Evaporative cooling strategies in urban areas: The potential of vertical greening systems to reduce nocturnal heat stress

Fabian Görgen, Monica Rossi-Schwarzenbeck

Leipzig University of Applied Sciences (HTWK Leipzig), Germany

fabian.goergen@htwk-leipzig.de, monica.rossi@htwk-leipzig.de

Abstract. This research is part of a project that aims to create a simulation workflow to design adaptive facades to not only reduce the energy demand of buildings and provide a good level of indoor comfort, but also to mitigate the urban heat island effect. The anthropogenic climate change results in a steady increase of hot days, tropical nights and heavy rainfall, affecting the quality of human comfort, especially in urban areas not only in hot regions of the world but also in Central Europe. Vertical greening systems are often a first-choice mitigation strategy to improve the deteriorating situation. By combining the use of natural resources like rainwater and solar radiation, the greening evaporates water and provides natural cooling. This paper deals with the efficiency and feasibility of vertical greening systems towards a relief in heat stress by simulating different constructions under local circumstances of three climate zones, focusing on the night-time. To carry out the simulations with microclimate simulation tool ENVI-met, an urban apartment complex was designed and provided with different kinds of vertical greening to investigate the various positive effects resulting from the green façade. As a shading device, the greened walls showed a significant decrease of wall surface temperatures of up to 18K. However, restricted transpiration fluxes obstruct exploiting the full potential of evaporative cooling, especially during night-time.

1. Introduction

Natural resources like sunlight or rainwater are valuable assets. However, the potential of solar radiation and rainwater to provide cooling needs to be fully exploited. Sealed surfaces avoid infiltration, the water is directly being deviated into the sewer system without making use of it, which has a negative impact on both: water quality and the microclimate [1]. As a result of climate change, statistics show not only an increasing amount of hot days ($T_{max} \geq 30°C$), but also a substantial increase in tropical nights ($T_{min} \geq 20°C$) for Central Europe [2]. Studies focusing on the city of Madrid confirmed a rise of summer tropical nights since 1961 and also discovered a more rapid increase when comparing centrally located Madrid-Retiro (0.56 days per year) to suburban Torrejón de Ardoz (0.26 days per year) during the period from 1961 to 2017 [3]. An emerging issue that has a massive effect on human health, as heat-related deaths are more likely to result from temperatures consistently above 20°C than from daily maximum temperatures of over 30°C [4]. The result emphasises the danger of nocturnal heat stress, which makes it important to find mitigation strategies to counteract the poor prospects. Revegetating our cities is only one way to cope with this issue. Vertical greening systems are able to store a remarkable amount of water and evaporate it through the leaves, which affects the microclimate through evaporative cooling.

Also, green facades act as a natural shading system, to prevent the wall surface from heating up and storing the heat. This paper aims to investigate the efficiency of vertical greening systems as a mitigation strategy in different climate zones by comparing various greenings to a bare concrete wall, focusing on orientation and the Leaf Area Index (LAI). The LAI is used to characterise plant canopies and is defined as the total one-sided green leaf area per unit ground surface area (LAI = leaf area / ground area, m^2 / m^2) [5]. The dimensionless index was included in the investigations to find out whether a higher density of greening increases efficiency and if potential advantages of a higher LAI prevail the increasing need for irrigation.

