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Reducing CO_2 concentration in city centres with green roofs implementation: Case study Belgrade, Serbia

M. Lalošević[1*], M. Komatina[2], B. Živković[3], M. Miloš[4]

[1]*Urban Planning Institute of Belgrade, Palmotićeva 30, Belgrade, Serbia*

[2,3,4] *Faculty of Mechanical Engineering, University of Belgrade, Kraljice Marije 16, Belgrade, Serbia*

This paper presents the results on reducing CO_2 concentration with green roofs implementation in a densely populated urban area in Belgrade city centre. The buildings on which green roofs are implemented have an average height of 15 meters. In order to investigate the impact of existing residential urban blocks and potential retrofitting model on CO_2 concentration, base model was designed (the model fully complied with the actual status and real conditions in the location) as well as retrofitting models (which present base model with added elements of extensive and intensive green roofs) and numerical simulations of CO_2 concentrations for all presented models were done. Differences in CO_2 concentrations at height of 1.5 m (pedestrian level), 7.5 m and 17.5 m at 7 am and 7 pm, on a typical summer day in Belgrade were investigated. ENVI-met software was used to perform the simulations. The resultant data of numerical simulation showed that utilizing the green roofs instead of classical flat roofs in Belgrade climatic area could reduce atmospheric concentration of CO_2 around the building up to 11%, average 2.3%. By using proposed strategy, it is demonstrated that applying vegetative roofs could be valuable instrument for noteworthy contribution to environmental protection in Belgrade and for climate change mitigation, both local and global.

Keywords: green roof, CO_2 reduction, urban area, sustainable development, ENVI-met

INTRODUCTION

Green roofs are part of green infrastructure in urban areas. Green infrastructure refers to a strategically planned and managed network of green spaces and other environmental features and technologies necessary for the sustainability of any urban area. Green infrastructure uses vegetation, soils, and natural processes to manage temperature, water, and air quality to create healthier, resilient, and more beautiful urban environments [1].

This study investigates an impact of green roofs implementation on reducing CO_2 concentration in a densely populated urban area in Belgrade city centre.

Green roofs, also known as eco-roofs, roof gardens, vegetative roofs and living roofs can be defined as the roofs with vegetation on the uppermost layer [2]. Green roofs can be split into two categories, ”extensive” and “intensive”, with respect to weight, substrate layer, maintenance, cost, plant community and irrigation. Intensive green roofs may include shrubs and trees and appear similar to landscaping found in urban parks. The depth of growth media on an intensive green roof usually varies between 20 cm and 1.2 m. Intensive green roofs have intense maintenance needs. Extensive green roofs are planted with low height and slow growing plants and require insignificant maintenance. The depth of the growth media is less than 15 cm. Due to additional load on building structure, and costs, shallow substrate extensive green roofs are more common than deeper intensive roofs, especially in retrofitting design scenarios when green roofs are installed onto existing buildings.

Green roofs offer multiple benefits. They reduce CO_2 emissions and they have a significant role in the strategies for adapting to high temperatures and reducing the effect of heat islands in urban environments. Establishing green roofs can improve stormwater management, conserve energy, increase longevity of roofing membranes, and improve return on investment compared to traditional roofs. They also contribute to increasing urban biodiversity, reducing noise, offering the possibility for development of urban agriculture, and having positive effects on human health. In addition, green roofs provide a more aesthetically pleasing environment. Reviews of the main environmental benefits of green roofs are available in papers [3, 4].

Green roofs reduce ambient CO_2 concentrations in the vicinities [5-8]. Besides direct amelioration of air pollutants by green roofs, they also reduce emissions indirectly [9]. Green roofs indirectly reduce CO_2 releases from power plants and furnaces by reducing demand for heating and cooling, suggesting long-term economic and environmental benefits of green roofs [6].

