Retrofitting solutions for a campus building to mitigate urban heat island in a hot humid climate

Vajreshwari Patil, Maite Bizcarguenaga, Katherine Lieberknecht, Juliana Felkner
School of Architecture, The University of Texas at Austin, TX, USA
patilvajreshwari54@utexas.edu; maitebizcar@utexas.edu; klieberknecht@utexas.edu; juliana.felkner@austin.utexas.edu;

Abstract. In this study we examine the summer cooling effects of trees and green facades on reducing urban heat island effects. Using ENVI-met model simulations, we investigate the influence of added greenery on the surface and ambient air temperature and its role on air fluctuations in the hot humid climate of Austin, TX, at pedestrian height. Under the specific conditions considered in this model, the results show the combination of trees and green facades has a greater cooling effect. Added greenery to the building mostly impacts the building’s surface temperature during the hottest hours of the day, registering a maximum surface temperature reduction of 20.33°C. Simulations also show a maximum overall potential air temperature reduction of 0.54°C, and a maximum potential air temperature cooling effect near the building of 0.91°C. Future research should be conducted to address this study’s limitations. Nevertheless, these findings can provide architects, designers, planners, and policymakers with a better understanding of the many benefits trees and green facades have, and provide them with the necessary tools to implement new solutions across sectors and scales to reduce the impacts urban areas have on the environment and provide a better living for all.

1. Introduction
The world is facing clear impacts of climate change, with increasing frequency and intensity of extreme weather events, as the average global temperature has increased by a little over 1°Celsius since 1880 [1]. At the same time, growing population density is exacerbating environmental degradation and presenting numerous challenges to human’s and other species’ survival. In addition to an already warming planet, cities are further impacted by the Urban Heat Island (UHI) effect [2] which is defined as higher temperatures registered in urban areas than in their surrounding suburban and rural areas. The intensity of the UHI is mainly determined by the thermal balance of the urban region and can result in a temperature difference of up to 10 °C [3].

Urban warming increases the frequency of extreme temperature events leading to the death of many people due to the impact of UHI which is estimated to be 1.1 deaths per million people [4] and has serious impacts on the peak and total electricity demand in buildings primarily due to increased cooling loads [5]. Urban greenery has been proposed as one of the most effective urban strategies to improve thermal performance, especially in high-density built-up areas. Trees and vegetation can reduce indoor energy consumption by enhancing thermal performance in outdoor spaces and mitigating urban heat islands. Urban trees can reduce the energy use from air conditioning by 20% and save over $10 billion per year [6]. Akbari
reported that increasing shade trees could reduce carbon emissions and directly reduce the cooling energy demand by 25% [7]. In addition, Chen reported a green wall can significantly cool the outer surface of the wall when compared to a building in a warm climate [8].

Many countries have imposed energy-saving policies for buildings, and studies focusing on reducing the environmental footprint of buildings have emerged around the world [9] as the need to reduce indoor temperatures, provide comfort, and protect vulnerable populations continue to increase [10]. Mitigation strategies can be found in bioclimatic design, and efforts need to be spent on learning and reincorporating these practices in architecture. The need for developing new products, technologies, educating architects, engineers, and the general public to follow these principles is imperative to moving away from energy-dependent systems and creating climate-adapted buildings with lower environmental impacts. Especially in the case of Austin, where population growth and climate change will increase energy consumption dramatically [11]. The purpose of this research is to investigate the effectiveness of green walls and trees for enhancing thermal performance in buildings and mitigating urban heat island in a hot humid climate.

2. Methodology

2.1. Description of the study area

We select the main courtyard building of the School of Architecture for this analysis. The site is located on the campus of The University of Texas in the central area of the city of Austin. It is located at a latitude of 30°N allowing for an average of over 12 hours of daylight with an elevation varying from 130m to over 305m above sea level with mainly flat areas with lower elevations to the east and rolling hills with higher elevations to the west [12]. Because of these variations in topography, weather conditions can differ between different sectors of the city. Austin belongs to the Humid Subtropical Climate under the Köppen Climate Classification which is characterized by long, hot, and humid summers and short, mild winters, with warm spring and fall transitional periods [13]. Summer temperature ranges from 24°C to 39°C in August. Winters are mild with cool nights and average temperatures nearing 13°C. The average temperatures in autumn and spring are 15°C and 24°C respectively [14]. The annual average humidity ranges from 59% registered in August to 75% registered in May. The average annual precipitation levels range from 81cm to 91cm and prevailing winds come typically from the south with some variety to the east, and in the winter occasionally from the north with passing cold fronts; the average annual wind speed is 3.96 meters per second [15].

