Modelling the Efficiency of Nature-Based Solutions to Decrease Extreme Summer-time Heat in Dense Urban Environment on Example of Vienna, Austria

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1 ABSTRACT

Densely built urban environments experience extremely high temperatures during summer heat waves. Nature-based Solutions (NbS), such as increasing green infrastructure by replacing sealed surfaces with vegetation, installing green roofs and especially planting trees can ameliorate severe heat conditions by providing cooling through evapotranspiration and shading. This study analyses the effectiveness of NbS to reduce the summer maximum temperatures in Vienna using an urban climate modelling approach that takes into account NbS performance criteria on micro-scale and upscales the application of NbS for the entire city.

Using existing data of the Viennese urban structure, status-quo urban climate simulations were performed. Further, based on evidence on NbS performance criteria different climate scenarios for implementation of NbS were designed. A densely-built area in Vienna, for which the possibility of implementation of NbS was analysed, was chosen as a study area for micro-scale simulations. The adaptation measures included: 1) reduction of soil sealing, 2) increase in surface reflectivity of sealed surfaces, 3) implementation of green roofs, 4) new park areas with trees and low vegetation and 5) a combination of all NbS.

The modelling simulations were performed for a representative clear-sky heat day for NbS scenario first for the selected area with the ENVI-met model and later for the entire city of Vienna with the MUKLIMO_3 model. The extent of NbS was proportionally scaled for the city-level simulations and the measures were applied for all densely-built areas in the city.

The results show the highest cooling effect for the combination of NbS with a similar intensity of cooling found both in microscale and city-scale simulations. In case of city-scale simulations, the results show mean difference in daily maximum temperature of about 0.1°C and maximum difference of about 1.4°C. The effect is strongest in the densely-built areas where the measures were applied. However, the cooling effect can be detected in the surrounding areas as well.

The robustness of the urban scale results was tested using different modelling setups, varying the parameters describing land-use properties, such as variations in land use mapping, soil sealing, building density and tree coverage. Different representation of land use characteristics in the model leads to variations in spatial pattern of heat load. The cooling effect also varies spatially, dependent on the possibility to implement the adaptation measure. However, the results confirm similar efficiency of NbS regardless of the background data and method applied.

Keywords: urban heat island, urban climate, nature-based solutions, microclimate, climate modelling

2 INTRODUCTION

Urban environments are particularly sensitive to negative impacts of climate change. Especially, increasing occurrence of extreme weather events like heat waves poses a serious threat for urban regions (e.g. EEA 2012), since the prevailing structures increase the the experienced heat due to the Urban Heat Island (UHI) effect (e.g. Oke et al. 2017). Regulating urban climate by reducing the UHI effect and extreme temperatures during heat waves has become an important issue in sustainable and climate sensitive urban planning. One approach towards UHI mitigation is the implementation of the so-called Nature-based Solutions (NbS), such as parks, forests, water bodies, green roofs, green facades and other green and blue infrastructure, that have positive effect on reducing temperature peaks and provide multiple other ecological and social benefits (e.g. Nesshöver et al. 2017).

In case of Vienna, strong increase in temperature and heat-related climate indices has already been observed and further intensification in urban heat is expected in the next decades (Chimani et al. 2016; Bokwa et al. 2018; Bokwa et al. 2019). This can cause severe impact on public health by increasing the level of heat-related mortality (Muthers et al. 2010). The climate trend towards higher temperatures relates also to growing energy demand for cooling of buildings (Bird et al. 2019). The energy consumption depends on the building performance as well as specific microclimate conditions. The NbS can provide further benefits in reducing cooling energy demand by reducing outdoor temperatures as well as regulating indoor temperatures through insulation of buildings, for example by implementation of green walls and roofs.

As a measure to reduce the negative aspects of urban climate, the City of Vienna developed an UHI strategic plan (UHI, 2015) to implement various climate adaptation measures on buildings and open space including urban ecology measures based on planning tools and instruments on different governance levels. The scientific data base for the strategic plan are a number of climate studies providing an urban climate assessment, future climate scenarios and possible impacts, climate function map including thermal imaging, as well as strategic papers and information on the physical implementation of actions such as green space networks, green roofs, living walls and rainwater management.

