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The Influence of Plant Community Characteristics in Urban Parks on the Microclimate

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Abstract: The hot and humid feeling of the urban environment enhances residents' discomfort indices. Although the cooling and humidifying effects of plant communities in various urban parks are significant, there is still insufficient evidence for the effects of plant community characteristics on temperature and humidity. In this study, 36 typical plant communities in the Changchun Water Culture and Ecological Park in China were selected in the summer (21–23 August 2020) from 8:00 to 18:00 for three days when it was sunny and windless. We obtained plant community characteristics through field measurements and drone recordings to explore the relationship between plant community characteristics and the mechanism of temperature and humidity. The study observed that (1) the canopy density and three-dimensional green amount were significantly related to the benefits of cooling and humidification. When the canopy density is between 0.7 and 0.8 and the three-dimensional green volume is above 4 m^3/m^2, the greatest benefit is achieved; (2) the discomfort index is between 0.6 and 0.8, and the three-dimensional green volume is 4 m^3/m^2–6 m^3/m^2 minimum; and (3) the changes in temperature and humidity are different for different types of plant communities, which lead to differences in people's perceptions of environmental comfort. The tree–grassland and tree–shrub–grass types had the most apparent improvement effects on comfort. The results show that in the design process of urban park plants, emphasis is placed on plant community configuration with apparent cooling and humidification effects, which can improve the comfort of tourists in hot and humid environments. The research results provide theoretical support for sustainable urban green space development.

Keywords: urban green space; plant community; outdoor thermal comfort; microclimate; canopy density; tridimensional green biomass

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1. Introduction

The deterioration of the urban environment and the unique nature of the underlying city surface have changed the thermal environment, forming the urban heat island (UHI) effect [1,2], reducing the comfort of urban residents, aggravating the negative impact of the urban environment, and causing more significant difficulties to the daily work and lives of the residents [3]. In recent years, solving the urban heat problem has become an urgent issue for worldwide urban development planning. The relevant studies observed that urban green spaces can effectively alleviate the UHI effect, reduce the temperature in urban spaces, and act as urban cold islands [4,5]. In addition, urban green spaces can meet citizens' spiritual, cultural, leisure, and entertainment needs, and provide various ecosystem services, such as the ecological adjustment and maintenance of biodiversity [6,7]. Moreover, it plays a vital role in biodiversity [8,9].

In recent years, the analysis of the improvement of the temperature and humidity in green spaces has begun to be refined from green park spaces to small-scale areas. The current study examines small-scale plant communities and different plant species. The relevant studies show that different plant types have different effects on temperature improvement [10,11]. The research conducted on hawthorn, *Robinia pseudoacacia* L., *Sorbifolia*, and other plants shows that the difference in their temperature-improvement effect was nearly four times greater [12,13]. It was observed that different plant communities, such as grasslands, woodlands, and ornamental shrubs, have different effects on improving temperature values in different environments [14]. Further research shows that the leaf characteristics of different types of plants affect the cool temperature of shaded air space [15].

With the progress of research methods, the research process tends to be quantitative. Canopy density, three-dimensional green yield, leaf area index, and other indicators began to be applied to studies on the environmental temperature and humidity changes [16]. For example, canopy coverage was adopted as an indicator to evaluate forest ecosystem services in an urban environment. A study conducted on tree cover and vertical leaves [17] indicated that trees with larger leaf area indices (LAI) were conducive to better property values. In other words, the more trees present with a larger leaf area index, the higher the attributed value of the property. The biomass and tree–shrub cover have a neutral effect, whereas replacing trees with grass cover results in a low value. In the current study, we determine the leaf area index, crown height, and plants, among which, for example, the height and crown width impact the plants' cooling effects [18].