Concerning CO_2 sequestration, studies reveal

* To whom all correspondence should be sent: marija.lalosevic@urbel.com

that green roofs directly sequester substantial amounts of carbon in plants and soils through photosynthesis [10-12]. Photosynthesis removes carbon dioxide from the atmosphere and stores carbon in plant biomass, a process commonly referred to as terrestrial carbon sequestration. Carbon is transferred to the substrate via plant litter and exudates. The time length that this carbon remains in the soil before decomposition has yet to be quantified for green roofs, but if net primary production exceeds decomposition, this man made ecosystem will be a net carbon sink, at least in the short term [10].

The extensive study for Chicago evaluated the impact of green roofs on air pollution control. By using a big-leaf dry deposition model, the air pollutants removed by green roofs in Chicago were quantified. The result showed that the green roofs can remove a large amount of pollutants from air. A total of 1675 kg of air pollutants was removed by 19.8 ha of green roofs in one year with O_3 accounting for 52% of the total, NO_2 (27%), PM□□ (14%), and SO_2 (7%). The highest level of air pollution removal occurred in May and the lowest in February. The annual removal per hectare of green roof was 85 kg [13].

Complete review that encompasses published research on how green roofs can help mitigate pollution is given in the paper [14].

Another asset of green roof carbon mitigation is that this urban greening strategy is not in space competition with the surface built environment, which is in contrast to other types of urban greening, e.g. urban parks and green spaces [13].

The green roof can be a solution in the environmental rehabilitation of urban zones since it makes use of rooftops, usually 40–50% of the impermeable area in a city.

To our knowledge, reliable data from the scientific literature are lacking on the impact of green roofs in Belgrade, based on which the impacts of their utilization could be determined. Therefore, for this research, the impact of green roof systems on the urban environment in the Belgrade climatic zone was studied using the software tool, ENVI-met. For research purposes, two scenarios of green roof systems (extensive and intensive) utilized on existing buildings were used and compared with a base (realistic) model as reference, in order to explore the influence on lowering carbon dioxide concentration in atmosphere around buildings, in city centre of Belgrade.

TERRITORY AND DATA

For this research typical residential neighbourhood in Belgrade, was chosen. According to urban structures, number of stories, and percentage of green and asphalt surfaces this area represents typical urban form of the Belgrade city centre. The studied location is part of the territory of the municipality of Vračar.

The model of the urban block fully complied with the actual conditions in the location (shape of the buildings, number of stories, position and type of vegetation, position of roads and pavements). The average building height is 15 m. View of the modelled structures in the location is given in Fig.1 (2D view) and Fig.2 (3D view).

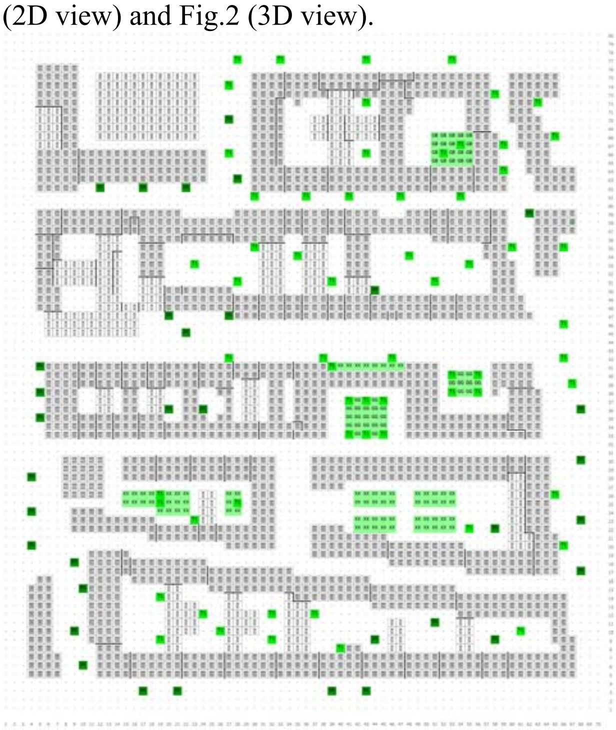


Fig.1. Base model input file – 2D view

Belgrade is located in a moderate continental climate zone, with warm summers, mean summer air temperature from 21 to 25 ºC, 30 to 55 tropical days and up to 26 tropical nights annually, with heat waves in July and August. In the current research, statistical data and parameters for a typical summer day in Belgrade were used (Tab.1).