As a supporting evidence for strategic plans for climate adaptation and sustainable urban development, many modelling applications have provided estimates on efficiency of NbS to reduce the UHI effect in Vienna. Most of the studies (e.g. Orehounig et al. 2014; Vuckovic et al. 2018) were focused on a specific building block and considered possible implementation and optimization of adaptation measures to find best-suitable solution for the particular study area, for example unsealing of paved surfaces and planting trees considering the orientation of streets and building geometry to enhance the shading effect. The quantitative results of these studies were difficult to transfer on other areas in the city, as well to draw general conclusions for implementation on a strategic level.

Another modelling approach considered implementation of adaptation measures on a city-scale, however, with limited spatial detail. For example, the implementation of blue and green infrastructure (Žuvela-Aloise et al. 2016) and application of green roofs and albedo modifications (Žuvela-Aloise et al. 2018) was modelled for Vienna and the results show that moderate to strong cooling effects can be achieved by extensive implementation of NbS. However, these studies calculated the cooling effect of NbS in terms of theoretical potential based on existing urban morphology, but not considering realistic application and actual urban development plans.

One of the main challenges of urban planning response to climate change impacts is that adaptation measures need to be implemented consistently at different planning levels and that the right amount of NbS needs to be identified in order to achieve a sufficient cooling effect as well as to engage appropriate planning instruments for the implementation (Reinwald et al. 2021). In the study of Reinwald et al. (2021) a combined approach with micro-, local- and meso-scale climate simulations and a green and open space factor was adopted to assess current and future urban heat stress and to evaluate the cooling effect of NbS in a standardized way on different spatial and planning levels.

Similar climate modelling approach was used in this study with a goal to identify appropriate NbS specifically for densely built urban environments, which are most severely affected by the UHI effect and quantify their cooling effect on the micro- and city-scale. The study examines a typical building block in dense urban environment in Vienna and considers different adaptation measures, including reduction of soil sealing, increase in surface reflectivity of sealed surfaces, implementation of green roofs, new park areas with trees and low vegetation and a combination of all NbS above. The modelling simulations are performed with a micro- and city-scale urban climate model and the results are analysed in the context of climate change adaptation for the use case example of “Supergrätzl” and the strategic plan on the level of the city of Vienna.

3 DATA AND METHODS

3.1 Micro-scale model

The state-of-the-art microclimate model ENVI-Met was selected to simulate status-quo and “resilience” scenario on a micro-scale level. ENVI-Met provides the possibility to design buildings, vegetation, surfaces, pollutant sources or waterbodies on a 3D grid and simulate atmospheric and surface interaction processes (ENVI-Met, 2023). Buildings and trees are explicitly resolved, thus enabling representation of adaption measures on a granular scale. The model domain focuses on a demonstrative quarter called “Supergrätzl” in the 10th district of Vienna and expands to 792 x 476 x 60 m with a spatial resolution of 2 m and higher resolved vertical resolution of 0.4 m within the lowest 5 model levels. The meteorological boundary conditions were chosen from a clear-sky hot day (19.07.2014), with fixed low wind direction from West to represent an autochthon weather situation. Around 350 m of the domain in the Western part are considered as buffer zone to account for effects induced by boundary conditions.

For the NbS scenario, different streets in the domain have been redesign with NbS. Surrounding streets of the quarter have been greened with additional trees and sealed parking lots have been unsealed or adapted to grass pavers. One street has been paved with higher albedo plaster and adjacent buildings gained façade and roof greening where applicable. Some streets received façade greening, removed and unsealed parking lots, additional trees, street greening, water features and higher albedo plaster, while others have been refurbished with technical solutions like sun sails, fog showers and as well higher albedo plaster to compare NbS and technical solutions (Fig. 1).

