Quantifying the impacts of green roof design factors on microclimate regulation: A case study in Washington, D.C.

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Abstract. This study explores and quantifies the impacts of green roofs' (GR) design factors on microclimate regulation. Against rapid urbanization and intensifying climate changes, green infrastructure has received increasing attention due to its contribution to dealing with the urban heat islands effect (UHIE) and increasing urban sustainability. GR is one example of green infrastructure and is widely used in cities. However, its microclimate regulation benefits have not been thoroughly explored and require more exploration. There are insufficient studies on quantifying GR design factors' impacts on microclimate regulation. Meanwhile, little research has explored the impact of regulating microclimate when accessibility is considered as a design factor. Using a GR in Washington, D.C., as a case study, this study models 14 roof scenarios with several common GR design factors, generates their simulated microclimate patterns, and quantifies each design factor's impact based on statistical analyses. Results present quantitative data on how studied design factors change microclimate patterns and find that accessibility does affect some microclimate aspects but only to a limited rate. This study provides suggestions and insights to optimize GR design guidelines. Overall, this study contributes to the refinement of GR research, promotes better GR design, and responds to urbanization and climate issues.

Keywords: Green Roof, Microclimate Regulation, Quantification, Green Roof Design Guidelines

1. Introduction

Rapid urbanization has changed the way that urban lands are used, displacing open or vacant spaces with urban structures and materials [1]. Intensifying climate changes increase the frequency and intensity of heat waves, significantly impacting the urban thermal environment [2]. Urbanization and climate changes lead to several urban environmental issues, such as the urban heat islands effect (UHIE), whereby the temperature in the city is significantly higher than in the adjacent suburbs and rural areas [3]. UHIE negatively impacts people's health and thermal comfort and leads to issues like higher energy use, altering water quality, and deteriorating air quality, which causes a severe danger to the environment and the long-term sustainability of urban development [4,5,6]. With the inevitably continuous advancement of urbanization and the impact of climate change, future scenarios predict that the UHIE will intensify [7].

Against this background, building and utilizing urban green infrastructures is recognized as one of the most efficient ways to mitigate the UHIE [8]. Green roofs (GR) are one representative example of these urban green infrastructures. Organizations and agencies such as the Landscape Architecture Foundation, World Green Infrastructure Network, the U.S. Green Building Councils, and the U.S. Environmental Protection Agency emphasize the strengths of GR in regulating microclimates and improving urban sustainability [9-12]. Due to the plant covering, GR can minimize solar radiation absorption, retention, and transmission [13-18]. GR lessens the thermal burden of the rooms located below in the summer as well as the wintertime heat loss via the roof [19]. GR can reduce the city's temperature and humidity through vegetation's transpiration and shading effect [20,21]. The soil in the GR can change the proportion of water in the local area by absorbing and retaining rainwater to form a more comfortable microclimate [22,23].

Although the relationship between GR and microclimate regulation has received some attention, some studies have only remained superficial and did not delve into how specific design factors affect the ability to regulate microclimate [24,25]. In addition, there is a need to quantify the relationship between various design factors of GR and their microclimate-regulating capabilities [20,25,26]. Professionals and decision-makers need quantitative results to prove the expected effects of GR to the public [20,27-29]. Also, due to the emphasis on social sustainability, more and more GR are designed to be accessible to the public [30-32]. However, most existing literature and research only analyses the benefits of inaccessible GR. Few studies have considered accessibility as a GR design factor and explored its impacts on GR's microclimate regulation ability. Understanding the most influential GR design factors for each aspect of microclimate regulation can help professionals optimize the design of GR for optimal benefits. Meanwhile, it can help governments and policymakers develop policies that encourage or require the implementation of specific types of GR.

This study aims to explore and quantify the impact of different GR design factors (plant configuration, soil volume, scale, and accessibility) on microclimate regulation. The research team uses a GR in Washington, D.C. as a case study, uses ENVI-MET microclimate simulation software to build models of 14 roof types (2 traditional grey roofs and 12 GR), and analyzes and quantifies the impacts of their design factors on the microclimate. Related research questions are: (1) How do the design factors of GR change the microclimate, and to what extent? (2) Does accessibility affect the microclimate regulating ability of GR? (3) How can this research contribute to guiding future GR design and promoting urban green infrastructure development? Figure 1 shows the research framework of this study.

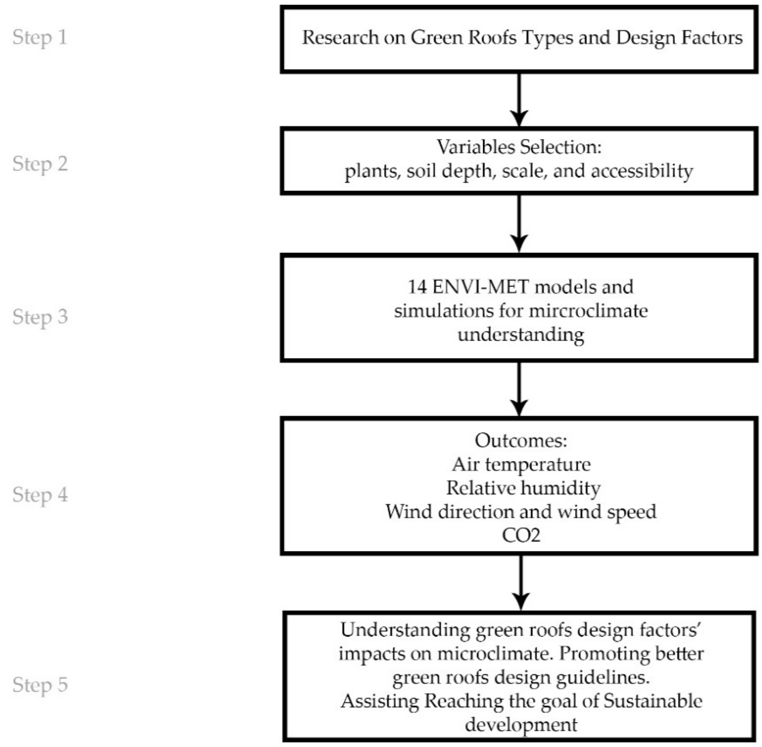

Figure 1. Research framework.

2. Materials and Methods

2.1. Study Site

The research site for this study is located in Washington, D.C. (Figure 2). The approximate latitude and longitude are 38.878°N and 77.008°W. There are four distinct seasons in this humid subtropical area, with the summer being particularly hot and muggy [33]. Temperatures are usually between -1.6°C and 31.1°C throughout the year [33]. An average of 37 days per year has daily maximum temperatures over 32°C. Furthermore, the length and frequency of heat waves in the area are growing yearly because of the UHIE [33]. According to the census in 2023, D.C. has a population of around 630,000 people, with about 410,000 transients [34].