METHODOLOGY

ENVI-met software is one of the most commonly used programs for investigating the microclimate influence of green roofs [15-19]. ENVI-met is a scientifically established prognostic, three-dimensional, high resolution urban microclimate model [20], which considers physical fundamentals based on the principles of fluid mechanics, thermodynamics and atmospheric physics to calculate three-dimensional wind fields, turbulence, air temperature and humidity, radiative fluxes, and pollutant dispersion. It is designed for microscale with a typical horizontal resolution from 0.5 to 5 metres and a typical time frame of 24 to 48 hours with a time step of 1 to 5 seconds. This resolution allows to analyze small-scale interactions between individual buildings, surfaces and plants.

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

In the first phase input file for a base (real) model was constructed and investigated.

The dimensions of the studied location were 350x400 meters, divided into a 3-D grid with 5 m gridline divisions. Building heights, the spatial distribution of buildings in the field, position of the vertical greenery, type of trees, and other spatial elements were modelled on real conditions in the location, so the ENVI-met model was properly representative of the urban structures in the location, with spatial relationships reflecting those in real life.

In second phase two models of sustainable retrofitting strategies were modelled and investigated.

The first retrofitting model, extensive green roof model, had all the same characteristics as the baseline model, with added element of extensive green roofs. The second retrofitting model, intensive green roof model, comprised the baseline model with added intensive green roofs.

None of the other characteristics were altered in the research of retrofitting models, so they remained the same as in the baseline model. The green roof structures are treated as an additional layer of insulation. The vegetation used as an element of green roof is of indigenous (native) variety.

In the investigation the base model was used as the reference for comparison with the green roof retrofitting strategies/models, both extensive and intensive.

An area input file with 3-dimensional geometry of the modelled structures for base model is given in Fig.3 (3D view), for green roofs model is given in Fig.4 (extensive green roofs, 3D view) and Fig.5 (intensive green roofs, 3D view).