2. Simulation process

To achieve this goal, a workflow combining different software solutions was used. An average neighbourhood was modelled using CAD software Rhinoceros 3D. On a total surface of 90m x 76m the north-orientated area included the main building (30m x 16m x 8m) in the centre, surrounded by eight buildings of the same height. The walls of all buildings consisted of concrete (18cm), insulation (12cm) and plaster (1cm). The 8m wide roads in between the buildings were made from tarmac. In the next step, Grasshopper, a visual programming language, was used to create an algorithm to connect the modelled buildings, the different types of greening, local weather data (average mean from 2004-2018) and boundary conditions (ENVI-met Full Forcing). Besides one reference scenario (bare walls, no greening), the façades of all buildings were provided with greening of different LAI respectively, creating one reference and three greening scenarios per location in total (*Bare*, *LAI=1*, *LAI=2*, *LAI=5*). The simulations were carried out and analysed using microclimate model ENVI-met, a software designed for the three dimensional simulation of surface-plant-air interactions in an urban environment [6] including the simulation of stomatal behaviour to simulate the effects of greening on the microclimate [7]. The model was validated in various case studies like Yang et al. [8] and Tsoka et al. [9]. Another case study by Simon et al. [10] compared modelled transpiration rates and leaf temperatures against in-situ measured data and proved ENVI-met as a reliable tool to simulate the effects of greening on the urban environment. The simulation period was set to 24 hours, starting on the 21st of June 6am and ending on the 22nd of June 6am, as a representative summer day with the maximum amount of sunlight, for the cities of Berlin (moderate climate), Madrid (subtropical climate) and Singapore (tropical climate). In terms of water supply, a water coefficient of 0.5 (range: 0..1) was selected for the substrates of all locations and LAI to simulate comparable scenarios with average water access. The grid size of the model was set to 2m x 2m.

3. Results

The results of the simulation scenarios were evaluated, focusing on evaporation, wall surface temperatures and outdoor microclimate, including data for the north and south façade, respectively. The evaluation focuses on the results for the city of Madrid in the first place.

3.1. Evaporation

Fig. 1 shows the transpiration fluxes of the different LAI respectively on both, a north and a south façade, measured on the 2nd floor of a building. The rates are not exactly linear with an increasing LAI, as the daily mean transpiration fluxes over the simulated period of 24 hours show. The data also shows that the north-orientated greening outperforms its southern counterpart by over 14% (Table 1). The evaporation performance of the greening depends on many factors and the charts are barely constant, as certain circumstances can cause rapid increases or decreases. To explain the points mentioned above and interpret the chart in the right way, we distinguished the volatility causes of the evaporation fluxes into *stomata-related causes* and *environmental-related causes*. The stomata, little pores in the leaves' epidermis and responsible for gas exchange, open and close after being triggered under certain circumstances. A high stomata resistance means less gas exchange and therefore less evaporation. Besides the phenomenon, environmental influences like wind, humidity and radiation may influence the evaporation performance in general, regardless of the stomata's state.

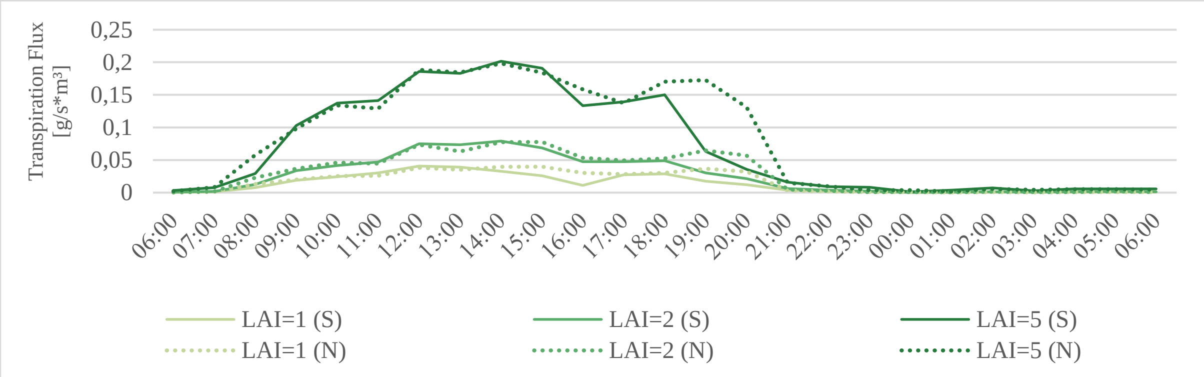

Fig. 1: Transpiration fluxes of different LAI (Madrid, 2nd floor, north and south façade)

