Evaluating the 3D cooling performances of different vegetation combinations in the urban area

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**ABSTRACT**
Vegetation has been considered as an effective strategy to combat the urban heat island effect. Most researches have focused on evaluating the cooling effect of trees in the urban thermal environment, while little attention has been paid to the cooling effect of the vegetation combinations. Moreover, most studies are focused on the horizontal cooling performance of plants, ignoring their vertical influence. Therefore, this study evaluates the 3D (horizontal and vertical) cooling performances of the three vegetation combination scenarios in the urban area using the ENVI-met model. The study indicates that the tree-grass (TG) combination has the best 3D cooling effect, followed by the tree-shrub-grass (TSG) combination, while the shrub-grass (SG) combination has the weakest 3D cooling effect. Besides, it is economical to plant TSG combinations because fewer trees are needed than planting TG combinations. Therefore, the study recommends the tree-shrub-grass combination rather than TG or SG combination in urban areas to effectively improve the thermal environment. The study also shows that the relationship between increasing tree coverage and the resulting cooling effect is not linear. The results of this study can effectively guide the design of greening strategies in urban areas to improve thermal comfort.

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1. Introduction

Global climate change and rapid urbanization have caused a drastic change in the energy balance, leading to various environmental problems such as urban heat islands (UHI) (Chow and Brazel 2012; Mills 2006). The UHI describes a phenomenon in which air and surface temperatures in a city are higher than in its suburban areas (Oke 1988). This phenomenon reduces the thermal comfort of urban residents and seriously affects the quality of their life (Massey, Habil, and Taneja 2016; Li et al. 2011). Besides, fighting the UHI effects may also require higher energy consumptions, aggravate air pollution, and increase the morbidity and the mortality caused by the heat stress, especially for the elderly people (Zittis, Hadjinicolaou, and Fnais et al. 2015; Wang et al. 2019; Wong et al. 2017; Ward et al. 2016).

However, due to the rapid growth of the world’s urban population, it can be expected that the occurrence and the intensity of urban heat islands will still increase in the future. Therefore, it is necessary now more than ever to develop effective strategies to mitigate UHI and improve the outdoor thermal environment of urban areas.

Many researchers have proposed some effective strategies to combat the UHI effects (Klemm et al. 2015; Li et al. 2019; Wang et al. 2017; Tan, Lau, and Ng; Morakinyo and Lam 2016; Aleksandrowicz et al. 2017) and urban greening is proven to be among the most effective ones (Hwang, Lum, and Chan 2015; Oliveira, Andrade, and Vaz 2011). Vegetation reduces carbon dioxide through carbon sequestration, which leads to a reduction in greenhouse gases (GHG) and thus heat (Duarte et al. 2015). Besides, vegetation increases the water vapor in the air through evapotranspiration, which leads to increased relative humidity and reducing air temperature (Wang and Akbari 2016; Richards et al. 2020). The shading effect of vegetation reduces incoming solar radiation, preventing it from penetrating street canyons and resulting in a decrease in mean radiant temperature (MRT) which critically affects thermal comfort (Tan, Wong, and Jusuf 2013). Urban greenery can also improve the urban natural environment, decrease biodiversity loss, and reduce indoor energy consumption by cooling outdoor air temperature and enhancing thermal performance in outdoor spaces (Boehme, Berger, and Massier 2015). Many previous studies have explored the cooling effects of various tree coverage rates on outdoor thermal environments (Klemm et al. 2015). The studies have shown that more tree cover leads to more significant cooling effects (Lin et al. 2008). A parametric study in Hong Kong suggests that tree coverage in urban areas should approach 30% (Ng et al. 2012). Furthermore, recent studies have shown that different tree species have different cooling potentialities (De Abreu-Harbich, Labaki, and...
Matzarakis 2015; Lin and Lin 2010). A study in Hong Kong to evaluate the cooling performance of various tree species in different urban morphology has suggested that tall trees of low leaf area density (LAD) should be planted in deep canyons and vice-versa for shallow canyons and open-areas (Morakinyo, Kong, and Lau et al. 2017). Nevertheless, a few studies have explored the cooling effects of plant combinations on the urban thermal environment (Lobaccaro, Acero, and Martinez et al. 2019; Lee, Mayer, and Chen 2016).

