



Article Impacts of Composition and Canopy Characteristics of Plant Communities on Microclimate and Airborne Particles in Beijing, China

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Abstract: As the basic component of urban green-spaces, plant communities regulate both the microclimate and air particle levels. Understanding the regulatory mechanism of plant communities represents the theoretical basis for using green spaces to improve the urban climate and mitigate air particle pollution. Based on field investigations, differences in the daily air temperatures (AT), relative humidity (RH), and PM10 and PM25 concentrations in eight compositional types of plant communities were quantitatively analyzed. In addition, the correlations between these variables and various canopy parameters were further established in order to detect critical thresholds. The results showed that, among the eight compositional types, significant differences existed in daily AT, RH, PM₁₀ and PM_{2.5} levels. The mixed tree, shrub and grass (M-TSG) community had the strongest cooling and PM₁₀ reduction effects; the broad-leafed tree, shrub and grass (B-TSG) community had the best humidifying effect; while the mixed tree and grass (M-TG) community most effectively reduced PM_{2.5} concentrations. The daily AT and PM₁₀ concentrations were significantly negatively correlated with canopy density (CD) and leaf area index (LAI), but positively correlated with canopy porosity (CP) and sky view factor (SVF), while these correlations were opposite for daily RH. The response of daily PM2.5 concentrations to canopy characteristics was complex, featuring multiple nonlinear relations. Critical thresholds were found in some cases. Overall, M-TSG or M-TG communities with about 75% CD, 55% CP, 2.5 LAI and 0.18 SVF perform most noticeable both microclimate and air particle regulation services.

Keywords: urban green-space; community composition; canopy structure; microclimate; airborne particles

1. Introduction

Due to rapid urbanization and industrialization, increased human activity has discharged large amounts of anthropogenic heat and pollutants into the atmosphere, which has triggered a series of urban environmental crises [1]. A large number of studies have reported that land surface temperatures, air temperatures (AT) and air pollutant levels within cities are significantly higher than those in surrounding rural areas [2,3]. The urban heat island (UHI) effect and air pollution have become prominent restrictions to the development of multiple cities in recent years. Taking Beijing as an example, the AT of Beijing has increased significantly at a rate of 0.45 °C per decade from 1960 to 2018. This has resulted in warmer winters and summer heat anomalies. In 2019, it was recorded that the air quality of Beijing was below the national standard for as much as 125 days, accounting for 34% of the whole year. Airborne particles remain the main form of air pollutant in Beijing [4]. Continuous high temperatures in urban areas reduce their atmospheric pressure



Citation: Fan, S.; Zhang, M.; Li, Y.; Li, K.; Dong, L. Impacts of Composition and Canopy Characteristics of Plant Communities on Microclimate and Airborne Particles in Beijing, China. *Sustainability* **2021**, *13*, 4791. https://doi.org/10.3390/su13094791

Academic Editor: Carmelo M. Musarella

Received: 17 March 2021 Accepted: 14 April 2021 Published: 24 April 2021

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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). to levels lower than the surrounding rural areas. This is not conducive to the diffusion or dispersion of pollutants, creating a reflux back into the urban area [5–7]. High temperatures can also catalyze the secondary reactions of some pollutants, further aggravating the deterioration of urban air quality. The long-term suspension of air particles can form a cover over the city, which not only hinders the outward radiation of urban heat [8], but also absorbs and scatters solar radiation, thus, indirectly contributing to a deteriorating local thermal environment. Therefore, it is crucial to explore the long-term feasibility, economic and effective control strategies for reducing both the UHI phenomenon and air particle pollution from the perspective of sustainable development.

Previously UHI research has mainly focused on the origin, strength, spatial and temporal distribution, simulation and prediction of UHI [9–11], while pollution studies have focused on the component characteristics, source apportionment, attenuation mechanisms and hazard assessment of airborne particles [12–14]. These studies have covered various topics ranging from large-scale analyses based on remote sensing retrieval, to local and micro-scale projects based on field observations and numerical simulations [15–18]. In recent years, the effects of landscape elements on UHI and airborne particle pollution have begun to attract increasing attention. As the most important natural component of the urban ecosystem, green-space is the main provider of urban ecosystem services (ES). Among the many ESs, thermal and particulate matter (PM) regulation services are considered as the key services provided by green-space vegetation. Such services are of great significance in coping with global climate change, alleviating urban heat island effects and improving urban air quality [19–22]. These regulatory services generated from plants can influence the level and distribution of water, heat and PM in the air via transpiration, isolation and blocking, as well as absorption and detention effects [23–25]. However, plants in urban green spaces rarely exist as individuals, but rather as plant communities, which generally refers to vegetation assemblages or patches constructed via plant selection, configuration, planting and management in urban green-spaces. The dense canopy of plant communities, comprising branches and leaves, can absorb and reflect a large amount of solar radiation and exerts a shading effect. Meanwhile, plants' evapotranspiration processes bring water into the air, which transforms and consumes ambient heat, thus, adjusting both the AT and relative humidity (RH) under the tree canopy and its surrounding environment [26–28]. In addition, complex community canopies can change the velocity and direction of airflow, create local circulation and promote the deposition of air particles. Moreover, this is coupled with the detention and absorption of different-sized particles by the canopy branches and leaves, leading to the regulation of airborne particle levels [29,30]. Therefore, the basic component of urban green spaces is plant communities. Additionally, when appropriately implemented, plant communities, as a basic functional unit, can produce a regulating effect on both UHI and air pollution.