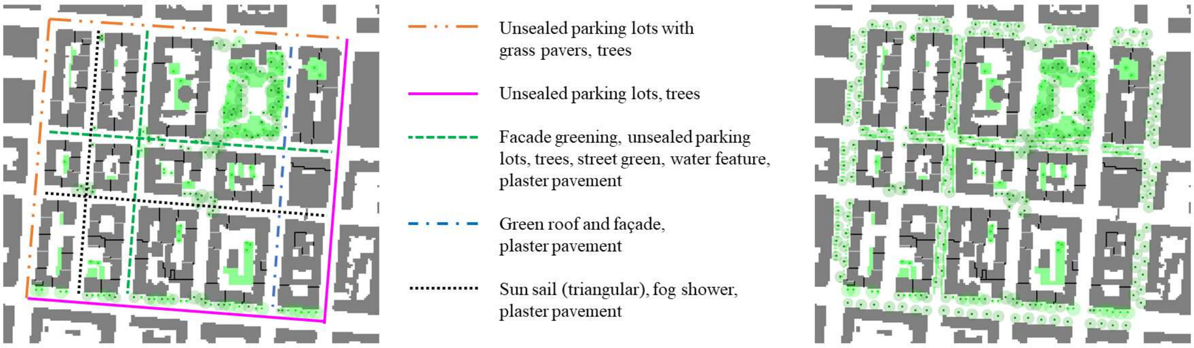

Fig. 1: Domain overview and depiction of status-quo and planned measures (left) and implemented measures (right) for urban quarter ("Supergrätzl") in the micro-scale simulation.

3.2 City-scale model

The simulations of urban climate for the city of Vienna were performed with the urban climate model MUKLIMO_3 (in German: 3D Mikroskaliges Urbanes KLImaMOdell) developed by the German Weather Service (DWD). The thermo-dynamical version of the model described in (Sievers, 2016) with model updates released in 2020 was used. The model is based on Reynolds-averaged Navier–Stokes (RANS) equations and includes parametrisation of vegetation and building morphology. The modelling approach takes into account terrain elevation, land use types and spatial distribution of land use parameters such as building density, building height and wall area index, sealing fraction and tree cover. The model domain covered the City of Vienna and its immediate surroundings with a grid size of 314 x 239 points and horizontal grid spacing of 100 m. The vertical resolution of the 3D model with 39 levels varied from 10 to 100 m with higher resolution near the ground and maximum height of about 1000 m. The simulations were conducted for a chosen clear-sky hot day (19.07.2014) representative for heat conditions during a summer period in Vienna, adopted from (Reinwald et al. 2021).

3.3 NbS assessment

The calculation of NbS cooling effect was performed by comparing the model results for mean and maximum air temperature between the reference simulation with current urban structure and the NbS scenario. In the NbS simulation the land-use parameters that are used as model input, as well as their spatial distribution, were adjusted to account for reduction of sealed surfaces and increase in vegetation (Table 1).

	Reference	NbS Scenario
Building area	43.6%	43.6%
Green roof area	0.0%	5.0%
Streets	53.7%	35.5%
Unsealed surface	0.0%	15.2%
Vegetation (low vegetation and tree trunks)	2.7%	5.7%
Number of trees	84	231

Table 1: Percentage of different land use areas in reference simulation and the NbS scenario as input parameters for the model simulations.

Realistic values of available surface area and possible greening measures were estimated on the example of Supergrätzl (Fig. 2). In case of the city-scale simulations the measures were applied in all densely built areas in Vienna. To account for increase of number of trees that could not be simulated in the city-scale model due to the low spatial resolution, a park area was assigned to grid cell with buildings for every ninth grid-point of the dense built-up area. Additionally, albedo value of sealed surfaces was increased by 30%, as the existing street areas where considered to be partially replaced by higher reflective concrete and porous pavement.

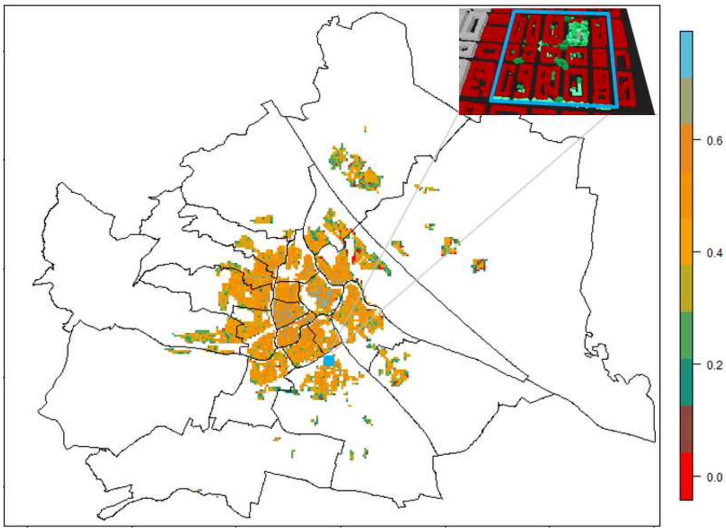

Fig. 2: Building density in Vienna for the dense built-up areas (land use typology: Blockrandbebauung; Green4Cities/GREENPASS, 2018, adapted from Reinwald et al. (2021)) and the location of the Supergrätzl.