Most researches have focused on the cooling effects of the physical characteristics of vegetation (Morakinyo et al. 2020; Shahidan et al. 2012; Sun et al. 2017; Altunkasa and Uslu 2020). Among a variety of plant elements, trees have received widespread attention, while other plant types are still ignored (Hami et al. 2019). Regarding the cooling effects of vegetation combinations, many existing studies only explored the combinations of different tree species (Lobaccaro and Acero 2015). The cooling effects of vegetation type combinations have not received much attention. Therefore, evaluating the cooling performances of different vegetation type combinations are necessary and interesting. Besides, most researches have only investigated the cooling performances of vegetation across horizontal scales (Battista, De Lieto Vollaro, and Zinzi 2019; Wu, Dou, and Chen 2019; Perini and Magliocco 2014; Aboelata and Sodoudi 2019). Researches have seldom explored the cooling effects of vegetation on the vertical scale. Focusing on the vertical cooling performance of vegetation will provide a new research perspective to investigate the cooling effect of vegetation. Investigating the vertical cooling effect of vegetation will also help improve the overall three-dimensional thermal environment of the city, not only at the pedestrian height level. Therefore, the purpose of this study is to explore the 3D (both horizontal and vertical) cooling effects of different vegetation combinations in the urban area.

This study takes a residential quarter in Chenzhou as an example to explore the 3D cooling performance of different vegetation combinations. This research uses the numerical software ENVI-met to simulate four scenarios, including a reference scenario (without vegetation) and three vegetation combination scenarios: trees and grass, shrubs and grass, and the combination of trees, shrubs, and grass. Finally, the MRT and Ta results were extracted in each of the scenarios to evaluate the cooling effects of different vegetation combinations. The results of this study will provide scientific guidance for the planning and design of green spaces in residential areas to improve the thermal environment and enhance thermal comfort effectively.

2. Methods
2.1. Study area

The study was conducted in Chenzhou, which is located at the northern foot of the Nanling Mountain system (112°13' E-114°14' E, 24°53' N-26°50' N). According to the climate zoning of the Building Thermal Design Code of China (GB50176-93), Chenzhou is located in the hot summer and cold winter climate zone, with Nanling Mountain blocking the cold current in winter, making it the most typical hot summer and cold winter climatic city in China. It experiences a typical subtropical monsoon climate with hot summer months (June to September) and abundant solar radiation. In summer, the average air temperature reaches 28°C, and the maximum temperature can reach 40.5°C (Chenzhou meteorological station). With the increased UHI, urban residents in the area are extremely uncomfortable in the summer, and it is vital to develop appropriate mitigation strategies to improve thermal comfort in the built area. Chenzhou was therefore selected as the study area because of the climate sensitivity that distinguishes it from other regions and the representativeness of the regional climate characteristics.

The study area is a traditional residential quarter with multistory residential buildings and low-rise commercial buildings. A 280 × 140 m zone around the study area was considered for the modeling and simulation. The heights of the buildings range from 6 to 27 meters. The residential area has the most common spatial arrangement of multi-story settlements in China. It is because of its typical spatial form that this settlement was selected as the study area. The model area is shown in Figure 1.

2.2. Description of the simulation model

The microclimate simulation model ENVI-met (version v4.0) was selected to simulate variables in the outdoor thermal environment of various vegetation combination scenarios. ENVI-met is a three-dimensional model based on computational fluid dynamics (CFD), which is designed to simulate soil-air-vegetation-building interactions (Wang, Berardi, and Akkari 2016). ENVI-met uses non-hydrostatic Navier-Stokes equations to describe the spatial and temporal evolution of airflow field turbulence (Bruse and Fleer 1998).

$$\frac{\partial u}{\partial t} + \rho \nabla \cdot (u \mathbf{u}) = -\nabla p + \nabla \cdot (\mu \nabla u) + f(u - u_d) - S, \# \quad (a)$$

$$\frac{\partial \rho}{\partial t} + \rho \nabla \cdot (u \mathbf{u}) = -\nabla p + \nabla \cdot (\mu \nabla u) + f(u - u_d) - S, \# \quad (b)$$

$$\frac{\partial \theta}{\partial t} + \rho \nabla \cdot (\mathbf{u} \theta) = -\nabla \cdot (k \nabla \theta) + g \left( \frac{\partial \rho}{\partial z} \right) - S, \# \quad (c)$$

$$\frac{\partial u}{\partial t} + \rho \nabla \cdot (u \mathbf{u}) = 0 \# \quad (2)$$

Where \( f \) is the Coriolis parameter, the value of which is \( 10^4 \) s\(^{-1}\), \( \rho \) is the local pressure perturbation, \( \theta \) is the
potential temperature at levelz. The reference temperature $\theta_m$ should represent average mesoscale conditions and are provided by a one-dimensional model running parallel to the primary model (Bruse and Fleer 1998).