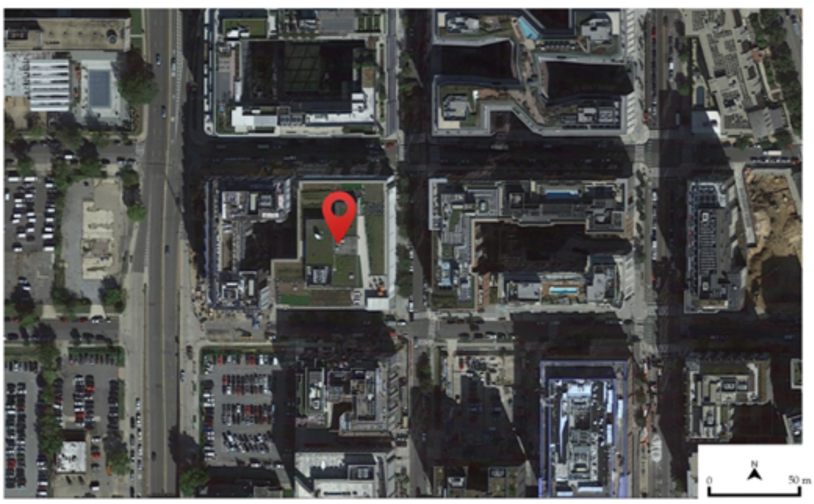

Figure 2. Research site location.

The research site selection refers to the Local Climate Zone (LCZ) theory, commonly used in UHIE studies and microclimate research. LCZ is a well-developed classification system based on urban climatology [35]. The LCZ is defined as zones with a consistent surface cover, structure, and human activity that range in size from a few meters to several kilometers [36]. According to the LCZ's classification, the research site belongs to the typical compact midrise built type (LCZ-2). LCZ-2 type refers to tall buildings with up to ten stories; most surrounding surfaces are covered with hard paving, and the building materials are concrete, steel, stone, or glass [37]. Although this research site is in the United States, LCZ-2 type exists in most global cities, so the universality of the research can be ensured. Meanwhile, the scale of the GR in this study is moderate and can be found in most global cities.

2.2. Research Method

GR is commonly divided into three types: extensive, semi-intensive, and intensive, with different factors [38]. The research team summarizes these three types and their characteristics in Table 1.

Table 1. General characteristics of three green roof types.

Type	Extensive	Semi-intensive	Intensive
Use	Ecological Landscape	Garden/Ecological Landscape	Garden/Park
Type of Vegetation	Moss-Herbs-Grasses	Grass-Herbs-Shrubs	Lawns/Perennials, Shrubs, Trees
Benefit	W, H, E	W, H, A, E	W, H, A, E
Depth of Substrate	60-200 mm	120-250 mm	150-400 mm

W=Water, H=Heat, A=Accessibility, E=Environmental Comfort

Based on these three types and studied GR design factors, the research team established 14 experimental roof scenarios. Figure 3 illustrates 14 scenarios along with their simplified codes. Meanwhile, Table 2 presents 14 scenarios in detail. The common GR scale in LCZ-2 ranges from tens to hundreds of square meters [39,40]. Therefore, the research team divided 14 scenarios into two scale groups, which are 10m x 10m and 20m x 20m. This study involves two different soil depths (60 mm and 250 mm). According to the GR design standard, the soil type is preset as mixed with crushed clay and perlite for subsequently simulating microclimate patterns [41]. Regarding the plant arrangements, there are four categories: concrete roof, ground cover solely, ground cover with shrubs, and ground cover along with shrubs and trees. The accessibility is classified as having a 2-meter-wide path and a 3-by-3-meter platform. According to the Washington, D.C. native plant list and relevant research on GR plant selection, the plant species involved in this study are as follows [42,43,44,45]. The plant materials in this study are: 200mm tall Sedum ternatum (Sedum ternatum Michx.) representing the groundcover, 500mm tall little leaf boxwood (Buxus microphylla) representing the shrubs, and 4.5m tall Japanese maple (Acer palmatum) with a 3m wide crown representing the trees.

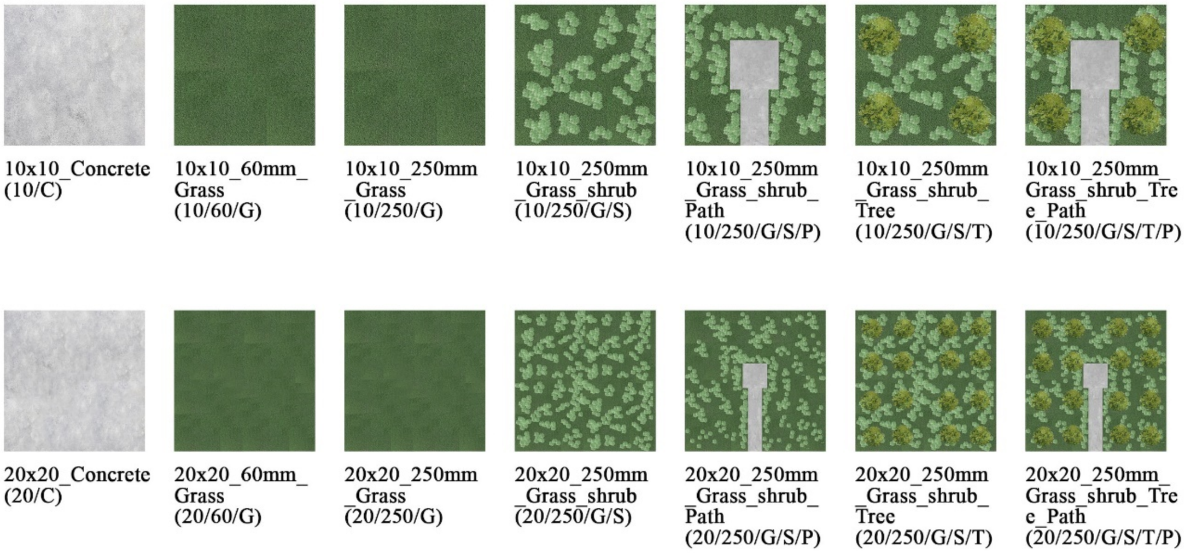

Figure 3. 14 Experimental scenarios with simplified codes.