4 RESULTS

4.1 Micro-scale simulations

Evaluation and comparison of NbS scenario with status-quo has been carried out for the parameters air temperature and mean radiant temperature (MRT) on pedestrian level. During the entire course of the day, NbS demonstrated stronger cooling capacities than technical solutions with averaged 0.8°C vs. 0.4°C during the day and 0.6°C vs. 0.3°C during the night for air temperature over the entire urban quarter. The cooling effect on air temperature is stronger during the day than during the night as differences of surface temperatures are higher during daytime (Fig 3, left, middle). Shading function of trees and evapotranspiration of vegetation are the main drivers of the temperature reduction. Sun sails only fulfil a partial shading function, as they can not be applied over the entire street scape for ventilation reasons. On the contrary, increased albedo on sun exposed areas even lead to higher MRT due to reflection of solar radiation (Fig 3, right).

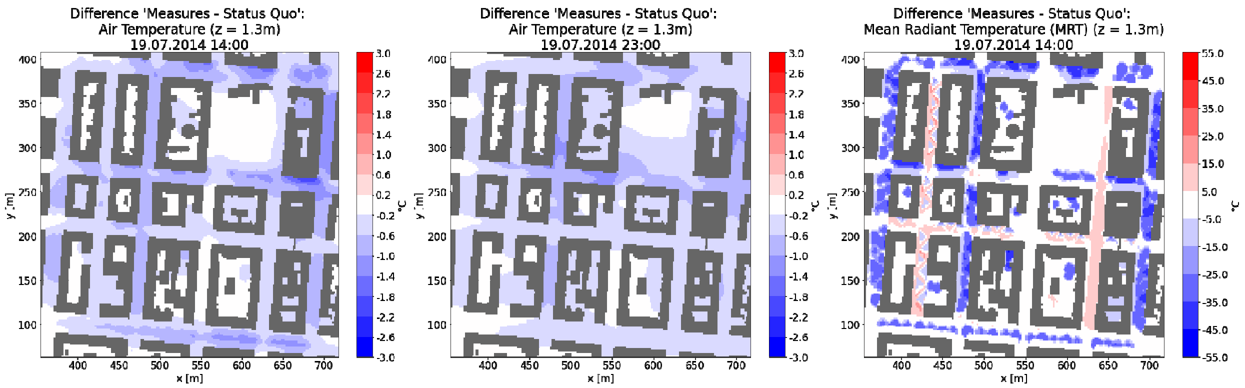

Fig. 3: Difference plots between scenario measures and status-quo of simulations for urban quarter ("Supergrätzl"). Left plot shows air temperature difference at 14:00, middle plot at 23:00. Right plot shows mean radiant temperature difference at 14:00.

4.2 City-scale simulations

A reference simulation based on the current urban morphology (Fig. 4, top) shows a typical development of the UHI in Vienna, characterized by higher temperatures in the densely built city-centre and lower temperatures in the surroundings, especially the elevated forest areas in the West and the national park Donau-Auen in East. By applying the NbS in densely built areas, a moderate cooling effect is found (Fig. 4

bottom). The maximum difference in mean air temperature was 0.7°C and 1.4°C in maximum air temperature. The mean difference is, however, lower and yields to 0.1°C in maximum temperature. The cooling effect varies spatially and depends on the availability of open spaces where NbS can be implemented. The cooling is most effective in the areas where the NbS is applied. However, due to the prevailing wind from Northwest, the cooling effect can propagate further Southeast and the surrounding areas where no measures where applied.