Equation (2) is used to keep the model mass conserving.

The typical spatial resolution of ENVI-met is 0.5 m-10 m and the temporal resolution is 10s which allows a near-accurate modeling (Li, J. et al. 2021; Tan, Lau, and Ng 2016). Furthermore, unlike other simulation software, vegetation elements are treated as active bodies in the ENVI-met model and it can simulate the evaporation and transpiration of different plant species (Wania et al. 2012). The ENVI-met model can also simulate plant types with different physical characteristics, such as LAD, height, leaf shape, crown shape, size, etc., which all affect micro-meteorological conditions (Tan, Lau, and Ng 2016).

The ENVI-met model has been widely used for modeling the effect of vegetation on urban thermal environments (Müller, Kuttler, and Barlag 2014; Tan, Lau, and Ng 2017). Previous studies have verified the accuracy of ENVI-met under different climates (Srivanit and Hokao 2013). A parametric study in Wuhan, a place with the same climate zone as Chenzhou, verified that ENVI-met accurately calculated the air temperature and the mean radiation temperature (Zhang, Zhan, and Lan 2018), and there is a strong correlation between the measured data and the simulation results with the R2 of Ta and MRT being 0.79–0.81 and 0.70–0.74 respectively (Zhang, Zhan, and Lan 2018). Hence, the ENVI-met model can be a reliable tool to study the microclimate issues involving urban greenings.

2.3. Field measurement and ENVI-met verification

The experimental measurement was carried out on 3 August 2019, from 07:00 to 18:00 in a typical residential area to verify the variability of the cooling effect of different vegetation combinations and the reliability of the numerical simulations using ENVI-met. This study uses CR1000 for temperature monitoring at the height of 1.5 m, with an interval of 1 hour. The date selected for this field measurement was a typical summer hot day. A total of four measurement points were selected for this measurement, where monitoring point S1 was located at a square with no obvious greenery around; monitoring point S2 was located at a grassland; monitoring point S3 was located at a combination of vegetation with more shrubs, and monitoring point S4 was located at a combination of vegetation with more trees. The location of the test and monitoring points is shown in Figure 2. The surroundings of the monitoring points are shown in Figure 3. For an accurate simulation, the input meteorological data were collected from the nearest national meteorological station (NO.57679) and used to force the boundary conditions. The input data of this simulation is shown in Table 1. This study evaluates the reliability and accuracy of numerical simulations using ENVI-met by comparing simulation results with field measured data.

2.4. Simulation scenario description

To investigate the cooling effects of different vegetation combinations on the outdoor thermal
Figure 2. Test area and location of the measurement point.

Figure 3. Surrounding environment of monitoring point, (a) point S1, (b) point S2, (c) point S3, (d) point S4, (e) the monitoring instrument.
environment, the study tested four scenarios in the residential quarter, shown in Figure 4. Based on high-resolution Baidu map images, this study manually digitizes building boundary information as accurately as possible. To focus the research on the cooling effect brought by the vegetation combinations, obstructions such as shelters, balconies, or decorative items have not been modeled. Therefore, the building blocks were modeled as completely straight simple volumes. This paper removed all the existing vegetation in the area to create a reference scenario and designed three vegetation scenarios: trees and grass (scenario TG); shrubs and grass (scenario SG); and the combination of trees, shrubs, and grass (scenario TSG). The plant locations and the total number of plants are the same in all design scenarios. In scenario TSG, the number of shrubs is equal to the number of trees. The details about the vegetation parameters in all three vegetation scenarios are reported in Table 2.