The cooling effect of plants on the environment can improve the comfort of urban residents, resulting in a sense of belonging and identity [4,19]. There are many indexes used for evaluating aspects of comfort, such as standard effective temperature (SET) [20], effective physiological equivalent temperature [5] (PET), and universal thermal climate index (UTCI) [21]. It has been shown that SET can be used to accurately evaluate the thermal comfort of people in a stable, indoor environment. We investigate the thermal comfort experienced on university campuses and observe that the average temperature is 20.6 °C in the current study. The comfortable temperature range is from 19.5 °C to 21.8 °C [22]. An in-depth study observed that green space had a positive effect on human comfort, not only because the transpiration of plants can reduce the air temperature, but also because plants can block part of the direct radiation of the sun [23–26]. By adding green spaces to the simulation, it was observed that the areas with higher greenery rates had higher comfort levels, and the correlation analysis concludes that if the park is entirely covered by green space, it is in a complete thermal-comfort state [27].

To summarize, there is a strong recognition that urban green spaces can alleviate urban thermal environment problems, and the cooling effect of urban parks is remarkable. It was observed that the scale, distance, and other factors of green space affect the cooling levels of green space. However, in urban forests and green space planning and designing, the connection between the configuration of plant community structures and ecological service functions is still insufficient. It is necessary to thoroughly study the relationship and mechanism of the spatial layout of vegetation, the structure of plants, and temperature and humidity in relation to comfort for human beings. In turn, the ecological function of urban green spaces will be enhanced, and the quality of living in that environment will be improved through the optimal allocation of plant communities.

In the current study, we propose the following research questions:

Research question 1 (RQ1): Are there significant differences in the effects of plant characteristics on the temperature and humidity in urban parks?

Research question 2 (RQ2): If the answer to research question 1 is positive, are there significant differences between plant community characteristics and comfort? What characteristics of plants reduce feelings of discomfort? Which ones improved?

Research question 3 (RQ3): If the answer to research question 2 is positive, does the vegetation's spatial arrangement affect the determined conclusions?

2. Methods

2.1. Study Area

Changchun City Water Culture and Ecological Park, 43°51′ N, 123°21′ E, is located at the intersection of Jingshui Road and Yatai Street in Changchun City, China (Figure 1, location and scope of the study). The park covers an area of 30.2 ha. It is an urban brownfield reconstruction project that won the ASLA 2019 comprehensive design award. The original site was the first water-purification plant in Changchun, built during the period of Puppet Manchuria. Changchun's water supply culture has experienced 80 years of historical evolution, and 300,000 square meters of scarce ecological green space have appeared in the city's hinterland. There are 17 families and 36 genera of woody plants at the site. The environment is pleasant and adjacent to a residential area and is thus highly recognized by the public. A representative mix of artificial and natural plant communities was selected for the study. Moreover, plant communities are widely used in cities and parks. The plant community is rich in layers, and the tree branches are higher than 3M, which is suitable for people to move freely in the forest space.

Figure 1. Location and scope of the study.

2.2. Data Acquisition

In the current study, four routes were selected in the Water Culture Ecological Park in Changchun City, as presented in Figure 2. Each route had 9 sample points out of a total of 36. The sample points were divided into five plant community types: arbor, arbor–grass, arbor–shrub–grass, shrub–grass, and grassland. The plot range for arbor, arbor–grass, and arbor–shrub–grass-type plant communities was set as 20 m × 20 m, while the shrub–grass and grassland types were set as 10 m × 10 m. Two groups of non-vegetation coverage areas were designated as reference groups 100 m outside of the park, as presented in Figure 2 and the reference group location map. To avoid interference, the distance between each sample plot was more than 10 m, and there was no water source within 50 m. The high-density population areas were avoided as much as possible. The measurement date was from 21 to 23 August 2020, from 7:50 to 18:10 every day—there were three consecutive days with clear sky conditions and there was no rainfall or irrigation during the sampling times. The details are presented in Table 1. The instruments used in the acquisition process are presented in Table 2.