2.2. Simulation model

We used the ENVI-met 4.4.5 to run simulations. It is a three-dimensional, grid-based, microclimate model used to simulate complex urban environments as holistic organisms. The model is based on the fundamental laws of fluid dynamics and thermodynamics and can simulate the dynamic interactions between plants, buildings, and the atmosphere on a microscale level with a typical spatial resolution ranging between 0.5 to 10 meters and time steps of one to 10 seconds [16]. This enables the capacity to analyze a wide range of spatial scales from a small courtyard to entire cities. The model’s detailed characteristics, structure, and mathematical equations are provided by Bruse, Fleer, and Huttner articles [16] [17]. Additionally, a review by Toska et al. on the ENVI-met microclimate model’s performance shows the software can be considered a helpful tool for urban climate analysis and lists several of its limitations [18].

The model area is 80 x 100 x 30m, including the measured building and its surrounding urban elements including roads, pedestrian corridors, and sections of adjacent buildings. A fine spatial resolution of 2m in all directions was used. The model was set to run for 24 hours with simple forcing boundary conditions using self-defined minimum and maximum air temperatures (25°C to 39°C), and wind speed and direction (3.5 m/s winds coming from the south) replicating a typical summer day in Austin. We generated six interventions and a reference baseline scenario. Two scenarios considered adding trees, two adding green walls, and two combining trees and green walls. The specific location and combinations of strategies are shown in Figure 1, and the maximum building heights, and tree type and distance from the building are shown in Figure 2. We left all other main parameters unchanged, to evaluate the effects of the described cases on the urban microclimate. We used ENVI-met default soil, building materials, and vegetation.
3. Results

Here we show the atmospheric temperature and relative humidity for the different cases. We analyzed the measurements at a pedestrian height of 1.40m, representing what people would be able to perceive. To better understand the temperature oscillations simulated by the software, and to compare modeled temperatures on specific areas, we selected nine different points at a pedestrian height of 1.4m were around the main building. Similarly, five points located at a height of 1.4m on all façade orientations were identified to examine the changes in the wall temperatures. The location of these receptors is shown in Figure 1. Table 1 shows the maximum temperature difference between the proposed scenarios and the baseline model for the overall minimum and maximum potential air temperature, the wall temperature, and the zone temperature.

The overall simulated potential atmospheric relative humidity slightly increased when trees were added, registering a maximum difference from 67.38% to 68.41% at 9 am, and no significant changes were registered when green walls were added. The minimum potential air temperature difference was strongest when both mitigation strategies were combined registering a cooling effect of up to 0.18°C (model “T_GW”), whereas the maximum potential air temperature difference was strongest where trees were added registering a cooling effect of up to 0.54°C (model “T”). In both cases, adding small trees farther from the building only improved the cooling effect by 0.01°C (models “T_GUAD” and “TGW_GUAD”). Thermal maps of the analyzed area are shown in Figure 3, depicting the potential air temperature at 3 pm at a pedestrian height of 1.40m.
Table 1. Simulated temperature differences between the baseline model and each of the overall minimum and maximum potential air temperature, wall temperature, and air temperature at the receptors.

|                   | T  | GW_1 | GW_2 | T_GW | T_GUAD | TGW_GUAD |
|-------------------|----|------|------|------|--------|----------|
| Minimum Overall Potential Air Temperature Difference (°C) | 0.12 | 0.01 | 0.07 | 0.18 | 0.12   | 0.19     |
| Maximum Overall Potential Air Temperature Difference (°C) | 0.54 | 0.00 | 0.01 | 0.54 | 0.55   | 0.55     |
| Maximum Wall Temperature Difference at Receptor (°C) F1 | 15.23 | 4.57 | 10.09 | 20.33 | 15.25 | 20.34     |
| F2 | 4.36 | 0.02 | 10.29 | 11.21 | 1.42 | 11.25     |
| F4 | 0.33 | 4.01 | 10.68 | 10.92 | 0.38 | 10.96     |
| F5 | 0.41 | 0.02 | 10.35 | 10.53 | 0.46 | 10.56     |
| F8 | 3.16 | 0.03 | 7.20 | 7.76 | 1.17 | 7.79     |
| Maximum Air Temperature Difference at Receptor (°C) R1 | 0.69 | 0.13 | 0.70 | 0.76 | 0.63 | 0.75     |
| R2 | 0.89 | 0.16 | 0.19 | 0.91 | 0.83 | 0.90     |
| R3 | 0.60 | 0.02 | 0.04 | 0.59 | 0.60 | 0.59     |
| R4 | 0.24 | 0.04 | 0.08 | 0.31 | 0.25 | 0.31     |
| R5 | 0.11 | 0.01 | 0.09 | 0.18 | 0.11 | 0.18     |
| R6 | 0.09 | 0.01 | 0.09 | 0.15 | 0.10 | 0.15     |
| R7 | 0.12 | 0.01 | 0.04 | 0.15 | 0.13 | 0.15     |
| R8 | 0.41 | 0.07 | 0.13 | 0.48 | 0.41 | 0.48     |
| R9 | 0.10 | 0.01 | 0.05 | 0.45 | 0.11 | 0.15     |

Figure 3. Potential air temperature at 3 pm, x-y views at z = 1.40m in a) Baseline b) Trees around the main building c) Green walls on main building d) trees and green walls.