### 2.5. Simulate parameters setting

Based on the actual spatial scale of the study area, the computational grid domain in ENVI-met is set as $70 \times 35 \times 35$, with the horizontal and vertical grid resolutions being 2 m and 4 m respectively. The respective grid was rotated 15° westward to correct the block structure. To improve the simulation stability and minimize the boundary effect, 9 nesting grids were added around the main area. Furthermore, considering that the surrounding area has buildings and green spaces, the nesting grid surface was set as a checkerboard pattern of two soil profiles (soil and grey concrete). Since the minimum simulation time of ENVI-met is generally 6 h and to better follow the solar radiation (Farhadi, Faizi, and Sanaieian 2019), the simulation was run for 14 h, from 03:00 to 17:00 for 23 July 2018. To ensure the authenticity and the stability of the simulation, the simple forcing function was applied to force hourly air temperature and relative humidity values. The meteorological data were collected from Chenzhou Meteorological Station (No.57972, 25.8°N, 113.03°E) near the study area. Table 3 shows the details about all the simulation input parameters.

### Table 1. The settings of validation simulation.

| Parameters                      | 2019.08.03 |
|---------------------------------|------------|
| Simulation Period               | 16 h       |
| Min Temperature of Atmosphere   | 30.0°C     |
| Max Temperature of Atmosphere   | 37.0°C     |
| Wind Speed                      | 2.1 m/s    |
| Inflow Direction                | 215°       |
| Minimum Relative Humidity       | 47%        |
| Maximum Relative humidity       | 91%        |

### Table 2. Details of vegetation parameters in the model.

| Vegetation   | Tree     | Shrub    | Grass    |
|--------------|----------|----------|----------|
| Plant height | 15 m     | 2 m      | 0.25 m   |
| Leaf type    | deciduous| deciduous| grass    |
| Albedo       | 0.18     | 0.20     | 0.20     |
| Transmittance| 0.3      | 0.3      | 0.3      |

Figure 4. The model scenarios.
3. Results

3.1. ENVI-met validation results

By comparing the measured data at each monitoring point, the study found that the cooling effect differs for different vegetation combinations. As shown in Figure 5, among the four monitoring points, the Ta value at point S1 is higher than the data at the other monitoring points, and the Ta value at point S4 was the smallest. At 16:00, the Ta value at point S1 is 0.7°C higher than at point S2, 1.2°C higher than at point S3, and 2.2°C higher than at point S4.

By comparing the simulated results with the measured data at each monitoring point, the study found just minor differences between the simulation results and the measured data and both have similar variation patterns. As shown in Figure 6, the simulated temperatures are lower than the measurements, the main reason being that ENVI-met simulations ignore anthropogenic heat conditions such as traffic. As shown in Figure 7, the correlation between the ENVI-met simulation and the measurements is very strong with an \( R^2 \) value of 0.873. Furthermore, the study used root mean square error (RMSE) to evaluate the reliability of ENVI-met simulation. RMSE is the square root of the average of squared differences between observation and simulation. In the verification result, the RMSE result is between 2.62°C–2.68°C. This validation result indicates that ENVI-met can be used as an accurate research tool to explore the cooling effect of vegetation combinations in the study area.

3.2. Cooling performances in the horizontal direction

This study extracted the average value of Ta and the average value of MRT at different times (8:00, 10:00, 12:00, 14:00, 16:00) within the study area at the height of 1.8 m. By comparing the Ta and MRT averaged values within different scenarios, this study found that in the horizontal direction, the TG scenario has the best cooling performance, followed by the TSG scenario, and the SG scenario has the worst cooling performance. It is noteworthy that the cooling effect of the TSG scenario is significantly better than that of the SG scenario in the horizontal direction for the same 50% increase in the number of trees, while the cooling effects of the TSG and TG scenarios in the horizontal direction are not significantly different.

The comparison of Ta showed that all vegetation combinations reduced the Ta between 8:00 and 16:00, with the most significant cooling effect at 8:00 and the weakest cooling effect at 12:00. As shown in Figure 8 (a), the cooling effect of the vegetation combination in the horizontal direction showed a trend of gradual decrease followed by a gradual increase over time. At 8:00, Ta in the TG scenario decreased by 0.14°C, Ta cooling value in the TSG was 0.11°C, while Ta in the SG decreased by only 0.01°C. Comparing the cooling effects on Ta between vegetation combinations, it was found that the cooling effect for the TSG scenario was significantly better than that for the SG scenario with an equal increase of 50% in the number of trees, while the cooling effect of the TG scenario on Ta differs slightly from that of the TSG scenario. At 8:00, the

![Figure 5. Comparison of measured Ta data at various monitoring points.](image-url)
The difference in Ta cooling between the TSG and SG scenarios reached 0.1°C, while the difference in Ta cooling between the TG and TSG scenarios was only 0.03°C. Moreover, Figure 10 shows that in the horizontal direction, the low-temperature area is larger in TG and smaller in SG.