Plant communities feature multiple composition types. Most scholars believe that different community types have variable effects on cooling, humidifying and are associated with different-sized particle concentrations. The regulatory effects of multi-layer communities dominated by trees are significantly better than those of other types [31,32]. Recently, canopy characteristic effects, such as canopy density (CD), leaf area index (LAI), plant height and ventilation coefficients, on the levels of AT, RH and PM concentrations under the canopy have been reported [30,33]. To influence ambient microclimate, CD and LAI are considered the most important factors affecting AT [34,35]. To influence airborne particle levels, most studies advocate that plant communities with high planting density, CD and LAI have greater total dust retention capacities, making them more effective at reducing PM [36,37]. However, in some cases, dense vegetation has been found to inhibit air exchange near the ground, which is not conducive to the diffusion and attenuation of PM [38]. Recently, further development of quantitative methods has led some researchers to focus on whether there is a critical threshold for the effects of plant community canopy on microclimate and air particle levels [21,39]. However, there are insufficient results to

define key thresholds to guide the construction of plant communities in urban areas to regulate these attributes.

Moreover, many studies have shown that there is a complex interaction between AT, RH and air particles, especially in the case of fine particles [40,41]. Studies have reported fine particles are particularly sensitive to microclimate factors. Some specific AT and RH conditions may not be conducive to the regulation of air particle levels [42]. As previous studies on the regulatory effects of green spaces mostly focused on the mitigation of either UHI or air pollution, they lack comprehensive consideration of both environmental issues [37,38,43,44], which may easily lead to neglecting one or the other in application. Therefore, finding a strategy to balance both issues is highly relevant to the construction of plant communities to improve urban thermal and dust environments.

To quantitatively investigate the regulating mechanisms and influential factors of plant communities on microclimate and air particle levels in highly heterogeneous urban environments, and provide theoretical guidance for future urban green-space design and management optimization, in this paper we focused on characterizing: (1) variations of microclimate and air particle levels in various plant community types; and (2) determining critical thresholds of plant community canopy characteristics on microclimate and airborne particle levels.

2. Materials and Methods

2.1. Study Area and Measurement Sites

Beijing (39°56′ N, 116°20′ E), situated in the northern part of the North China Plain, has a monsoon-influenced humid continental climate, with hot and humid summers and generally cold and dry winters. Based on meteorological data for 2019, the annual average temperature of Beijing was 12.5 °C and the average annual precipitation was 511.1 mm, which mostly occurred in summer. The predominant wind direction in summer was southeast to northeast, while the reverse direction dominated in winter [45]. In 2019, the average concentrations of PM_{2.5} and PM₁₀ were 42 μ g/m³ and 60 μ g/m³ in Beijing [4].

Urban residential areas, featuring highly heterogeneous internal environments and complex underlying surface patterns, which could be considered as "miniatures" of urban environments, are highly suitable for local and micro-scale studies. In this study, Wangjinghuayuan (WJHY; 40°0′ N, 116°28′ E), Xiuyuan (XY; 39°59′ N, 116°24′ E), Shuiduizi (SDZ; 39°55′ N, 116°28′ E) and Hepingjiayuan (HPJY; 39°57′ N, 116°25′ E) residential areas were selected for field monitoring (Figure 1). These four residential areas are evenly distributed in the northwest Chaoyang District of Beijing, with an average separation distance of 6.58 km and no large green spaces around them. Their surrounding streets enclose them as internally isolated spaces with typically flat interior terrain. The vegetation coverage in all residential areas is around 40%–60%. Descriptions of these four residential areas are given in Table 1.

Table 1. Information about the four sampled residential areas.

Residential Area	Build Time	Total Area (m ²)	Vegetation Area (m ²)	Vegetation Coverage (%)	
WJHY	2002	239,167.20	113,197.80	47.33	
XY	2003	135,437.57	58,915.34	43.50	
SDZ	1993	129,022.85	64,214.67	49.77	
HPJY	1985	499,524.66	292,521.60	58.56	



Figure 1. Locations of 4 sampled residential areas and 33 plant community sites (picture source: Google Maps, September 2016).

Experiments aiming at examining the influence of community composition (Experiment A) were carried out in the green spaces of WJHY, XY and SDZ residential areas. Based on pre-investigation, eight plant community types were defined, which are: mixed coniferous and broad-leaved trees, shrubs and grasses (M-TSG); broad-leaved trees, shrubs and grasses (B-TSG); mixed coniferous and broad-leaved trees, shrubs and grasses (C-TSG); mixed coniferous and broad-leaved trees and grasses (M-TG); broad-leaved trees and grasses (B-TG); coniferous trees and grasses (C-TSG); mixed coniferous and broad-leaved trees and grasses (M-TG); broad-leaved trees and grasses (B-TG); coniferous trees and grasses (C-TG); broad-leaved shrubs and grasses (B-SG); and coniferous shrubs and grasses (C-SG). We selected 24 plant community plots with a size of 10 m \times 10 m. Additionally, all these community types are common in Beijing urban green spaces.