The added green walls impacted all facades similarly, showing a wall temperature reduction between 10.09°C and 10.68°C in the south, east, and west facades, and up to 7.20°C in the north façade (model “GW_2”). The highest differences were registered between 1:00 pm and 6:00 pm except for the east façade which registered its maximum difference at 11:00 am. The green walls also slightly increased the wall temperatures from 2:00 am to 7:00 am, showing a maximum wall temperature increase of 2.08°C on the west façade at 7:00 am. Adding trees impacted the façade temperature only when their shadow was cast onto the building. As a result, a cooling effect was only registered on the west-facing façade, reaching a maximum wall temperature difference of 15.23°C at 5:00 pm (model “T”). The combination of both mitigation strategies yielded the most significant wall temperature reduction on the west façade showing a 20.33°C reduction at 5:00 pm, but no significant improvements were found on the other wall orientations (model “T_GW”). Finally, adding small trees further from the building did not significantly change the wall temperatures (models “T_GUAD” and “TGW_GUAD”).

Figure 4. Simulated wall temperatures at 4 pm in a) Baseline b) Trees around the main building c) Green walls on main building d) trees and green walls.
The simulated potential air temperature difference at the nine points around the building was strongest primarily from 3:00 pm to 6:00 pm, except for receptor R3 where the maximum difference was registered at 11 am. The added trees near the building showed air temperature reductions ranging between 0.09°C and 0.83°C (model “T”), and the green wall covering all the building registered air temperature reductions from 0.04°C up to 0.20°C (model “GW_2”). The maximum potential air temperature difference was strongest when both mitigation strategies were combined, registering a cooling effect from 0.15°C to 0.91°C, the highest improvement recorded at 3:00 pm in R2 (model “T_GW”). Once again, adding small trees farther from the building did not significantly change the air temperature near the building (models “T_GUAD” and “TGW_GUAD”).

4. Discussion and conclusion

In this work we studied the cooling potential of trees and green facades to reduce UHIs in summer conditions. Using ENVI-met model simulations, we investigated the influence of green facades and trees on the surface and ambient air temperature and their role on air fluctuations in the hot, humid climate of Austin, with a primary focus on pedestrian height (1.40 meters) temperature variations.

The simulation results show the combination of trees and green facades has a greater cooling effect and the results are congruent with previous research. The added greenery mostly impacts the building’s surface temperature between 3:00 pm and 6:00 pm, registering a maximum surface temperature reduction of 20.33°C. The simulation results also show a maximum overall potential air temperature reduction of 0.54°C, and a maximum potential air temperature cooling effect around the building of 0.91°C at a height of 1.40m. Additionally, the results indicate the added greenery slightly increases the relative humidity, and the added trees on the street located further away from the building do not have a meaningful impact.

Conclusively, in this particular setting, the added greenery reduced the surface temperature during the peak heat hours when the energy demand is at its highest, which could help reduce the stress imposed on the electrical grid and diminish the likelihood of power outages caused by this demand surplus. Furthermore, the surface temperature reduction indicates the greenery protects the building facades from the heat, reducing its heat absorption which could potentially reduce its cooling load.

5. Limitations and future research

This research has several limitations that could be addressed in future studies. First, this study ran the model for a 24 hour period due to time limitations, but other studies have found better results running the model for a 48 to 72 hour period; therefore, a longer period should be considered. Second, the wind speed and direction are kept constant in the study because the full forcing of the flow of these variables is not possible in ENVI-Met model [18]. Third, other mitigation strategies such as adding trees, green roofs, or combinations of these, which previous research has found to provide additional cooling effects, would provide a wider understanding of the possible cooling effects resulting from integrating greener in the built environment. Fourth, validating the computer simulation results with field measurements would provide additional scientific evidence of the thermal benefits of façade greening. Fifth, a more detailed and varied building materials selection would be beneficial for understanding and comparing the cooling potential of different structures. Finally, simulating the building’s energy loads would provide a more holistic analysis and an accurate estimation of the energy impacts of this added greenery.

6. References

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