The comparison of the MRT results shows that the cooling effects of the various vegetation combination on the MRT are more significant than that on the Ta, where the effect on MRT is the weakest at 8:00 and the best at 14:00. At 14:00, the MRT was reduced by 2.13°C in TG and 1.96°C in TSG, while the cooling value of MRT in SG was only 0.97°C. As shown in Figure 8(b), the cooling effects on MRT in the horizontal direction showed a gradual increase then a gradual decrease with time. This observation is mainly caused by the variation of solar radiation. Besides, the study found that the cooling effect of the TG and the TSG was significantly better than that of the SG, while the difference between the TG and TSG was smaller. At 16:00, the cooling difference between TG and TSG is only 0.16°C, while the cooling difference between TSG and SG reaches 0.92°C. Moreover, Figure 11 shows that low-temperature areas in TG are the largest and low-temperature areas in SG are the smallest. Furthermore, the MRT in the shaded area is significantly lower than the MRT in the surrounding environment.

Figure 6. Comparison of measured Ta and simulated Ta data at each monitoring point, (a) S1, (b) S2, (c) S3, (d) S4.

Figure 7. The relationship between ENVI-met simulated Ta results and measured Ta results.
3.3. Cooling performances in the vertical direction

As shown in Table 4, 16:00 is the hottest time in the study area, so 16:00 is used as a typical time to evaluate the cooling performance of different vegetation combinations in the vertical direction. The average values of Ta and MRT at different vertical heights were extracted for each model scenario, and the data of each vegetation combination were compared with those of the reference scenario. The comparison shows that in the vertical direction, the TG scenario has the best vertical cooling effect, followed by the TSG scenario, and the SG scenario has the worst vertical cooling effect. Besides, it was found that the vertical cooling effect of the TSG scenario was significantly stronger than that of the SG scenario with an equal 50% increase in the number of trees, while the difference in cooling between the TG and TSG scenarios was smaller, and all these observations are similar to the results in the horizontal direction.

Table 4. The averaged Ta at different times at 1.8 m within the study area for each scenario.

| Model scenarios | 8:00  | 10:00 | 12:00 | 14:00 | 16:00 |
|-----------------|-------|-------|-------|-------|-------|
| reference       | 28.09°C | 31.12°C | 33.99°C | 35.35°C | 35.72°C |
| TG scenario     | 27.95°C | 31.07°C | 33.97°C | 35.33°C | 35.66°C |
| TSG scenario    | 27.99°C | 31.09°C | 33.98°C | 35.34°C | 35.68°C |
| SG scenario     | 28.08°C | 31.12°C | 33.99°C | 35.35°C | 35.72°C |

Figure 8. Comparison results of the average values of each meteorological data at different times within the study area of each scenario (at 1.8 m), (a) the comparison results of the Ta, (b) the comparison results of the MRT.

From the comparison of the Ta results, the TG scenario has the best cooling effect on Ta, while the SG scenario has the weakest. Moreover, in the vertical direction, the cooling effects of TG and TSG scenarios on Ta have gradually decreased, while the cooling effect of the SG scenario on Ta has changed less. As shown in Figure 9(a), at a vertical height of 25 m, the Ta decreases by 0.02°C for the TG scenario and by 0.01°C for the TSG scenario, while there is almost no difference in the SG scenario compared to the reference scenario. Figure 10 shows that the low-temperature areas in TG are the largest and they are the least in SG, which is consistent with the observations in the horizontal direction. Figure 10 also shows that the low-temperature region is mainly concentrated at the location of planted vegetation.

From the comparison results of the MRT, the vegetation combination can effectively reduce MRT in the vertical direction, where the TG scenario has the best cooling effect on MRT, while the SG has the worst cooling effect. Figure 9(b) shows that in the vertical direction, the MRT cooling effects of both TG and TSG scenarios showed a trend of gradual increase then a gradual decrease, while the MRT cooling effects of the SG scenario kept gradually decreasing. The main reason for this phenomenon is due to the different vegetation heights of trees and shrubs. Since the canopy position of trees is around 9 m, which can block more solar radiation irradiation, the cooling
Figure 10. Spatial distribution of TA in each scenario (at 8:00, 12:00, 16:00).