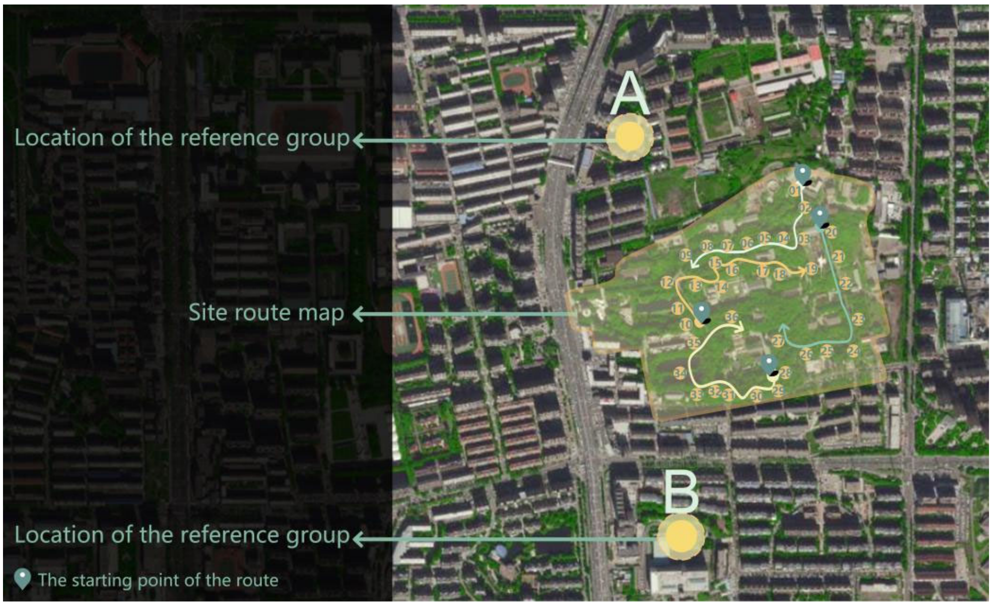


Figure 2. Site route and reference group location, A and B are both reference groups.

Table 1. Weather information for Changchun from 21 to 23 August 2020.

Measurement Date	Temperature Condition	Weather Condition	Wind Direction
21 August 2020	26 °C/14 °C	Sunny	Northeasterly wind, levels 1–2
22 August 2020	27 °C/ 17 °C	Sunny/cloudy	Southwesterly wind, levels 1–2
23 August 2020	27 °C/17 °C	Sunny/cloudy	Southwesterly wind, level 3

Table 2. List of experimental instruments.

Instrument Name	Model and Origin	Experimental Use	Parameter Range
Aerial unmanned aerial vehicle (UAV)	Phantom 4 Pro/China	Takes photos of the sample to obtain the real picture	Maximum altitude: 6000 m Fov84° 20 megapixels Photo resolution: 5472 × 3648/4864 × 3648/5472 × 3078
Temperature and humidity recorder	Tes-1361c/Taiwan	Measures the temperature and humidity of the sample	Measurement range: Humidity: 10%–95% R.H Temperature: −2–20 °C −60 °C/−4 ° F − + 140 ° f Measurement accuracy: Humidity: ±3% R.H − ±5% R.H Temperature: ±0.8 °C, ±1.5° f

2.2.1. Temperature and Humidity

A temperature and humidity recorder was used at a vertical height of 1.5 m above the ground. The flow measurement was conducted for three consecutive days from 7:50 to 18:10 and at every other hour for each sample plot. It took approximately 20 min for each line to complete the measurement. Five groups of values at four corners and middle points were obtained for each sample point, and the average value was the temperature and humidity value of the sample.

2.2.2. Canopy Density

Canopy density refers to the ratio of the total projected area (crown width) of the arbor (shrub) crown under direct sunlight to the entire scope of the forestland (stand) [28]. The unmanned aerial vehicle (UAV) collected vertical projection pictures of the sample points. The sample areas of the arbor, arbor–grass, and arbor–shrub–grass-type plant communities were 20 m × 20 m, and the flight height was 40 m. The shrub–grass and grassland types were 10 m × 10 m and the flight height was 20 m.

2.2.3. Tridimensional Green Biomass

Green biomass refers to the three-dimensional area of green plants in a certain area, and tridimensional green biomass density refers to the proportion of plant stems and leaves in a unit space. Infrared rangefinders were used to measure the plot's tree- and shrub-height characteristics. The characteristics, such as diameter at breast height, base diameter, crown width of trees, shrub diameter, height, and other characteristics of shrubs and herbs, were measured individually. The four corners and the focal point of the diagonal line were set at 2 m × 2 m in the five positions of the grassland community.