The transpiration flux of the south-orientated greening, as in Fig. 2, shows a major decrease during midday, with a low at 4pm. As stated above, decreases in evaporation can have different causes, yet, by looking at the stomata resistance over the day, the low happens to be contrary to a peak of the stomata resistance. This implies that the stomata were being triggered to close, a phenomenon that happens mostly during night-time with the absence of light. However, in this case the reason for the stomata closing is a self-preservation mechanism to prevent dehydration. The graph of the leaf temperature also peaks at 4pm, with the leaves reaching temperatures of over 40°C. The stomata close and transpiration minimises. To explain the correlation stated, Fig. 2 shows the transpiration flux of a thin layered greening (LAI = 1m²/m²). However, with a thicker layer, the peak in the stomata resistance graph relativises, as only the top leaves reach higher temperatures. The shaded leaves below stay cooler, the stomata remain open. The same happens on the north façade. Not being fully exposed to the sun and therefore having lower leaf temperatures, the north-orientated greening does not show stomata resistance during midday. However, when looking at the graph of the transpiration flux of the north façade, we still witness a slight decrease between 3pm and 7pm. The simulated data reveals a significant decrease of wind speed during this period, dropping from 2,1m/s at 3pm to 0,54m/s at 4pm. As wind being one of the key factors for evaporation due to air circulation, a lack of it creates an increase in humidity in the canopy (14,96g/kg at 3pm to 20,16g/kg at 4pm). As the air around the greening becomes more and more saturated, the evaporation rates drop. However, with the cause being of a physical nature it does not relate to the leaves' stomata. Comparing the transpiration fluxes of the different climate zones, a stomata resistance due to overheating was only found on the south façades of Madrid and Berlin. Nevertheless, the differences between the evaporation rates are significant. The differences of Madrid's and Berlin's south façade are minor compared to the doubling seen on the north facades. The increased performance can be traced back to the vast difference in received short-wave radiation during midday.

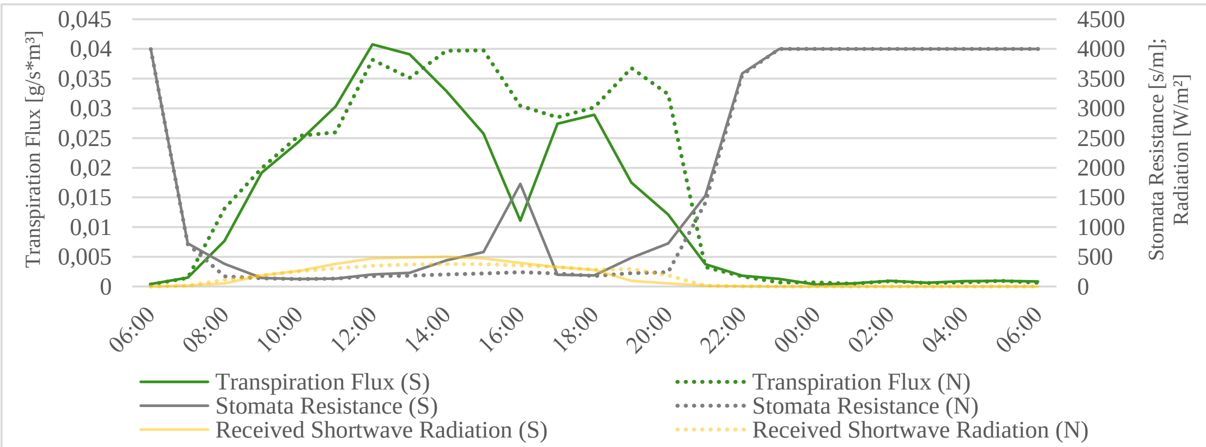

Fig. 2: Correlation between transpiration flux and stomata resistance (Madrid, LAI=1, 2nd floor, north and south façade)

The simulated data for Singapore, however, show considerably lower rates compared to the European cities (Table 1). The main reason for the low rates found in Singapore is the high humidity, with an average of 83.64% over the period from the 21st of June 6am to 22nd of June 6am (Berlin (55.0%), Madrid (41.48%)).