Table 2. 14 Experimental scenarios' details

Scenario Code	Scale (m^2)	Concrete (m^2)	Soil Volume (m^3)	Grond Covered Area (m^2)	Shrub Covered (m^2)	Tree Covered Area (m^2)	Path and Platform (m^2)
10/C	100	100	0	0	0	0	0
10/60/G	100	0	6	100	0	0	0
10/250/G	100	0	25	100	0	0	0
10/250/G/S	100	0	25	50	50	0	0
10/250/G/S/P	100	0	25	41.5	41.5	0	17
10/250/G/S/T	100	0	25	36	36	28	0
10/250/G/S/T/P	100	0	25	27.5	27.5	28	17
20/C	400	400	0	0	0	0	0
20/60/G	400	0	24	400	0	0	0
20/250/G	400	0	100	400	0	0	0
20/250/G/S	400	0	100	200	200	0	0
20/250/G/S/P	400	0	100	185.5	185.5	0	29
20/250/G/S/T	400	0	100	144	144	112	0
20/250/G/S/T/P	400	0	100	129.5	129.5	112	29

This study uses ENVI-MET to model these 14 scenarios and generate their simulated microclimate patterns. ENVI-MET is a professional microclimate simulation software, and its reliability has been proved by numerous studies [46,47,48,49,50]. ENVI-MET requires the input of some specific fundamental site factors (temperature, humidity, wind speed, etc.) for a microclimate simulation. If more precise study results are needed, meteorological conditions collected from the site are essential. Therefore, the research team randomly selected August 6, 2023, and conducted field data collection. As air temperature, humidity, wind direction/speed, and carbon dioxide (CO_2) are key factors of

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microclimate and related to UHIE, the research team used them as the dependent variables in this study. 14 scenarios' simulated microclimate data is analysed through SPSS to conduct descriptive statistics analyses and multiple regression analyses.

The equations used to quantify each factor's impact on a specific microclimate aspect are presented in this section, and all equations strictly follow statistical research standards [51,52]. A unit change in an independent variable's (such as 1 m^2 ground cover area) impact on a dependent variable (such as air temperature) is calculated by equation (1). ΔX_i represents the change in the independent variable X_i, ΔY_i represents the change in the dependent variable Y_i, and β_i is the coefficient that quantifies the effect of a unit of X_i on Y_i [51,52]. When a study aims to quantify the impact of N units of X_i on Y_i, the equation should be equation (2). The studied units in this paper are either 100 m^2 or 10 m^3. Meanwhile, for the air temperature variable and CO_2 concentration variable, this study focuses on the impacts of GR design factors on their daily average. As all data exported by ENVI-MET is the hourly average, the daily averages for these two variables are calculated by equation (3). As the humidity, wind directions, and wind speed factors have no meaning in the daily average, the effects of GR design factors on them only need to be calculated by equation (2). All the equations are as follows.

$$\Delta Y_i = \beta_i \cdot \Delta X_i \tag{1}$$

$$\Delta Y_i = N \cdot \beta_i \cdot \Delta X_i \tag{2}$$

$$\Delta Y_i = 24 \cdot N \cdot \beta_i \cdot \Delta X_i \tag{3}$$

3. Results

3.1. Air Temperature

The research team first selected 14:00 (August 6, 2023) as the time for the air temperature analysis because the temperature reached the highest value that day at that time point. Figure 4 presents the 14 scenarios' air temperature distributions at 14:00. The presence of both shrubs and trees could reduce the air temperature, while the impact of trees is more prominent, leading to a significant change presented in Figure 4. However, it is worth noting that when the ground cover replaced concrete as the roof covering, the air temperature at 14:00 was not reduced but increased. Further investigations are necessary to explain this phenomenon. The preliminary results also indicate that air temperature positively correlates with soil volume. The higher the soil volume is, the higher the air temperature reaches. The findings suggest that larger-scale models show more pronounced effects on reducing air temperature when other factors are the same. Due to the direction of the wind, the lower temperature in all these scenarios is in the south, while the temperature in the downwind direction would be relatively high. Moreover, this phenomenon is not affected by other variables.

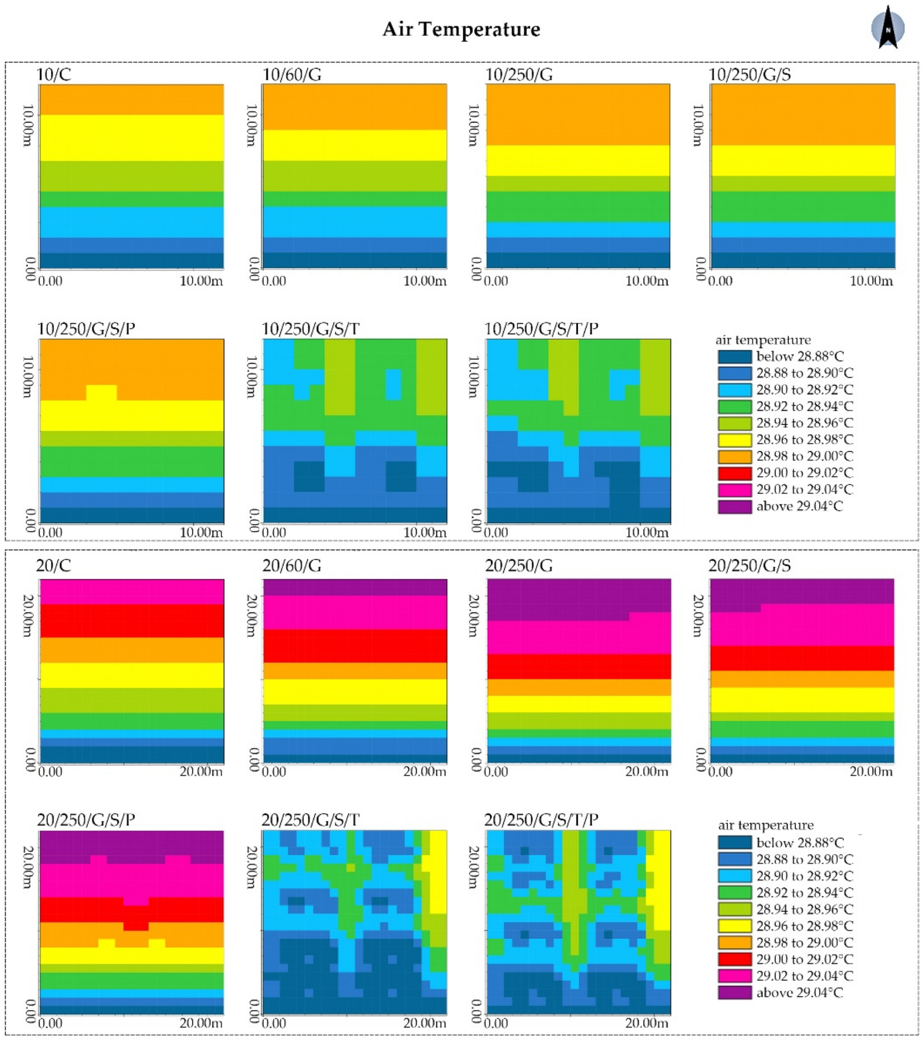

Figure 4. Air temperature distribution.