4. Discussion
This study investigated the 3D (horizontal and vertical) cooling effects of different vegetation combinations on the urban outdoor thermal environment. Compared with the simulation results, it was found that the TG scenario has the best 3D cooling effect, followed by the TSG scenario, and the SG scenario has the smallest 3D cooling effect. The reason for this finding is that trees can provide more shading effects and prevent more solar radiation than shrubs. This result is in line with some previous studies, which showed that the shadow-cast effect reduces the radiant load and improves thermal comfort (Morakinyo, Kong, and Lau et al. 2017). Furthermore, it is worth noting that the 3D cooling effect of the TSG scenario is close to that of TG, while SG’s 3D cooling effect is quite different from that of TG. In this study, with an equal increase in the number of trees by 50%, a first increase brought obvious 3D cooling benefits, but a further increase brought much less 3D cooling benefits. That is to say, continuously increasing the coverage of the same proportion of trees will not bring the same proportion of cooling benefits. That means there is no linear relationship between increasing tree coverage and the cooling effect it brings. The main reason for this phenomenon is that the first 50% increase in the number of trees adds a large area of shade to the scenario, resulting in a significant cooling benefit. After the 50% increase in the number of trees, the shade provided overlaps with the previous one, and the increased shade area is not as large, so the cooling benefit is not as obvious as before. This result supports the result of a previous study, which showed that the relationship between the cooling capacity and the vegetation coverage is not linear (Wu, Dou, and Chen 2019). Besides, it was found that the shading can directly affect the 3D cooling effect of vegetation combination. In this study, the temperature at shaded areas
was significantly lower than that of the surrounding environment. Furthermore, the larger the area of shading is, the better the 3D cooling effect will be. Therefore, this study recommends that planners and designers should focus not only on the green space coverage but also on the shading area.

This study helps urban planners and landscape designers to formulate the urban greening strategy to improve the outdoor thermal environment of urban areas. Although this study found that the TG scenario has the best 3D cooling effect, the effect of TSG is close to that of TG. The TSG scenario planted a smaller number of trees, resulting in a cheaper cost, so the study strongly recommends that urban areas should plant a combination of trees, shrubs, and grass. Beyond our findings, the urban area should also adopt a combination of various mitigation strategies such as green roofs. It was found that the cooling effect of the vegetation combination was gradually decreasing in the vertical direction. However, roof greening has a better cooling effect on the roof level (Daemei et al. 2018). Hence, multiple mitigation strategies should be combined to improve the city’s overall outdoor thermal environment.

It is worth describing some of the limitations of the current study which are mainly related to the ENVI-met model. One is that wind flow and cloudiness remain constant throughout the diurnal cycle simulation, which does not correspond to the real atmosphere (Morakinyo, Kong, and Lau et al. 2017). Furthermore, all building facades and roofs of ENVI-met use similar thermal performance as a single wall material, which oversimplifies the heterogeneity of the urban environment (Morakinyo, Kong, and Lau et al. 2017). Moreover, we only explored the cooling performance of different vegetation combinations. Further study is recommended to investigate the 3D cooling performance of different ratios of trees, shrubs, and grass.

5. Conclusions

In this study, we have applied the ENVI-met model to evaluate the 3D cooling performance (horizontal and vertical) of different vegetation combinations to improve the outdoor thermal environments of urban areas. Our results provide three interesting views that relate to improving thermal comfort in urban areas:

(1) Among all greening combinations, the TG scenario has the best 3D cooling effect, followed by TSG, and SG has the worst 3D cooling effect. Furthermore, the 3D cooling effect of TG and TSG is significantly better than that of SG, but the difference between the cooling effects of both TG and TSG is extremely small. Therefore, considering that fewer trees would cost less, this study strongly recommends a combination of trees, shrubs, and grass in urban areas.

(2) Shading can directly affect the 3D cooling effect of the vegetation combination. The larger the
shaded area, the better the cooling effect for the same vegetation cover, so the study suggests that designers should focus not only on vegetation cover but also on shading proportion.

(3) Increasing the tree coverage can significantly cool the outdoor thermal environment, but the relationship between increasing tree coverage and the cooling effect it brings is not linear. Indeed this study sequentially applied an equal increase in the number of trees by 50% but that did not result in equal cooling benefits.

This study provides some insights into the 3D cooling performance of different vegetation combinations, which can provide an effective guidance for planners and designers to improve the urban thermal environment and enhance the thermal comfort in urban areas.

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