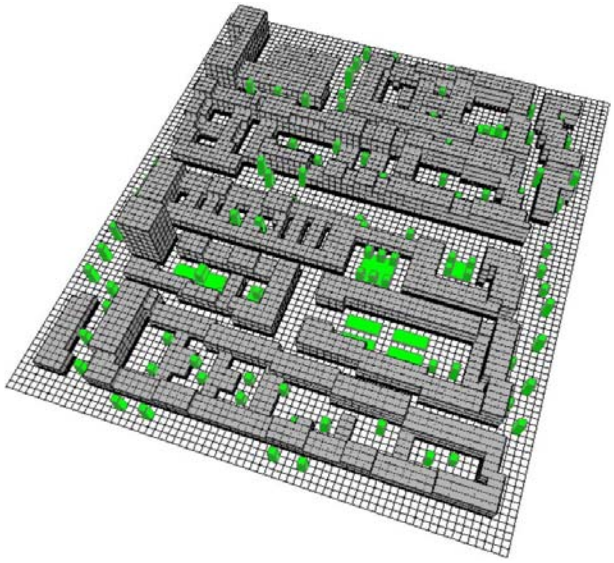


Fig.2. Base model input file – 3D view

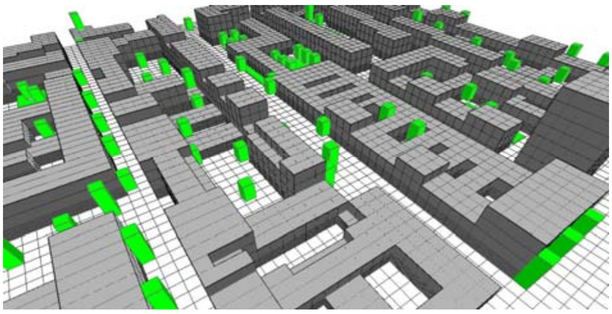


Fig.3. Base model input file, detail – 3D view

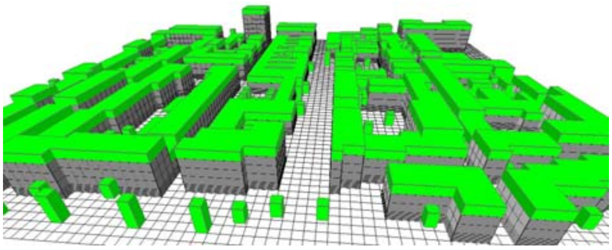


Fig.4. Model with extensive green roofs implemented, input file, detail – 3D view

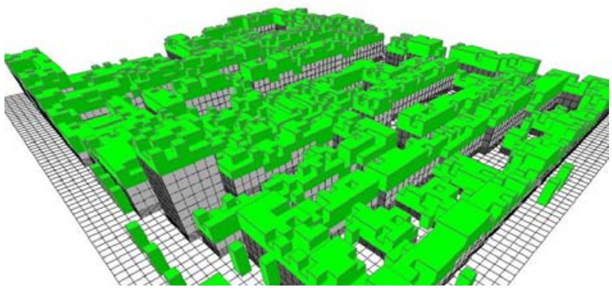


Fig.5. Model with intensive green roofs implemented, input file, detail – 3D view

Simulations were conducted for a 24 h period, for a typical summer day in Belgrade on 23 June. The simulations commenced at 05:00 am.

Table 1. Conditions and details of initial parameters for the simulations used in ENVI-met

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 (m/s): 1.9
Wind direction: 150 ° (SSE)
Roughness length at measurement site: 0.01
Model rotation out of grid: North was set for the 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: 350x450 m
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

RESULTS AND DISCUSSION

Fig.6 shows the CO_2 concentration in the atmosphere around buildings at different levels: pedestrian level (1.5 m), 7.5 m and 17.5 m respectfully, for the base model and two models of retrofitting strategies (extensive green roofs and intensive green roofs). The concentration of CO_2 in the atmosphere is shown at 7 in the morning, for a typical summer day in Belgrade, with a mild wind of 1.9 m/s.

Observing the CO_2 concentration, a decreasing trend in reducing concentration in the investigated retrofitting strategies is observed, respectively. A larger impact on CO_2 reduction has a strategy with intensive green roofs than extensive one.

At all examined cross-cuts, intensive green roofs give a greater contribution than extensive green roofs.

Reduction intensity is directly related from the distance of the green roof. The results of the numerical simulation show that the most intensive impact is at a height of 7.5 meters. This can be explained by the fact that the percentage of buildings with roof tops at 18, 20, 25 and 40 meters is lower than those with roof surfaces at level of 8, 10, 12 and 15 meters, and the result of the impact is expected to be higher at 7.5 meters than 17.5 meters.