To further explore and quantify the impacts of GR design factors' impacts on air temperature distribution and address the phenomenon mentioned above, the research team conducted analyses of the 24-hour average temperature change (Table 3). Figure 5 presents the air temperature fluctuation for the 14 roof models over the studied 24 hours. The findings support the previous results. Meanwhile, the findings demonstrate that ground covers can contribute to decreasing the air temperature even though the effect is relatively limited compared to trees and shrubs.

Table 3. Descriptive statistics of 24-hour average air temperature for 14 scenarios.

Types	Average Air Temperature	Numbers	Std. Deviation
10/C	26.85451	24	1.51051
10/60/G	26.85344	24	1.53704
10/250/G	26.87329	24	1.57220
10/250/G/S	26.87307	24	1.56658
10/250/G/S/P	26.87468	24	1.56442
10/250/G/S/T	26.84220	24	1.50753
10/250/G/S/T/P	26.84696	24	1.50890

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Table 3. (continued).

20/C	26.81126	24	1.49785
20/60/G	26.80625	24	1.51270
20/250/G	26.81126	24	1.49785
20/250/G/S	26.79479	24	1.53147
20/250/G/S/P	26.79527	24	1.52865
20/250/G/S/T	26.78900	24	1.50065
20/250/G/S/T/P	26.78896	24	1.49970

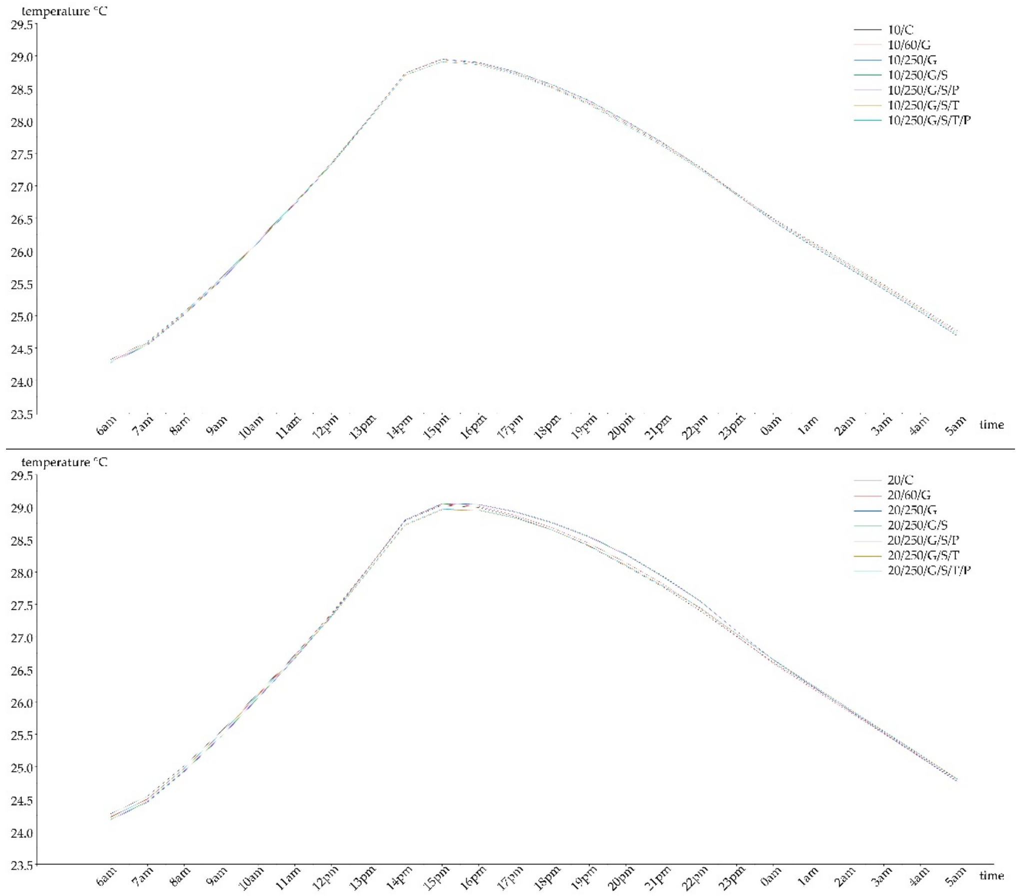

Figure 5. The air temperature changes in 24h.

The research also conducted multiple linear regression tests and based on the equations shown in section 2.2. to quantify each factor's impact on air temperature change (Table 4). The results indicate that every 100 m^2 of trees can decrease the air temperature in the roof area by about 0.415 °C in one day, while shrubs by about 0.243 °C and ground covers by about 0.048°C. Soil volume has a slightly positive relationship with air temperature; every 10 m^3 of soil could increase the air temperature by 0.030 °C. Meanwhile, when other GR factors are the same, every additional 100 m^2 of GR area could decrease the temperature by 0.421 °C. As the accessibility increases grey areas on the roof, it slightly increases air temperature by approximately 0.031 °C per 100 m^2.

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Table 4. GR design factors' impacts on air temperature.

Design Factors	Implications for Air temperature (°C /24 h)
Scale (/100 m^2)	-0.421
Soil Volume (/10 m^3)	0.030
Ground Cover (/100 m^2)	-0.048
Shrub (/100 m^2)	-0.243
Tree (/100 m^2)	-0.415
Path and platform (/100 m^2)	0.031

3.2. Humidity

Figure 6 shows the simulated relative humidity distributions of all scenarios at 14:00. Regarding the 100 m^2 scale roof model group, findings indicate that the relative humidity increased significantly when the ground covers were added. The results also show that the relative humidity increased when the soil depth was adjusted from 60mm to 250 mm. It can be found that shrubs do not seem to be a variable that affects relative humidity, but trees can cause a significant relative humidity deduction. The path and platform could reduce the relative humidity. The relative humidity changes in 400 m^2 scale models are more obvious than in 100 m^2 scale models. However, one result is different, shrubs seem to cause a significant increase in relative humidity in 400 m^2 scale models. Similar to the 100 m^2 scale group's results, trees, and the path and platform could reduce relative humidity. Combining the findings from both two groups, the scale shows the relative humidity reduction ability. Meanwhile, the distribution of relative humidity in larger GR scenarios is more fragmented.