2.3. Data Processing

The calculation method of the discomfort index (DI) with the highest adaptability in the outdoor environment was adopted for the thermal comfort degree [29], and the calculation formula was as follows:

$$DI = Tair - 0.55(1 - 0.01RH)(Tair - 14.5) \quad (1)$$

where DI is the discomfort index, TAIR is the air temperature (°C), and RH is the relative humidity (%). According to this procedure, the comfort level distribution for each square point can be obtained, and the comfort level can be classified according to the interval division of the discomfort index according to the criteria presented in Table 3 [30,31]. The greater the discomfort, the lower the comfort level of the human body.

Table 3. Division of discomfort index and human comfort.

Grade	Temperature Humidity Effect on Discomfort Index (DI)	Sensory Level
1	<21.0	No discomfort.
2	21.0–23.9	A small number of people felt uncomfortable. Discomfort expressed by <50% of the population.
3	24.0–26.9	Most people did not feel comfortable. Discomfort expressed by >50% of the population.
4	27.0–28.9	Most people did not feel comfortable. Discomfort expressed by the majority of the population.
5	29.0–31.9	Almost everyone felt uncomfortable. Discomfort expressed by all.
6	>32.0	Risk of heatstroke. Stages of medical alarm.

The cooling and humidifying effects of the plant community are expressed by the average temperature percentage (T_p) and average humidity percentage (H_p), respectively. The calculation formula is as follows:

$$T_p = \frac{\sum_{i=1}^{n} \frac{T_{ci} - T_i}{T_{ci}} \times 100\%}{n} \quad (2)$$

$$H_p = \frac{\sum_{i=1}^{n} \frac{H_i - H_{ci}}{H_i} \times 100\%}{n} \quad (3)$$

where T_{ci} is the temperature value of the control plot at the i-th time in °C; T_i is the temperature value of the community plot at the i-th time in °C; H_{ci} is the relative humidity value of the control plot at the i-th time (%); H_i is the community plot; and n is the recording-time period.

3. Results

3.1. Influence of Canopy Density on Temperature and Humidity Effect

3.1.1. Relationship between Canopy Density and Cooling Effect

To explore the relationship between a plant community's canopy density and temperature, the quadratic curve fitting of the two variables is presented in Figure 3. The results show that with the increase in canopy density, the cooling capacity of the plant community increases within one day, with a correlation coefficient of 0.868, significant at $p < 0.01$. When the canopy density is greater than 0.91, the fitting curve tends to be stable, and the cooling level of the plant community reaches the maximum level.

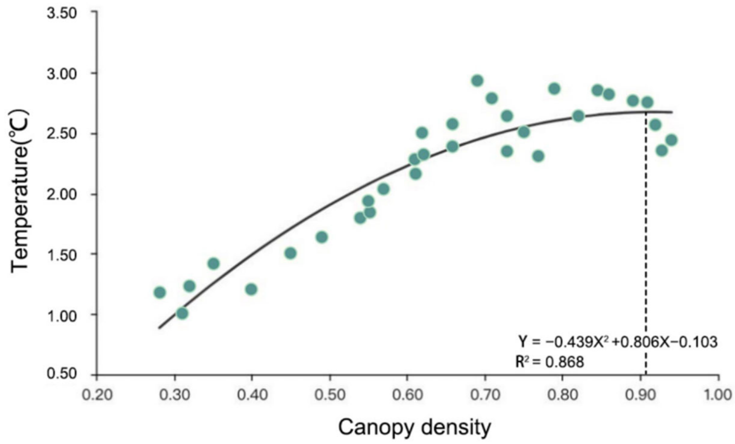


Figure 3. Relationship between temperature and canopy density.

3.1.2. Relationship between Canopy Density and Humidification Effect

By fitting a quadratic curve between the plant community's canopy density and humidity, their relationship is presented in Figure 4. As the plant community's canopy density increases, so does the humidification benefit it creates. The correlation coefficient was 0.413, with a significant $p < 0.01$. In comparison to the abilities of plant canopy density and the humidification effect, the canopy density produces a better cooling effect.

