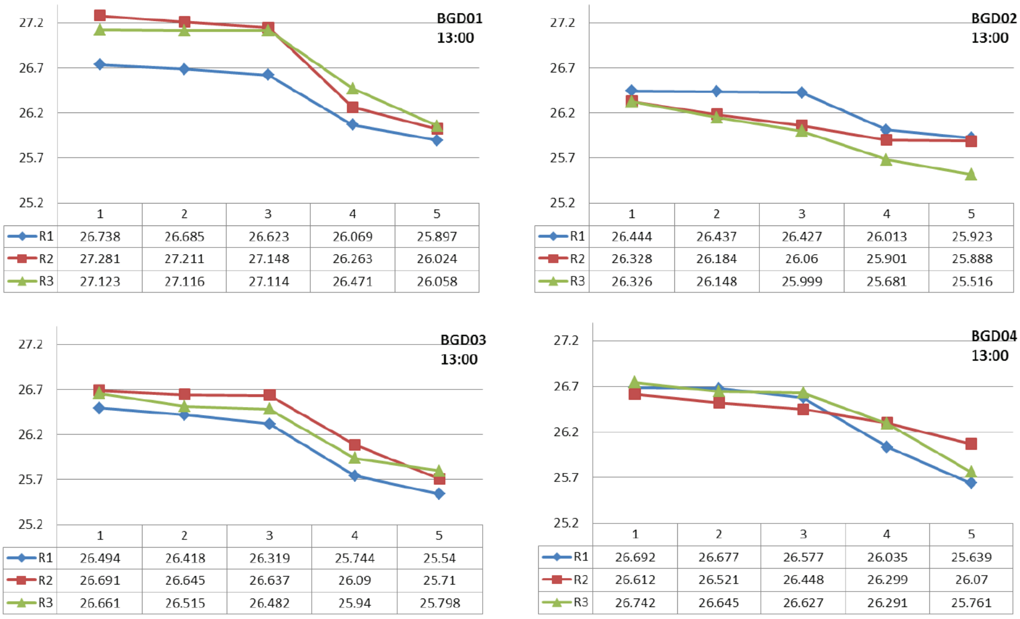

Figure 6. Overview of temperature comparisons at pedestrian level (1.5 m) recorded in control points R1, R2, and R3 for the baseline model (1) and calculated for four models (RC+Ex green roof, RC+IN green roof, F, and F+) at four Belgrade locations (BGD01, BGD02, BGD03, BGD04) on June 23 at 13:00 h; *Legend: y-axis: T [ºC], x-axis: models (1) RC, (2) RC+EX, (3) RC+IN, (4) F, (5) F+*

BGD02, indicating the temperature reductions and, importantly, the greater human thermal comfort that is achievable in interior courtyards by using green roofs.

Control points placed above asphalt surfaces showed that changing the upper layer of finishing materials in public spaces would reduce the air temperature at pedestrian level, which is particularly significant for those parts of the city with large open spaces for parking, playgrounds, sports grounds, squares, plazas and open lots associated with storage warehousing. The use of high albedo materials during renovations of roads and pavements would also be significant, as it would lead directly to reducing the outdoor air temperature in the urban environment and contribute to mitigating the effects of urban heat islands, as can be seen by comparing the outputs of models RC+EX and F and the outputs of models RC+IN and model F+, for all four studied locations.

Conclusions

It can be concluded from this numerical research that installation of green roof systems on larger urban matrices or in urban neighborhoods would contribute to outdoor air temperature reductions. This would improve the comfort of residents and reduce energy consumption for buildings cooling. We also studied the effect of installing green roofs in combination with the use of cool materials in public spaces within urban zones, which produced improved results in terms of mitigating the effects of urban heat islands.

Quantification of the environmental impact factors of extensive and intensive green roofs and high albedo materials in typical urban structures in Belgrade were studied at four locations with the help of the scientifically well-established microclimate model, ENVI-met. The resultant data showed that utilizing green roof systems in the climatic zone of Belgrade would be an acceptable urban design strategy, which would lead to mitigation of urban heat islands and potentially to the contraction of urban cool islands in the city for all types of urban structures. Exchanging the existing low albedo materials for high albedo ones in public spaces would also contribute to reducing the exterior air temperatures in urban areas.

Four potential retrofitting strategies were modeled in comparison with the baseline model, and results showed that installing extensive green roof systems in the Belgrade urban environment would reduce the exterior air temperature by a maximum of 0.47 °C at pedestrian level and 0.53 °C at roof level, while intensive green roofs would reduce the temperature up to 1.51 ºC and 1.45 ºC at pedestrian and roof level, respectively. Reconstruction of existing public spaces by using higher albedo-value materials together with extensive green roofs could potentially reduce the air temperature up to 1.60 ºC and 0.90 ºC at pedestrian and roof levels, respectively. The maximum mitigation effect for urban heat islands would be obtained using the strategy of intensive green roofs combined with high albedo materials, which would potentially lower the temperature in urban environments by a maximum of 1.80 ºC at pedestrian level and 1.45 ºC at roof level. The results of numerical modelling are compared with verified data from other researches.

The numerical modelling results shows that increasing the albedo of pavements, roads and playgrounds helps to decrease their surface temperature and reduce the amount of sensible heat released to the atmosphere. Albedo may increase by provide an appropriate surface coating such as proposed in F and F+ retrofitted models. Effects at pedestrian level are more pronounced because the surface with high albedo is closer to pedestrians, which increases urban thermal comfort. Potential of high albedo materials is important to optimize the rehabilitation of urban zones and mitigating urban heat island in the cities.

This study reports the positive thermal effects of green roofs and provides a scientific basis for understanding the use of vegetative roofs on existing and planned buildings. It also affords evidence for promoting the use of green roofs among the academic community, decision makers, residents and investors living and working in the Belgrade climatic zone.

The results obtained offer evidence showing the potential of applying natural elements – vegetative roofs – in the urban rehabilitation and creation of sustainable and attractive cities, contributing to ecologically, economically, and socially sustainable urban development. Additionally, the results show this type of modeling could be useful during urban planning and building design processes.

A mix of regulatory, fiscal, informational and market-based policy instruments are needed to promote energy renovation of buildings, use of energy efficient technologies and behavior in the residential sector in Serbia.

Further research will focus on the impact of green roofs on CO_2 emissions and the roofs' potential contribution to air quality improvement in Belgrade.

Also, a part of the future research may go in a direction that would show that the outer shadow effects have more effects than internal insulation.

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