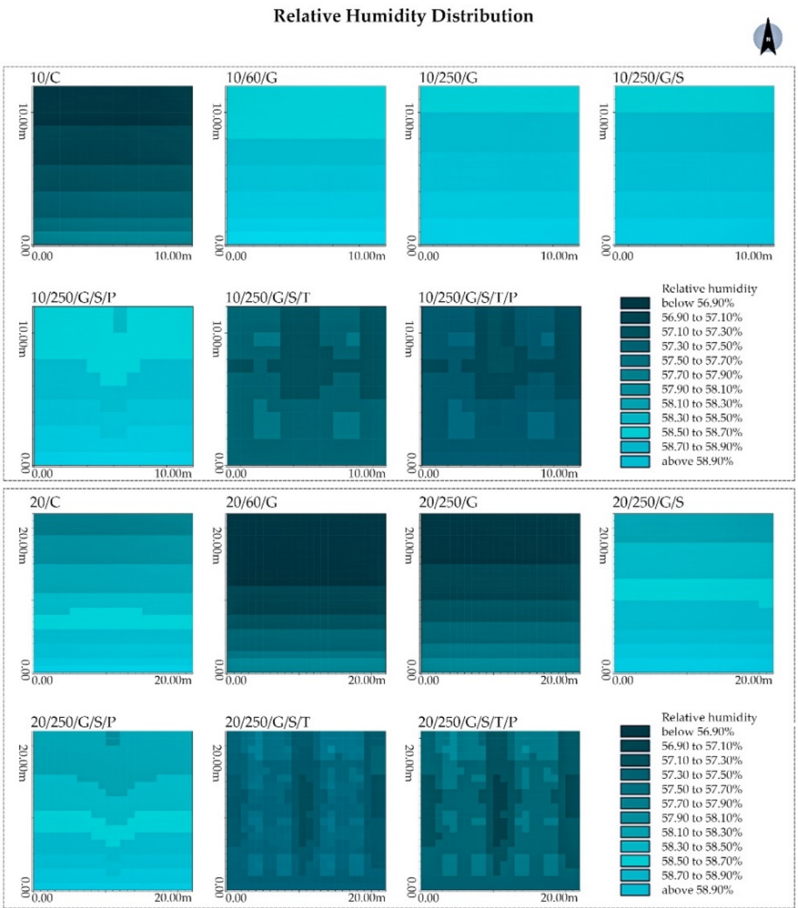

Figure 6. Relative humidity distribution.

The research team also analyzed the relative humidity of the 14 models in the 24-hour period. Figure 7 shows the change in the average relative humidity over a 24-hour period. Between 13:00 and 22:00, the 14 scenarios relative humidity increased while decreasing for the rest of the period. But 14 scenarios' change rates are different, demonstrating that GR design factors impact relative humidity. Table 5 shows the hourly average relative humidity for 14 scenarios. Results confirm that the plants, roof scale, and accessibility can indeed affect the relative humidity of the roof. In the 100 m^2 scale group, ground cover causes the relative humidity to increase, but in the 400 m^2 scale group, it causes a deduction. Table 6 presents the quantified impacts of GR design factors on relative humidity. Regarding plants, the results indicate that trees can reduce average daily humidity by 0.477% per 100 m^2 canopy area, and ground covers can decrease humidity by 0.069% per 100 m^2. However, the finding indicates that shrubs do not impact roof areas' relative humidity; they only increase relative humidity by 0.009% per 100 m^2. Soil volume can lead to a 0.074% increase in relative humidity per 10 m^3. The accessibility could help to decrease the humidity by -0.268 %.

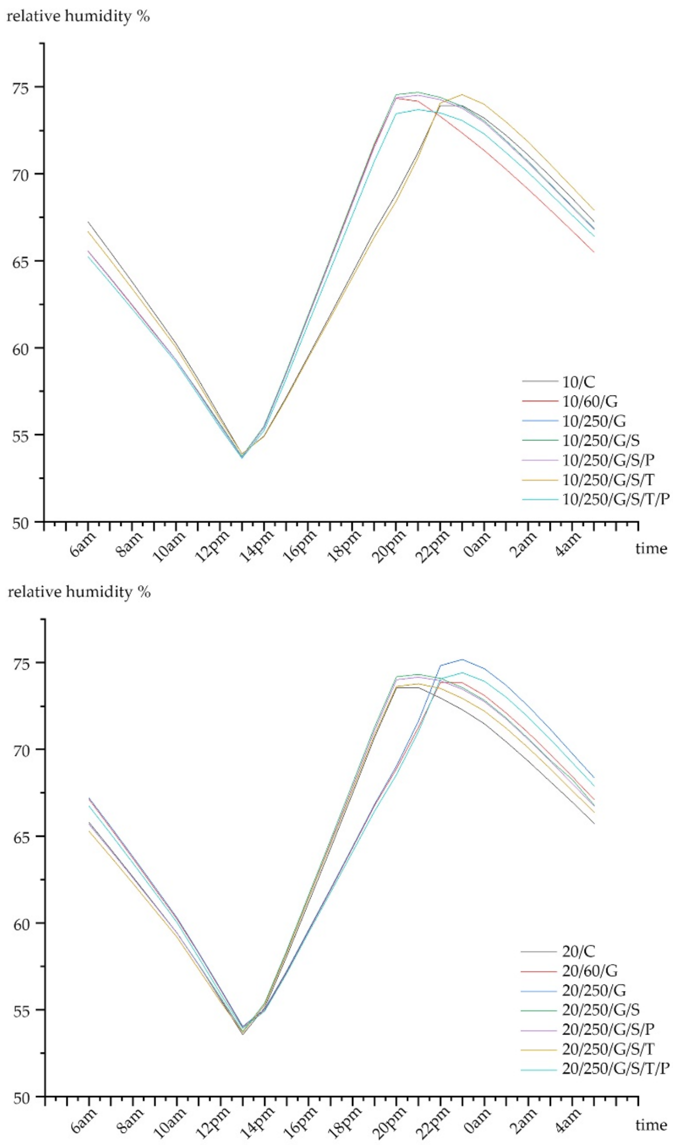

Figure 7. Relative humidity changes in 24h.