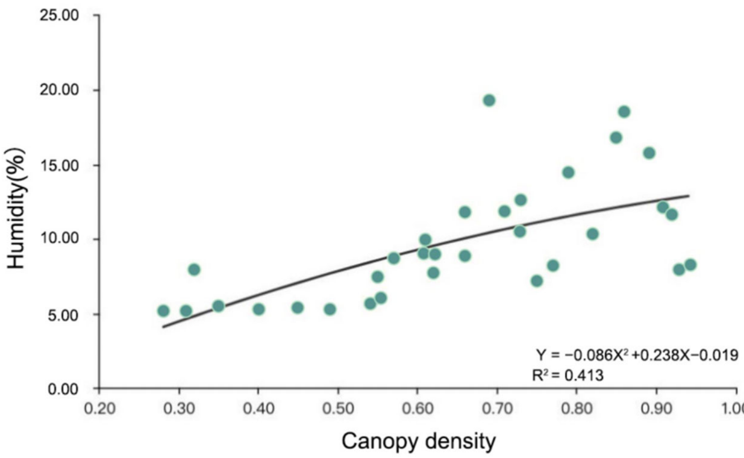


Figure 4. Relationship between humidification and canopy density.

3.2. Influence of Tridimensional Green Biomass on Temperature and Humidity Effect

3.2.1. Relationship between Tridimensional Green Biomass and Cooling Effect

To answer research question 1 (RQ1), the tridimensional green biomass was fitted with a delicate logarithmic temperature change curve, as presented in Figure 5. The correlation coefficient was 0.761, with a significant $p < 0.01$. Especially when the three-dimensional green biomass was more remarkable than 4 m^3/m^2, for every increase of 1 m^3/m^2 for the three-dimensional green biomass, the significant cooling benefit was less than the increase in the three-dimensional green biomass less than 4 m^3/m^2.

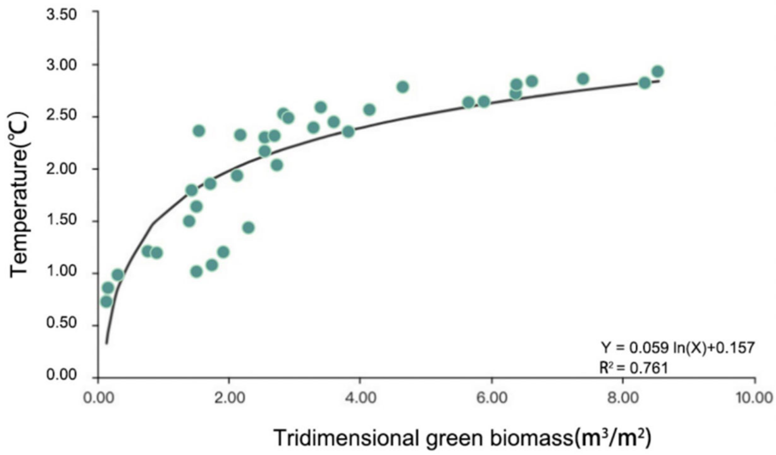


Figure 5. Relationship between temperature and tridimensional green biomass.

3.2.2. Relationship between Tridimensional Green Biomass and Humidification Effect

A quadratic curve fitted the tridimensional green biomass and humidity change. The results are presented in Figure 6. The correlation coefficient between the tridimensional green biomass and humidity was 0.840, with a significant $p < 0.01$. The humidification benefit of the plant community increased with the increase in the tridimensional green biomass density. The effect was better when the density of the tridimensional green biomass was greater than 2 m^3/m^2.