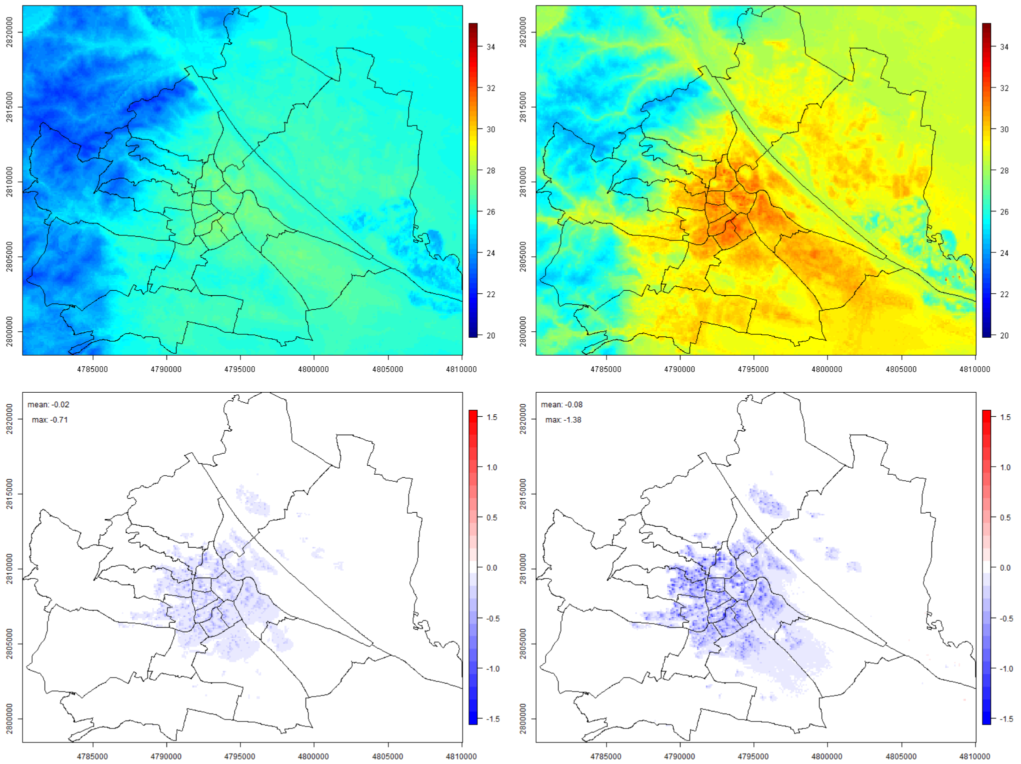

Fig. 4: City-scale simulations of air temperature (°C) in Vienna for July 19, 2014. Upper panel indicates daily mean (left) and daily maximum temperature (right) values for the reference simulation. The lower panel shows the difference in respective temperatures between the NbS simulation and the reference simulation.

5 CONCLUSION

This study demonstrates the cooling effect of NbS applied in a densely built environment based on the micro-scale and city-scale model simulations. The results from both modelling approaches confirm similar efficiency of NbS. The maximum cooling effect when different greening measures are applied is a difference in maximum air temperature of about 1.5°C. The cooling effect is limited by the availability of free spaces in densely built environment.

On the micro-scale the cooling effect of NbS is stronger than of technical solutions like sun sails or fog showers. The applied measures show stronger cooling effects (absolute) during the day than during the night. On the city-scale, the highest cooling effect is achieved by implementing green areas with trees (ΔT_{max}~1.2°C), while unsealing of surfaces has minor effect (ΔT_{max} ~0.3°C). The effect of green roofs, which was limited to 5% in the study area, is negligible (ΔT_{max} ~0.1°C). With higher availability of green roofs (30%) a larger, but still minor, cooling effect (ΔT_{max} ~0.4°C) could be achieved.

These results show that the NbS has a moderate cooling effect even in densely built environment, where their implementation is physically limited. As such, the NbS are an important instrument to address negative impacts of climate change and particularly to reduce the UHI effect. In further steps, the results of this study will be analysed in scope of climate risk assessment, where social aspects and vulnerability of urban population will be considered. These results can help improve existing urban development plans and accelerate the urban adaptation to climate change in Vienna.

6 ACKNOWLEDGEMENT

This study was conducted within the project SENSUS - *The social equality of Nature-based Solutions to urban heat stress* (Project Nr. ESR20-011) supported by the Vienna Science and Technology Fund (WWTF) under the Environmental Systems Research „Urban Regions“ Call 2020.

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