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Table 5. Descriptive statistics of 24-hour average relative humidity distribution for 14 scenarios.

Types	Average Relative Humidity	Numbers	Std. Deviation
10/C	65.06543	24	6.27467
10/60/G	65.21349	24	6.30652
10/250/G	65.75139	24	6.73054
10/250/G/S	65.74796	24	6.73235
10/250/G/S/P	65.66425	24	6.70497
10/250/G/S/T	65.11135	24	6.51252
10/250/G/S/T/P	65.22198	24	6.46411
20/C	65.23209	25	6.16691
20/60/G	65.03839	24	6.21929
20/250/G	65.55553	24	6.69616
20/250/G/S	65.64120	24	6.61812
20/250/G/S/P	65.55136	24	6.59118
20/250/G/S/T	65.25667	24	6.45860
20/250/G/S/T/P	65.14032	24	6.49564

Table 6. GR design factors' impacts on relative humidity.

Design Factors	Implications for Relative Humidity (%)
Scale (/100 m^2)	-0.080
Soil Volume (/10 m^3)	0.074
Ground Cover (/100 m^2)	-0.069
Shrub (/100 m^2)	0.009
Tree (/100 m^2)	-0.477
Path and platform (/100 m^2)	-0.268

3.3. Wind Direction

Figure 8 presents the results of the wind direction for 14 roof models. It is evident that the tree greatly influences the wind direction. However, the simulated wind directions are likely to be random. This might be because the wind is blocked by tree trunks, branches, and eddies generated when wind passes through the complex canopy structure, which affects the wind direction. Also, the statistical analysis results demonstrate no statistical meaning between trees and the changes in wind directions. Meanwhile, results show that ground covers and shrubs are not variables that could change the wind direction. The comparison of the two groups of results indicated that the scale and path could change the wind direction to a certain extent, but the change is subtle and not significant. Overall, GR design factors do not directly impact wind directions in statistical meaning. Those changes in this study are all because of physical blocks.

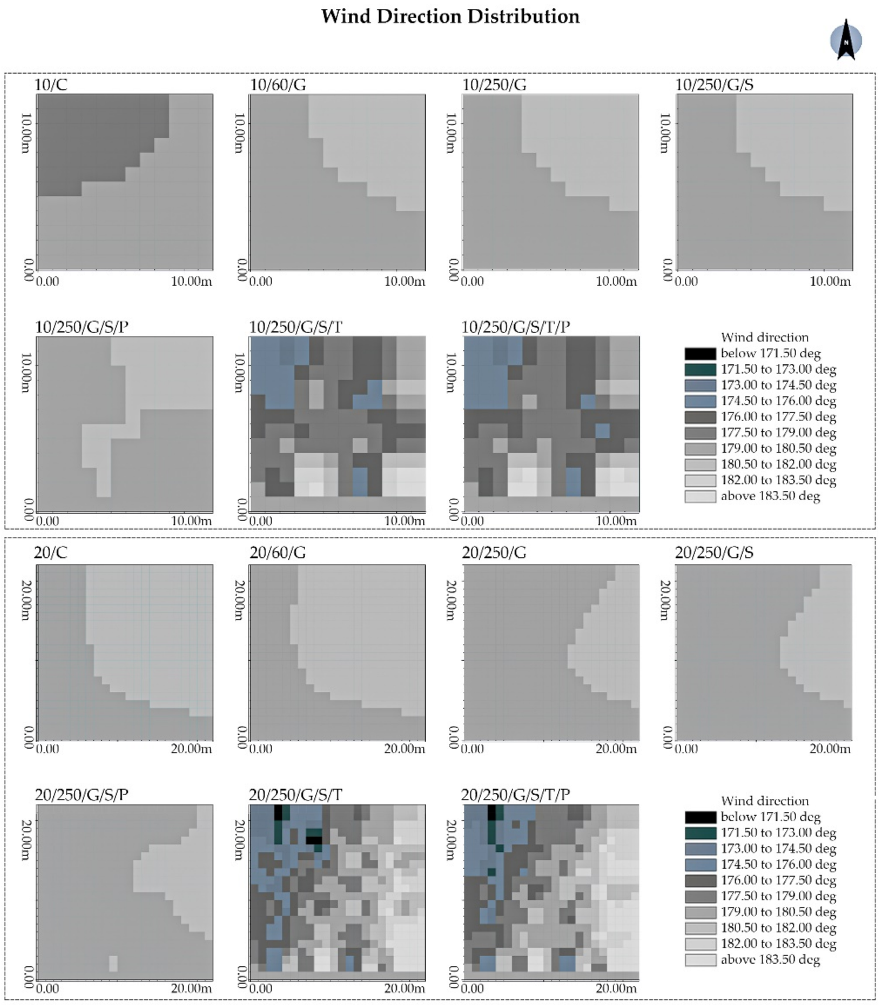

Figure 8. Wind direction distribution.

3.4. Wind Speed

The impacts of GR design factors on wind speed are more obvious and pronounced than on wind directions (Figure 9). Findings indicate that the impact of scale on wind speed is insignificant. Plants have a significant effect on reducing wind speed. Trees influence wind speed most among all plants, which could significantly reduce wind speed. However, shrubs do not seem to affect wind speed. An unexpected finding is that soil volume seems to affect wind speed. Table 7 presents each factor's impact on wind speed. First, it refutes that soil volume could affect the wind speed as the per 10 m^3 soil can only decrease the wind speed by 0.019 m/s. Regarding plants, every 100 m^2 roof area covered by trees can reduce wind speed by 0.356 m/s, while shrubs and ground covers by 0.014 m/s. Meanwhile, scale is an important factor which can influence the wind speed. Every additional 100 m^2 GR area reduces wind speed by 0.058 m/s. As accessibility would increase uncovered/unblocked spaces on GR, leading to a 0.141 m/s wind speed increase per 100 m^2.