Table 1: Daily mean transpiration fluxes (north and south façade)

	LAI=1 (S) [g/s*m³]	**LAI=2 (S)** [g/s*m³]	**LAI=5 (S)** [g/s*m³]	**LAI=1 (N)** [g/s*m³]	**LAI=2 (N)** [g/s*m³]	**LAI=5 (N)** [g/s*m³]
Berlin	0.0125	0.0219	0.0523	0.0085	0.0137	0.0351
Madrid	0.0132	0.0259	0.0708	0.0163	0.0294	0.0805
Singapore	0.0036	0.0057	0.0115	0.0040	0.0063	0.0126

3.2. Wall Surface Temperatures

The vertical greening systems showed a significant effect when comparing wall surfaces with and without greening. As the charts of the observed locations have similar shapes when comparing the inside and outside surface temperature of a bare wall to a greened wall, Fig. 3 exemplifies the differences by using the data of Madrid's south façade over a period of 24 hours.

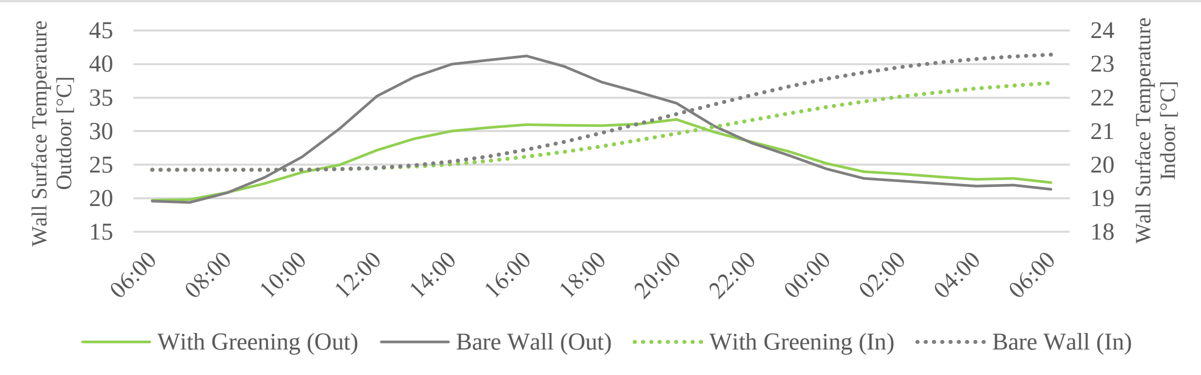

Fig. 3: Wall surface temperatures with and without greening (Madrid, LAI=1, 2nd floor, south façade)

The graph shows a significant improvement of the outside wall surface temperature during midday with peak differences of up to 18.28K in Berlin, as the greening works as a shading system and reflects the radiation. When looking at how the greening affected the inside wall temperature of the building, a reversion of the graphs can be noticed. While the greening stops the wall from storing the heat and from heating up during the day, the effect is reflected in the inside wall temperature during night-time. The simulation showed an average decrease of indoor wall temperature between 6pm and 6am of 1.19K with a maximum difference of 1.45K in Berlin (Table 2).When it comes to shading, the simulation showed that a thicker layer of greening does not guarantee a cooler wall surface. In fact, a shading device with a LAI of 2 was the most efficient in Berlin and Madrid, as Table 2 states. Nevertheless, as all types of greening made a difference, the increasing amounts of water needed for thicker layers are not worth the minor differences between the LAI. Compared to Madrid, the chilly nights in Berlin allowed the façade, including the air gap between greening and wall, to cool down. Also, as the temperatures rose earlier in Berlin (~40°C at 12am) compared to Madrid (~40°C at 2pm), the cool night air and the early rising temperatures caused the massive differences in the wall temperature of Berlin's south façade.

Table 2: Maximum surface temperature difference compared to bare wall (LAI=1/LAI=2/LAI=5; north and south façade)

	Outside (S) [K]	**Inside (S)** [K]	**Outside (N)** [K]	**Inside (N)** [K]
Berlin	17.51/18.28/17.84	1.40/1.45/1.34	7.18/7.48/6.40	1.05/1.09/0.94
Madrid	10.25/11.00/9.88	0.88/0.96/0.64	6.45/6.81/5.00	0.75/0.81/0.47
Singapore	6.96/6.94/6.24	0.85/0.85/0.76	7.05/7.03/6.77	0.86/0.86/0.77

3.3. *Outdoor Microclimate*

Transpiration provides cooling. However, we need to evaluate all locations' data in order to make a precise statement of how the vertical greening systems affect the outdoor air temperature. To do so, we picked a grid of 2m x 2m in the middle of the street canyon in between two buildings to compare the scenarios. Fig. 4 shows the respective potential air temperature and relative humidity values with and without greening from 2pm to 8pm. As the relative humidity increased up to 6.19 pp., the potential air temperature decreased by 0.71K (Madrid, 6pm, LAI = 5).