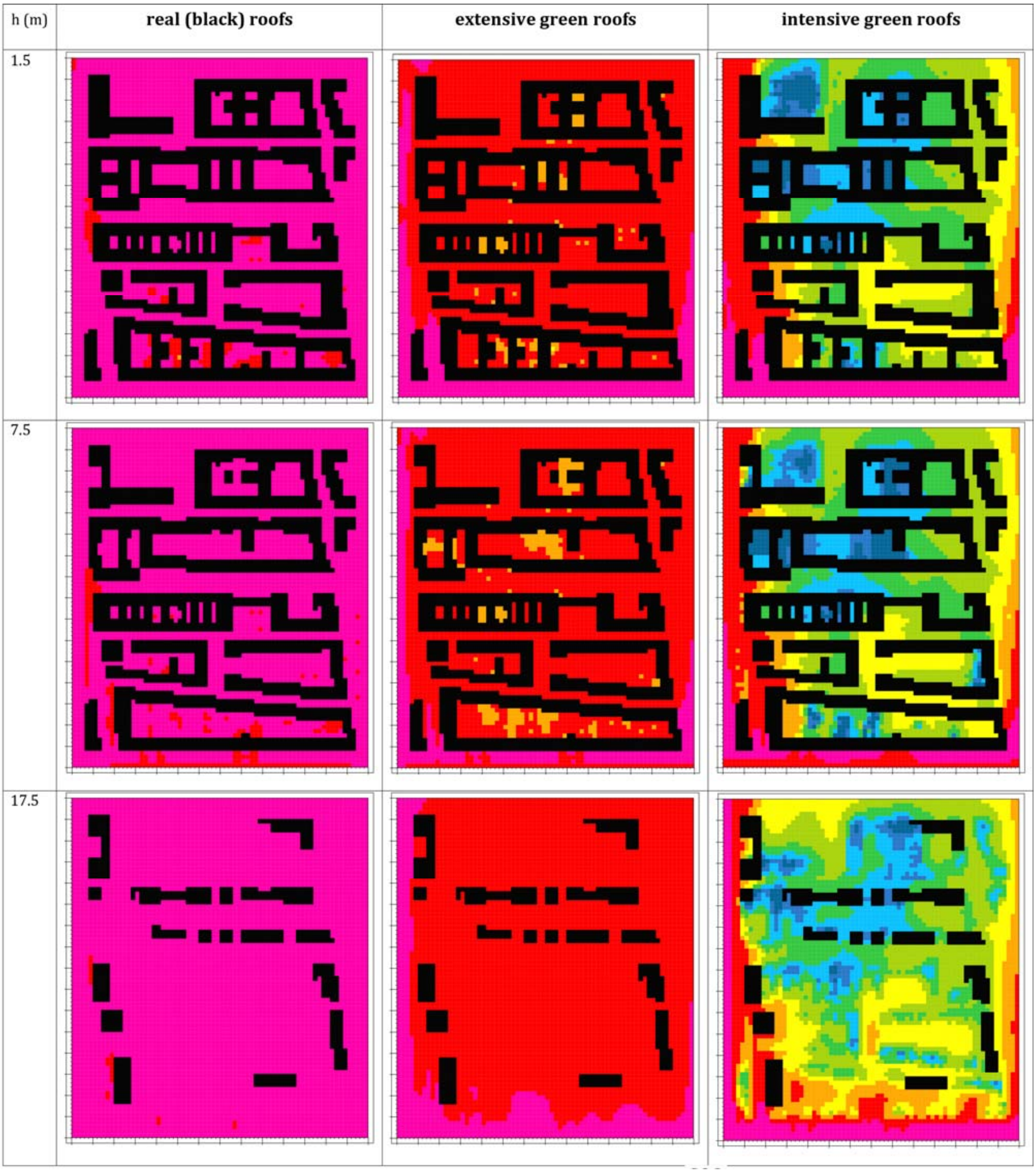
Fig.7 and Fig.8 present comparisons for three models – base model with black roofs, model with extensive green roofs and model with intensive green roofs. Minimum and maximum values are displayed for 7 am and 7 pm.

Since the vegetation is more active during the morning hours, decrease in the concentration of CO_2 around objects is observed with the use of vegetative roofs. Intensive green roofs make a greater contribution than the extensive (Fig.7).

Plants absorb CO_2 from the atmosphere for photosynthesis and release CO_2 to the atmosphere during respiration. The rate of photosynthesis depends on the intensity of light. In the daytime with a lot of sunlight, photosynthesis is very active and plants absorb CO_2, resulting in reducing the CO_2 concentration in the surrounding. At night photosynthesis becomes weak and vegetation acts as a source of CO_2 due to respiration, resulting in a higher CO_2 concentration. Because of this process, it is noticeable that there is a small contribution to increasing the concentration of CO_2 in the evening hours, as can be seen in Fig.8.

During periods of direct sunlight intensive green roofs with its denser and higher vegetation contributes to greater impact on improving air quality. Therefore in periods of intense respiration of plants vegetation on intensive green roofs emits more CO_2 than plants on an extensive green roof, which contains only low-growth plants.