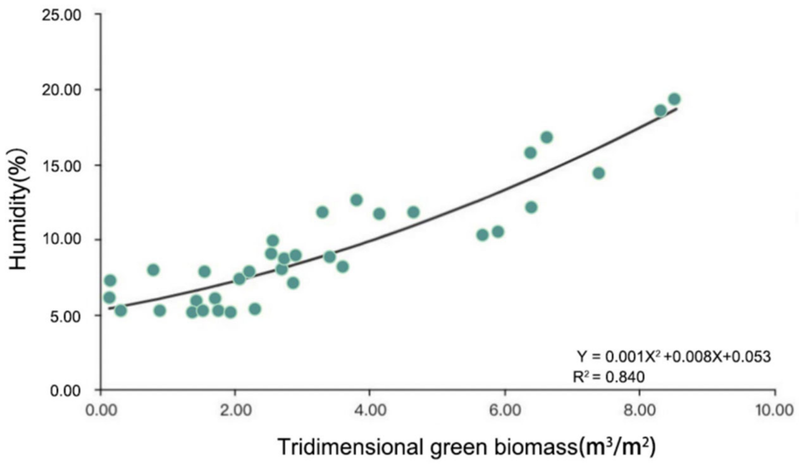


Figure 6. Relationship between humidification and tridimensional green biomass.

3.3. The Relationship between Discomfort and Plant Community Characteristics

3.3.1. The Relationship between Discomfort and Canopy Density

As presented in Figure 7, the plants' discomfort indices and canopy densities are used as scatter points, and they are fitted by a quadratic curve. The effect of the plant community's canopy closure on the discomfort index was analyzed. The results show that as the canopy density of the plant community increased, the discomfort index decreased. When the canopy density reached 0.7, the discomfort index was at its lowest level. The canopy density of the plant community was between 0.6 and 0.8, and the range of the discomfort index was relatively suitable, which could effectively create a comfortable environment.

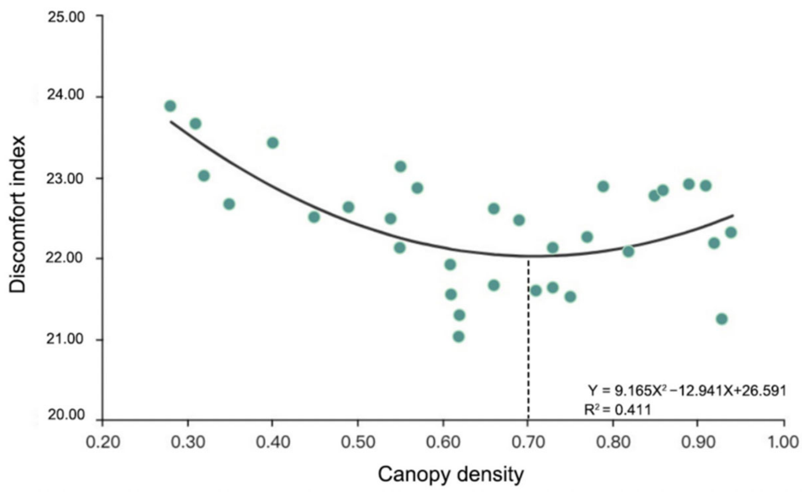


Figure 7. Relationship between discomfort index and canopy density.

3.3.2. The Relationship between Discomfort and Tridimensional Green Biomass

Using a scatter plot, a quadratic curve fitting was performed between the discomfort index and tridimensional green biomass to explore their relationship. As shown in Figure 8, the discomfort index first decreased and then increased with the increase in plant tridimensional green biomass. The discomfort index was relatively low when the density of the tridimensional green biomass was 4–6 m^3/m^2, which provides an answer for research question 2 (RQ2).

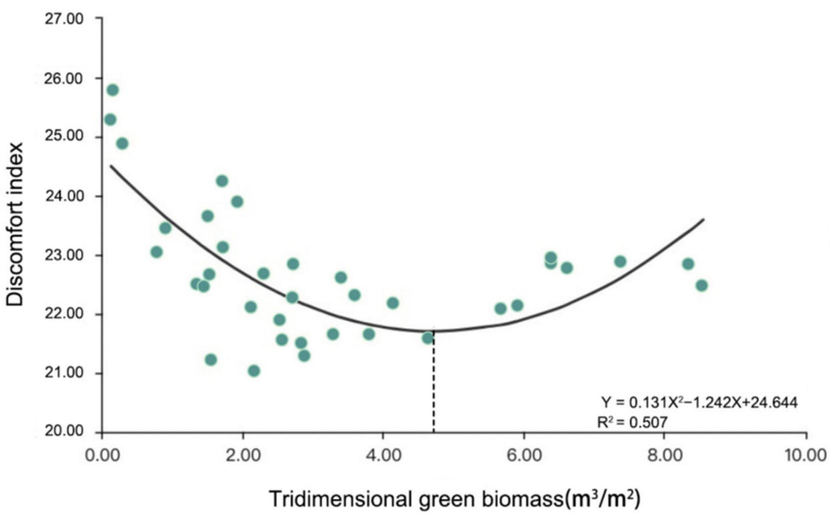


Figure 8. Relationship between discomfort index and tridimensional green biomass.