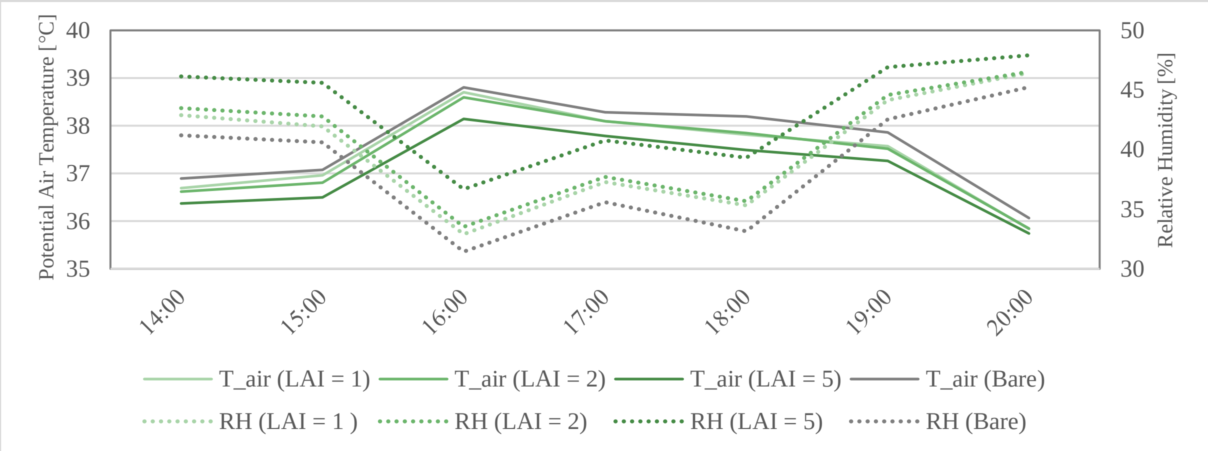

Fig. 4: Potential air temperature and relative humidity in between two buildings with and without greening (Madrid)

The maximum changes for both parameters and for the selected LAI on all locations are shown in Table 3. Facing nocturnal heat stress, the results for the night-time seem less promising. On average, between 6pm and 6am, we observed a slight cooling effect of up to 0.1K in Madrid (LAI = 5). However, in the late night-hours (12am to 6am), the potential air temperatures in front of the building in Madrid were even slightly higher with greened walls than without (≤ 0,07K). Nevertheless, the impact on the potential air temperature during night-time by greening is neglectable due to its minor impact. One of the main reasons for that, as mentioned above, are the reduced transpiration fluxes during night-time due to a high stomata resistance. The results show that there is an impact on the microclimate by vertical greening systems. However, if the little cooling effect prevails, the increase in humidity needs to be investigated.

Table 3: Maximum differences in potential air temperatures and relative humidity (south of the central building)

	max. ΔT_{air} [K]	**max. ΔRH** [pp.]	**mean** $\Delta T_{air,night}$ [K]
Berlin	0.33/0.41/0.71	2.70/3.50/7.95	0.083
Madrid	0.39/0.35/0.71	2.18/2.54/6.19	0.108
Singapore	0.16/0.09/0.30	4.17/4.27/6.94	-0.224