In a typical summer sunny day in Belgrade, the CO_2 absorption rate of a green roof vegetation in the daytime is much greater than the CO_2 emission rate at night, as other authors also stated for their location [5].



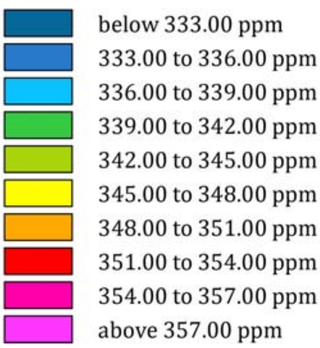


Fig.6. Detailed maps of CO_2 concentration (ppm) for base model, extensive green roofs model and intensive green roofs model, at pedestrian level (1.5 m), 7.5 m and 17.5 m high for typical summer day in Belgrade at 7 am

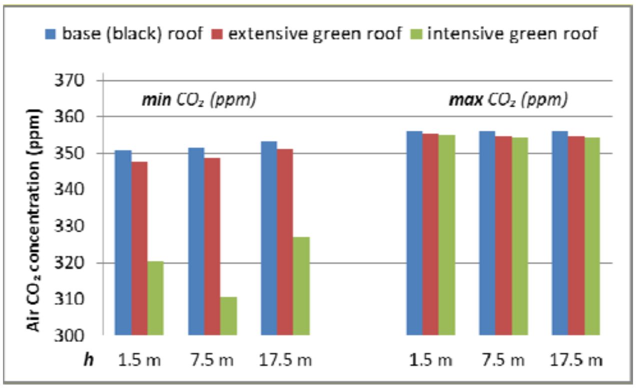


Fig.7. Minimal and maximal CO_2 concentration (ppm) for base model and two retrofitted models (extensive and intensive green roofs models) at levels of 1.5 m, 7.5 m and 17.5 m on 23 June at 7 am

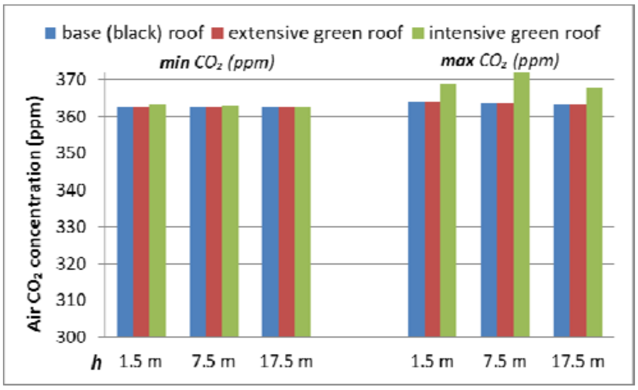


Fig.8. Minimal and maximal CO_2 concentration (ppm) for base model and two retrofitted models (extensive and intensive green roofs models) at levels of 1.5 m, 7.5 m and 17.5 m on 23 June at 7 pm

At Fig.9 is shown a potential difference in the CO_2 concentration at a height of 7.5 meters, between the base model with black roof and the models with implemented intensive green roofs.

It is noticeable that the impact of intensive green roofs is significant, especially in the interior of housing blocks. At the observed height of 7.5 meter, it is concluded that impact is smaller in areas where the roof level is 20, 25 or 40 meters. A numerical simulation was run for a typical summer day with a mild wind, so this difference is noticeable. It can be assumed that, in days with strong wind, air mixing is more intense, which would lead to a more unified CO_2 concentration in the air around the objects.

In an explored case with intensive green roofs, the reduction is up to a maximum of 44.81 ppm (up to 11%) compared to the base model. The average decrease in the concentration for the observed comparison of CO_2 is 9.41 ppm (2.3%).

General conclusion is that green roofs contribute to the reduction of the CO_2 concentration to a large extent.

Also, it can be concluded that the closer to the green roof region is, the greater the reduction of CO_2 concentration will be.