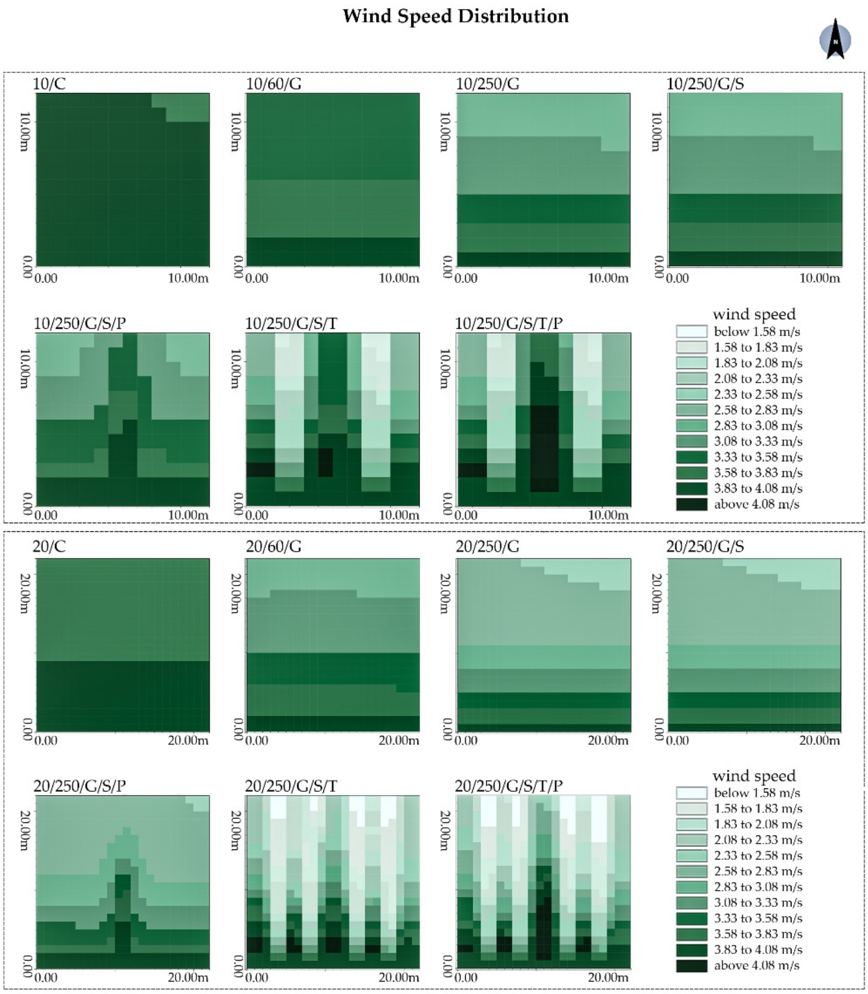

Figure 9. Wind speed distribution.

Table 7. GR design factors' impacts on wind speed.

Design Factors	**Implications for wind speed** (m/s)
Scale (/100 m^2)	-0.058
Soil Volume (/10 m^3)	-0.019
Ground Cover (/100 m^2)	-0.014
Shrub (/100 m^2)	-0.014
Tree (/100 m^2)	-0.356
Path and platform (/100 m^2)	0.141

3.5. Carbon Dioxide Concentration

Figure 10, Table 8, and Table 9 present the influence of GR on CO_2 concentration in the air. Results indicate that all studied plants could decrease the CO_2 concentration. Results indicate that trees are more effective in reducing the CO_2 concentration than shrubs and ground covers. In one day, 100 m^2 of trees can reduce 1.482 ppm of CO_2 concentration in the roof area, while every 100 m^2 of shrubs and ground covers decreases the CO_2 concentration by 0.225 ppm and 0.314 ppm. The accessibility and the scale have no impact on CO_2 concentration. Soil volume could cause an increase in CO_2 concentration by 0.348 ppm. It might be because of the microorganism's respiration effect.

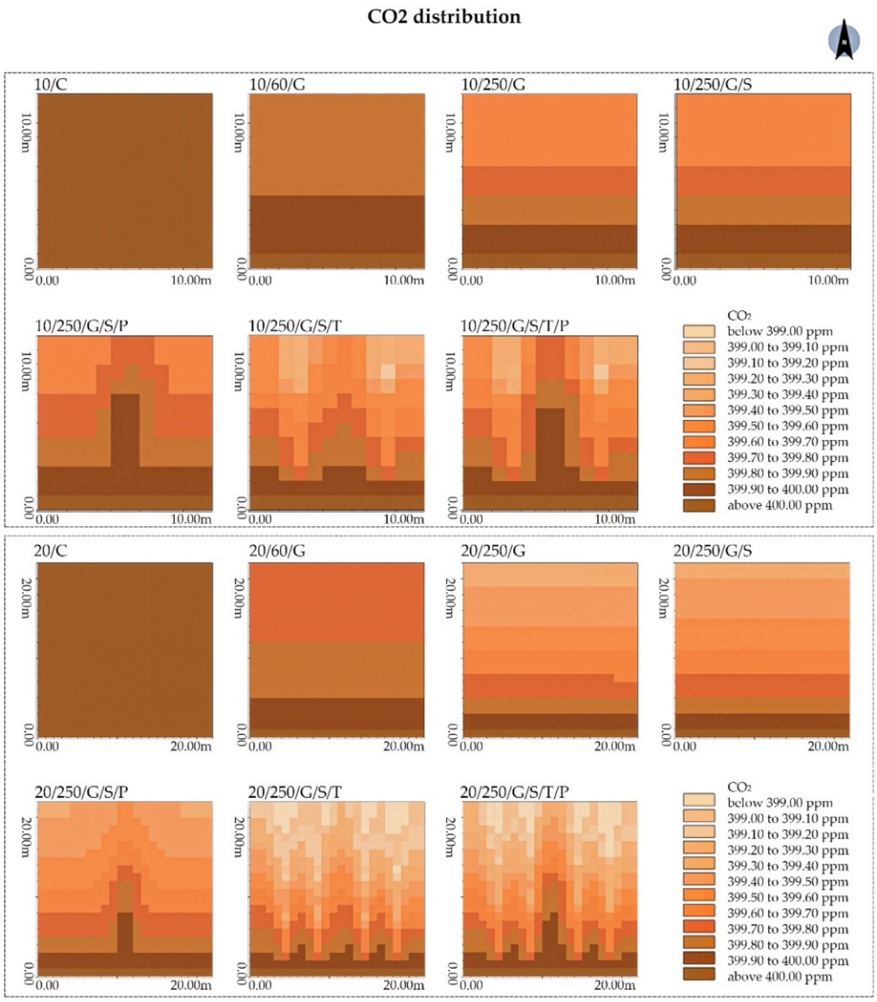

Figure 10. Carbon dioxide (CO_2) distribution.

Table 8. Descriptive statistics of 24-hour average CO_2 concentration for 14 scenarios.