4. **Conclusion**

The results show that vertical greening systems in general do have a positive impact on the microclimate and on the building surface temperatures. The temperature differences from up to 18.28K during midday on a Berlin south façade showed that shading concrete walls, which are usually absorbing the heat, has an impact on the thermal comfort inside the building in the night-time. Yet, it is to say that shading, in general, is not a unique feature only vertical greening systems can provide, although it is highly efficient as the results show. As the tested constructions show only minor differences between each other in terms of shading, vertical greening systems with lower densities (i.e. LAI = 1) can be recommended as the water consumption is kept within limits. The main object of this paper, however, was to investigate if vertical greening systems offer potential in terms of evaporative cooling. Considering the simulation results of the transpiration fluxes, we can conclude that the effects resulting from evaporation, especially during night-time, were sobering. The simulation results showed a decrease in potential air temperature outside the building of 0.71K at their peak during the day, whereas the average night-time difference was only 0.1K at its maximum. The main reason for the results, that were below our expectations, is that plants, as living organisms, react to certain circumstances and are hard to be regulated. As the stomata close when overheating, transpiration stops and the cooling effect decreases to a minimum. However, the biggest issue in reducing nocturnal heat stress is that the stomata open as a response to blue- and red-light [11], which makes it impossible to use the advantages of evaporative cooling during night-time due to a lack of light. Green walls do have many advantages like supporting biodiversity, improving air quality, protecting the building from heavy rain and radiation, upgrading building stock or even noise protection. However, green walls do not fully exploit the potential of evaporative cooling, due to the mentioned restrictions. Evaporation in general is not limited by hotter temperatures or a lack of light. Therefore, evaporative cooling offers a huge potential to help cities cope with the increasing heat waves, by collecting and storing rainwater. The key to developing a well-functioning evaporative cooling system lies in its regulation. Higher transpiration fluxes, a plant cannot provide, could make an even greater difference when controlled and used in need. In this context, innovative façade solutions using evaporative cooling as a mitigation strategy against overheating urban areas need to be developed and tested.

References

[1] B. Reichmann, C. Steffen, M. Schmidt, M. Köhler, I. Hübner and I. Junge-Reyer, "Konzepte der Regenwasserbewirtschaftung," Senatsverwaltung für Stadtentwicklung Berlin, Berlin, 2010.

[2] J. Fallmann, S. Wagner and S. Emeis, "High resolution climate projections to assess the future vulnerability of European urban areas to climatological extreme events," *Theoretical and Applied Climatology 127(3-4),* pp. 667-683, 2017.

[3] D. Rasilla, F. Allende Alvarez, A. Martilli and F. Fernández, "Heat Waves and Human Well-Being in Madrid (Spain)," *Atmosphere 10(5),* pp. 1-21, 2019.

[4] K. Gabriel and W. Endlicher, "Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany," *Environmental Pollution 159(8-9),* pp. 2044-50, 2011.

[5] D. J. Watson, „Comparative Physiological Studies on the Growth of Field Crops: I. Variation in Net Assimilation Rate and Leaf Area between Species and Varieties, and within and between Years," *Annals of Botany 11(1),* pp. 41-76, 1947.

[6] M. Bruse and H. Fleer, "Simulating surface-plant-air interactions inside urban environments with a three dimensional numerical model," *Environmental Modelling and Software 13(3-4),* pp. 373-384, 1998.

[7] M. Bruse, "ENVI-met implementation of the Jacobs A − gs Model to calculate the stomata conductance," 2004. [Online]. Available: http://envi-met.net/documents/new_a_gs.pdf. [Accessed 21 05 2021].

[8] X. Yang, L. Zhao, M. Bruse and Q. Meng, "Evaluation of a microclimate model for predicting the thermal behavior of different ground surfaces," *Building and Environment 60,* pp. 93-104, 2013.

[9] S. Tsoka, K. Tsikaloudaki and T. Theodosiou, "Analyzing the ENVI-met microclimate model's performance and assessing cool materials and urban vegetation applications – A review," *Sustainable Cities and Society 43(1),* pp. 55-76, 2018.

[10] H. Simon, J. Lindén, D. Hoffmann, P. Braun, M. Bruse and J. Esper, "Modeling transpiration and leaf temperature of urban trees – A case study evaluating the microclimate model ENVI-met against measurement data," *Landscape and Urban Planning 174,* pp. 33-40, 2018.

[11] K.-i. Shimazaki, M. Doi, S. M. Assmann and T. Kinoshita, "Light Regulation of Stomatal Movement," *Annual Review of Plant Biology 58(1),* pp. 219-47, 2007.