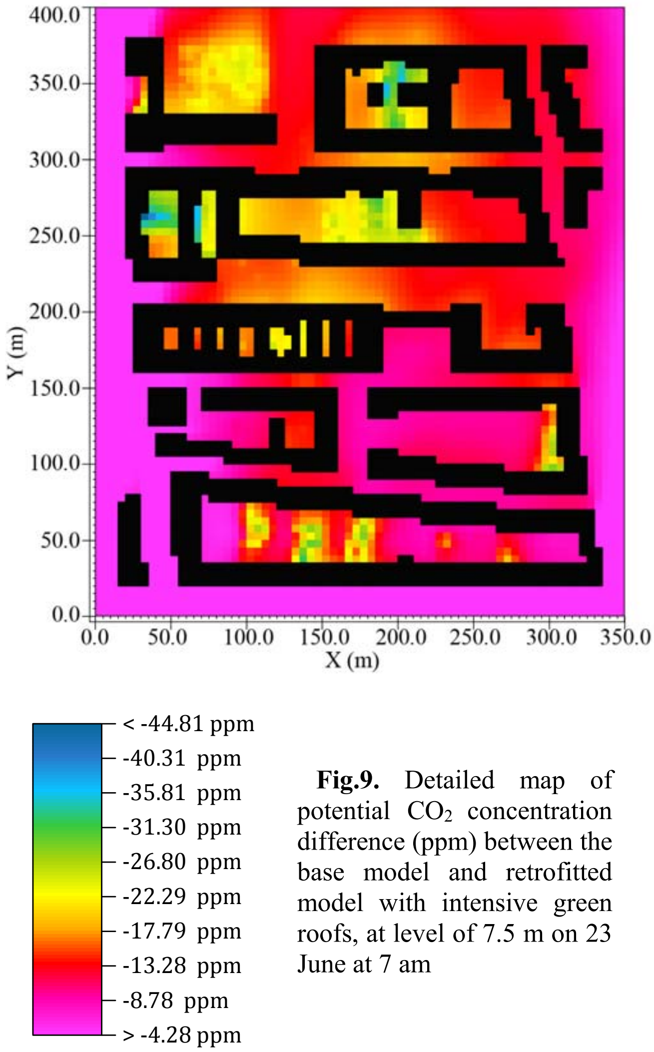


Fig.9. Detailed map of potential CO_2 concentration difference (ppm) between the base model and retrofitted model with intensive green roofs, at level of 7.5 m on 23 June at 7 am

Result validation of ENVI-met numerical modelling is done by comparing it with verified data from other researches.

In a case study of Hong Kong [5] the authors concluded that the decrease of ambient CO_2 concentration near green roofs is substantial. The paper studied the effect of a green roof on the ambient CO_2 concentration as an example to assess the benefit of urban greening. The study comprises three parts. Firstly, field measurement of the difference of CO_2 concentration at a location in the middle of the plants in a small plot of green roof and one in the surrounding area with bare roof were done. Data showed that the CO_2 concentration above the green roof, on a typical sunny day with light wind, was 4.3 mg/m³ lower than at the control roof during the day time before 4 pm and slightly higher during the night time. In the second part, in order to further evaluate the effect of green roofs on ambient CO_2 concentration, the authors measured the CO_2 of the green roof in a chamber to construct an absorption/emission velocity curve. In the third part of research, the author modelled the green roof effects in an urban area with a species transport module from commercial computational fluid dynamics software, using absorption/emission velocity curve. Simulation results showed that CO_2 concentration around the green roof fell noticeably. Depending on the amount of wind facilitating the mixing, the reduction of CO_2 concentration in the green roof vicinity reached up to 9.3 %. In Belgrade, the maximum values with the implementation of intensive green roofs are similar (up to 11%). Authors for Hong Kong stated that in a sunny day, a green roof may lower the CO_2 concentration in the nearby region as much as 2%. In our case average difference in CO_2 is 2.3%, which is in a similar range.