3.4. The Relationship between Discomfort and Plant Community Structure

3.4.1. Vertical Structure

In order to answer research question 3 (RQ3), the analysis of variance (one-way ANOVA) was used to study the differences in community types for discomfort factors. Community type was significant at a 0.01 level for comfort (F = 26.323, p = 0.000), as presented in Table 4. The compared results of the groups' average scores with noticeable differences were grassland type > shrub–grass type > arbor type > arbor–grassland type > arbor–shrub–grass type.

Table 4. Discomfort and the results for the variance analysis of plant community structures.

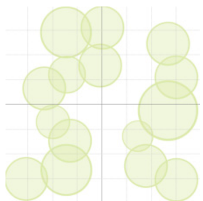
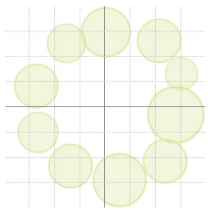
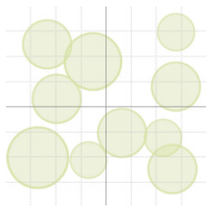
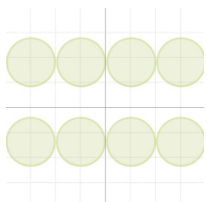
	Community Type (Mean ± SD)					F	p
	Arbor Type (n = 6)	Arbor–Shrub–Grass Type (n = 20)	Arbor–Grassland Type (n = 3)	Shrub–Grass Type (n = 3)	Grassland Type (n = 4)		
Discomfort index	22.89 ± 0.35	22.07 ± 0.61	22.28 ± 0.31	23.52 ± 0.45	25.04 ± 0.65	26.323	0.000 **

** $p < 0.01$.

3.4.2. Plane Layout

We explored the relationship between the layout of the plants and the discomfort index. According to the plant community's quadratic structure, the plant plane layout was divided into five forms. The data comparison and analysis of the discomfort index were conducted, as presented in Table 5. We integrated the plant floor plans according to the typical quadrats. The order of discomfort index in the plane layout was grass type > adaptive type > determinant type > encircling type > encircling type, which contributes further to answering research question 3.

Table 5. Plant community's plane characteristics.

Item	Schematic Diagram of Plane Layout	Real-Life Example	Average Discomfort Index
Adaptive type			22.49
Encircling type			21.93
Grass type			24.70
Encircling type			21.91
Determinant type			22.47

4. Discussion

4.1. Temperature and Humidity Effects under the Influence of Plant Characteristics

Compared to the urban environment, urban vegetation has been proven to play an essential role in mitigating the heat island effect. The intense transpiration of green plants can play a specific role in cooling and humidifying effects. Additionally, the leaves of plants can partially block and absorb solar radiation, so the internal environment of urban parks has trends of low temperature and high humidity [32,33]. In summer, they feel more comfortable and present distinct differences during different periods.

During the day, the temperature change and plant canopy density presented a positive, upward trend. They reached a critical point when the canopy density was 0.80. The cooling capacity reached a maximum value of 2.61 °C, similar to the previous results [5]. In addition, the high plant canopy density had no significant effect on the cooling and humidification of the local microclimate, which could lead to the formation of excessively high numbers of green closures that would result in the spread of the local, brutal, and hot climate. On the other hand, when the tridimensional green biomass of the plants was approximately 4 m^3/m^2, the humidification effect was the best. The green biomass density of the plants was closely related to the shaded areas they produced, which absorbed and blocked solar heat radiation [34]. However, the effect of excessive green biomass on the microclimate was not apparent.