Types	Average CO_2 Concentration (ppm)	Numbers	Std. Deviation
10/C	400.00201	24	0.00000
10/60/G	399.89826	24	0.07001
10/250/G	399.77888	24	0.15866
10/250/G/S	399.78260	24	0.15558
10/250/G/S/P	399.83184	24	0.12202
10/250/G/S/T	399.72407	24	0.21915
10/250/G/S/T/P	399.75997	24	0.19251
20/C	400.00201	24	0.00000
20/60/G	399.83867	24	0.11300
20/250/G	399.64503	24	0.26755
20/250/G/S	399.65125	24	0.26327
20/250/G/S/P	399.68701	24	0.23775
20/250/G/S/T	399.58813	24	0.37820
20/250/G/S/T/P	399.61587	24	0.35143

Table 9. GR design factors' impacts on CO_2 concentration.

Design Factors	**Implications for** CO_2 **concentration (**ppm/**24 h)**
Scale (/100 m^2)	0.002
Soil Volume (/10 m^3)	0.348
Ground Cover (/100 m^2)	-0.314
Shrub (/100 m^2)	-0.225
Tree (/100 m^2)	-1.482
Path and platform (/100 m^2)	0.000

3.6. Summary of Quantitative Results

The research team summarized the quantified effects of each studied GR design factor on microclimate aspects and presented in Table 10.

Table 10. GR design factors' impacts on microclimate aspects.

Design Factors	**Implications for Air temperature (°C /24 h)**	**Implications for Relative Humidity (%)**	**Implications for wind speed (m/s)**	**Implications for** CO_2 **concentration (ppm/24 h)**
Scale (/100 m^2)	-0.421	-0.080	-0.058	0.002
Soil Volume (/10 m^3)	0.030	0.074	-0.019	0.348
Ground Cover (/100 m^2)	-0.048	-0.069	-0.014	-0.314
Shrub (/100 m^2)	-0.243	0.009	-0.014	-0.225
Tree (/100 m^2)	-0.415	-0.477	-0.356	-1.482
Path and platform (/100 m^2)	0.031	-0.268	0.141	0.000

4. Discussion

This study identifies and quantifies the effectiveness of some GR design factors (plants, soil volume, scale, and accessibility) in regulating microclimate. All quantified results are listed in the result section. This study contributes to filling the gap of insufficient quantitative research in landscape architecture and could provide optimized guidelines for better GR design in the future.

This study demonstrates that trees have a great ability for microclimate regulation regarding reducing air temperature, relative humidity, wind speed, and CO_2 concentration, which is aligned with other GR studies' findings. Shrubs can also help to down the air temperature. However, regarding reduction in relative humidity, wind speed, and CO_2 concentrations, shrubs show lower ability than ground covers in this study. This phenomenon violates conventional theories that shrubs have better capabilities in these aspects due to the larger biomass [53,54,55]. Some potential explanations are: 1) Due to the different plant growing characteristics, ground cover may be more compact, creating a denser layer of vegetation that is more effective at reducing wind speed and relative humidity [56]. Ground covers have smaller, more numerous leaves than shrubs, which leads to more transpiration and affects relative humidity [57]. Although the total biomass of a shrub may be more significant, its biomass may be primarily distributed in the stems and roots rather than the leaves [58]. This may affect its efficiency in reducing CO_2 concentrations [58]. Further research is needed to explore this phenomenon to provide a better theoretical basis for the GR design. As soil type and volume have some impacts on relative humidity and CO_2 concentration, professionals should fully consider soil selection and implementation to optimize GR's microclimate regulation ability. The findings demonstrate that the accessibility has little influence on air temperature and CO_2 concentration. It does have limited impacts on relative humidity and wind speed because it would decrease the green area' rate and add open space on the roof. These effects may be further diminished when considering accessible GR's great benefits on social sustainability.

Some quantified microclimate regulation effects of GR might not be very significant. However, these were the benefits produced by a single GR in one day. When GR is used to replace more gray roofs in cities, these benefits will be huge in the long term.

Based on this study's findings, the research team provides some suggestions for optimizing the GR design guidelines. 1) When building future urban buildings, designers can consider strengthening structures to install intensive gratings that can support trees due to the great ability of trees to microclimate regulation. 2) Because the findings indicate the selected shrub species have limited capacities to regulate the relative humidity and reduce wind speed, adequate attention needs to be paid to selecting GR shrubs in the future. 3) When selecting plants, the geographical location and trees' characteristics (cold resistance, growth speed, mature size, root structure, etc.) must be considered to suit the application in GR. 4) Building more accessible GR in urban areas is highly recommended. It allows GR not only to provide environmental contributions to urban areas but also to provide benefits from the socially sustainable aspect. Although accessible GR increases the open area on the roof and decreases the wind speed deduction ability of GR, designers can reduce this impact by using trees and shrubs to form physical barriers in upwind direction and by planning routes properly. 5) Meanwhile, the scale of GR can be increased on the top of buildings as other conditions permit. Or consider using GR on buildings connected or close to each other to create a continuous GR corridor. This can further improve the benefits of GR.

It is important to acknowledge that this study has certain limitations and further research on GR's abilities is necessary. This study selected the research site based on the LCZ theory, and the LCZ-2 type can be commonly found worldwide. However, the findings are all based on the background of Washington, D.C., which might limit the universality of the results to a certain extent. Future studies need to be expanded to include more urban settings. Also, microclimate simulation should include more weather conditions (including extreme weather) to examine the study's findings. More plant species and configurations also have to be fully considered to explore GR's benefits further. This study has considered the common GR design factors, but some other potential factors still exist (such as different building materials). More exploration of these variables is necessary. Quantified results in this study are based on simulation. The actual effects of these GR design factors in the real world might be different. Meanwhile, the benefits of GR are not limited to microclimate regulation. Other potential benefits are also worth further exploration.

5. Conclusion

Overall, this study aims to explore and quantify the impacts of GR design factors (plants, soil volume, scale, and accessibility) on microclimate regulation. It uses a GR in Washington, D.C., as a case study. 14 roof scenarios are simulated through ENVI-MET, and GR design factors' impacts are analyzed from aspects of air temperature, relative humidity, wind speed and direction, and CO_2 concentration. This study demonstrated GR's abilities to regulate the microclimate and clearly quantified these abilities' relations with GR design factors. All the quantified results are presented in detail at the end of the result section. This study also demonstrated that when other variables are the same, there is little difference in the microclimate regulation capabilities between accessible GR and inaccessible green GR. In other words, the accessibility slightly decreases GR's overall environmental benefits to a limited degree. Meanwhile, this study provided suggestions and insights to optimize GR design guidelines. This study contributes to the insufficiency in the GR quantification research field and accessible GR research field. This study provides urban planners, policymakers, and designers with valuable quantified data and insights to help them better design and implement GR projects to promote sustainable city development.

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