The paper [7] that was aimed at evaluating the potentials of extensive green roofs in increasing the ecological function in urban areas compared to impervious surface rooftops by discussing a green roof case study from the South-eastern Tehran is interesting to compare with our results. The main objective of the study was to evaluate the genuine effect of extensive green roofs on microclimatic conditions and air quality parameters. Two buildings with different roof covers (green and bitumen roof) were selected. Air temperature, relative humidity and carbon dioxide concentration data loggers were installed on both of them in two different conditions. For a typical sunny day, results demonstrated that average air CO_2 concentration inside and outside of the screen box above the green roof during the studied period were on average 27.98 and 20.71 ppm lower than the reference roof. In our research we have lower results for extensive green roof case (4.71 ppm), which can be explained by the fact that the concentration of CO_2 in South-eastern Tehran experiment was measured at 1 meter above the roof surface. In such case CO_2 concentration is expected to be lower due to the immediate proximity of the plants that are responsible for carbon sequestration. Also, there is a great difference in the climatic condition between South-eastern Tehran and Belgrade.

It can be concluded that even low rise vegetation on a roof surface can contribute to the reduction of the CO_2 content in the air, as the other authors concluded [7].

Carbon dioxide is an essential component of the air, and very important for the photosynthesis of vegetation. Plants use photosynthesis to convert the CO_2 from the air into glucose. The higher the biomass of a plant, the higher it absorbs the CO_2. The result of that process is reducing CO_2 concentration in atmosphere around buildings with vegetative roofs on the top. Intensive green roofs have higher biomass than extensive, which results higher lowering CO_2 concentration in case with retrofitting strategy with intensive green roofs model.

The increase of green space in the urban area may potentially contribute to reduce of CO_2 atmospheric concentration.

In densely populated urban units and built-up zones such as investigated one, 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 43 %.

CONCLUSIONS

This paper uses green roofs systems (extensive and intensive) in densely built urban neighbourhood as an example to quantify their effect on the ambient CO_2 concentration.

After the construction and investigation of the base model, two additional sustainable urban models were constructed. Base model contained all the relevant characteristics of the existing condition – the position, size and shape of buildings, position and type of plants, distribution of surface materials and soil types – representing the current condition for the urban location.

The base model was used as the reference for comparison with the sustainable retrofitting strategies, in which extensive green roofs or intensive green roofs were implemented on all buildings. Except the implementation of green roofs, other parameters of the model were not altered.

The discussion concentrates on how green roofs, both extensive and intensive, influence on reducing carbon dioxide concentration in atmosphere in urban environment.

It can be concluded from this numerical research that installation of green roof systems on larger urban matrices or in urban neighbourhoods would contribute to CO_2 concentration reductions.

The CO_2 concentration around the green roofs falls noticeably due to the green roof serving as a sink of CO_2.

Atmospheric CO_2 concentration above the base (reference) roof was more than the extensive green roof model and intensive green roof model, due to the effect of vegetation on CO_2 absorption.

This research showed the use of intensive green roofs would produce greater reductions of the CO_2 concentration than did extensive green roofs, at all investigated levels, for a typical sunny day in Belgrade.

The greatest influence of the mitigation of the concentration of CO_2 is felt in the immediate vicinity of the plants.

The paper also refers to green roofs as a new technology and one of the segments of green construction that represent a modern approach to finding sustainable solutions. Green roofs are important for modern architecture and add new value to the role of buildings in urban planning. They are designed not only to return the natural element to the urban environment, but also to provide solutions for important problems such as the effect of urban heat island and high CO_2 concentration.

Innovative and sustainable approaches in urban areas can be adopted to remove existing air pollutants thereby reducing air pollution concentrations. One way to reach that goal is the use of green roofs which can reduce air pollutants through microclimate effects.

While it is desirable to use trees for controlling air pollution, it is not always easy to plant trees in cities, especially in densely populated urban areas. Green roofs can be used to supplement the use of urban vegetation in air pollution improvement and control.

Presented study reports the positive environmental effects of green roofs and provides a scientific basis for understanding the use of green 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.

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