4.2. Discomfort under the Influence of the Plant Community

The current study obtained the discomfort index under the influence of different plant communities, grassland type > shrub–grass type > arbor type > arbor–grassland type > arbor–shrub–grass type, which is roughly the same as the results obtained by previous studies [28,29,35]. During the summertime, the canopy density of small-scale plants is an essential indicator for reducing temperature intensity. Since the influence of lawns on the microclimate is weak, plants can be added to areas with low thermal comfort levels [30].

It is worth noting that dense vegetation communities surrounded subsidence depression, and the wind speed was low. It is easy to create a microclimate with low temperatures and high humidity levels [4]. On the other hand, the factors affecting the local microclimate may have been related to the surrounding large-scale fields [36]. The relevant studies show that hard paving materials are affected by thermal conductivity, specific heat capacity, and surface reflectivity, and have a certain warming effect on the surrounding environment [37]. Although the quadratic point is a certain distance away, it is still affected by its thermal radiation.

4.3. Impact on the Design of the Park's Climate and Environment

The sustainability of urban green spaces has been proven time and time again. Increasing urban green spaces will improve the quality of urban life [38] and, by improving the microclimate and reducing urban pollution levels [39], create a space that is beneficial to the health of human beings, allowing them to perform exercises for fitness purposes, thereby reducing the risk of some chronic diseases.

In previous studies, increasingly more people began to pay attention to the critical role of green park spaces in cooling and humidifying the environment. According to our research experiments and analysis of the results, we concluded that different types of plant communities have apparent differences in the regulation of temperature and humidity levels. We observed that multi-layered plant communities were most effective in terms of their cooling and humidification effects. This plant community is diverse in structure and rich in species [40]. The point-like tree layout had a more pronounced cooling effect, which may be attributed to the synergistic effect of the trees and the underground cover, so we encourage the mixing of trees and grasses and the expansion of the urban forest belt [41]. This can be used as part of the basis for the design of parks and green space plants. In the spatial layout of vegetation, a higher level of vegetation canopy density is also essential for regulating temperature and humidity levels. It seems that the perceived comfort levels in different areas should also be an essential part of the design of a park environment.

4.4. Limitations and Future Research

This study highlighted the importance of plant community types and spatial layouts in parks for assessing the benefits and discomfort levels created by temperature and humidity effects. However, it is still necessary to study the relevant influencing factors, such as wind and building environments, in the broader range of the physical environment of a park's green space to strengthen the accuracy of the results produced by this study. A park's green space is an open-space environment, not a relatively stable environment inside a laboratory, which is restricted and affected by multiple factors. In addition, in order to describe the discomfort factors, the most apparent temperature and humidity levels sensed by the human body were selected. Therefore, the influence of the external, physical environment was considered in the green space, and the environment simulation was conducted in an indoor laboratory to couple and superimpose more accurate quantitative research as the goal of future studies.

5. Conclusions

This study investigated five different plant community structure types and the relationship between temperature and humidity benefits in urban parks. Aiming to address the internal temperature and humidity changes in urban parks can ensure an improved perception of the environment by people in green park spaces. The study further revealed the importance of urban green spaces for ecosystem services. The degree of effect of urban green spaces on environmental cooling and humidification was determined. The average cooling effect in the green space was significantly related to plant canopy closure and three-dimensional green volume. In order to create a more ecologically beneficial urban park and green space, more attention should be paid to the planting designs in the parks.

Secondly, environmental temperature and humidity changes affected peoples' perceptions of environmental comfort in different ways. Through the cooling and humidification effects of different plant communities and their impact on human comfort, it was observed that the arbor and grassland types, as well as the types of trees, shrubs, and grasses, impacted individuals' comfort levels. The effect of improvement was the most apparent outcome. The construction of the same type of urban park in the same area could increase the allocation ratio of these two types of plant communities. The cooling and humidifying capacity of the park could be enhanced to reduce the discomfort of tourists during outdoor leisure activities. Therefore, scientifically planned urban green spaces can provide multifunctional habitats for ecosystem services and increase human wellbeing in a more effective manner.

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