Experiments aiming at examining the influence of canopy characteristics (Experiment B) were carried out in the green space of HPJY. We selected nine mixed plant communities with different canopy structures with a size of 15 m \times 15 m. Each plot features moderate and similar proportions of trees, shrubs and grasses. We ensured that the distance between the center of each selected community and the surrounding buildings was more than 10 m to avoid any interference with the measurement results.

Basic information about the above 24 and 9 plots is detailed in Tables 2 and 3, respectively. The locations of the residential areas and 33 plant community plots are shown in Figure 1.

No.	Composition Types	Average Height (m)	Average Crown Diameter (m)	Average DBH/GD (cm)	
A1	M-TSG	6.21	4.30	11.25	
A2	B-TSG	5.40	3.95	16.00	
A3	C-TSG	8.84	3.26	10.18	
A4	M-TG	9.29	4.46	14.53	
A5	B-TG	2.93	2.22	15.35	
A6	C-TG	4.79	3.91	8.73	
A7	B-SG	1.63	2.48	13.44	
A8	C-SG	0.73	1.47	5.02	
B1	M-TSG	4.06	3.92	18.70	
B2	B-TSG	3.86	5.77	8.78	
B3	C-TSG	7.19	3.45	8.75	
B4	M-TG	5.32	3.03	17.69	
B5	B-TG	7.39	3.30	8.13	
B6	C-TG	5.43	2.84	12.11	
B7	B-SG	1.58	1.15	16.81	
B8	C-SG	0.58	2.08	5.25	
C1	M-TSG	5.32	3.19	12.87	
C2	B-TSG	7.91	4.54	14.36	
C3	C-TSG	6.27	2.63	19.67	
C4	M-TG	8.33	4.22	20.04	
C5	B-TG	4.45	3.53	15.93	
C6	C-TG	5.32	3.08	14.04	
C7	B-SG	1.93	2.46	7.60	
C8	C-SG	0.61	1.35	4.37	

Table 2. Details of the sampling community for community composition experiment.

Note: Ax, Bx and Cx used to distinguish the plant communities from WJHY, XY, SDZ, respectively. Average height, crown diameter and DBH/GD only for trees and shrubs.

No.	Composition Types	Average Height (m)	Average Crown Diameter (m)	Average DBH/GD(cm)
D1	M-TSG	9.10	4.50	19.50
D2	B-TSG	5.63	4.53	11.47
D3	B-TSG	4.67	4.01	9.13
D4	M-TSG	11.15	6.34	18.53
D5	M-TSG	8.92	6.48	19.49
D6	M-TSG	6.40	4.77	14.39
D7	B-TSG	11.74	4.70	29.89
D8	M-TSG	8.57	5.69	28.74
D9	M-TSG	6.97	3.21	15.55

Table 3. Details of the sampling community for community canopy experiment.

Note: Dx refers to the plant communities from HPJY. Average height, crown diameter and DBH/GD only for trees and shrubs.

2.2. Microclimate and Airborne Particle Level Measurements

In this study, all monitoring was conducted on clear (pollution levels of mild or good) and windless (wind velocity < 2 m/s) days in summer (July–August 2016) with similar basic weather conditions (AT, RH and air quality) to avoid the influence of significantly different meteorological factors, e.g., cloudiness, precipitation, wind and heavy pollution. Experiment A was carried out in August 2015 and experiment B was carried out in July 2015. To reduce the potential interference of the variation in measurement time on the results of mobile monitoring, a two-way route mobile monitoring method was employed. Movements between measurement points were in one order on the first day and reversed on the second. The two consecutive days of data monitoring, which is comprised of three

replications, were conducted. Data were collected every 2 h from 8:00 to 18:00 h in each day, with a total of six standard time periods.

AT and RH were measured by using TES-1341 thermistor temperature tester (nominal accuracy of 0.1 °C; TES, Taiwan, China), which was housed in radiation shields to avoid direct sunlight. PM_{10} and $PM_{2.5}$ concentrations were synchronously measured using handheld DUSTMATE particle collectors (Turnkey Instruments Ltd., Northwich, UK). All instruments were placed at the center of each plot, sampling at 1.2 m-height aboveground. Six sets of repeated measurements were made at each site, with a recording interval of 1 min. One line transect observation took about 60 min for each residential area. The monitoring time was also simultaneously recorded at each measuring plot.

Considering that AT, RH and PM concentrations may be sensitive to local climate changes during measurement time, an independent set of instruments was installed on a paved area within the study site to record local climate change from 8:00 to 18:00. Based on mathematical correction methods used in some thermal environment research [46], these data were used as a reference to correct mobile measurements to each standard time.

2.3. Classification of Plant Community Types and Measurements of Canopy Characteristics

In this study, plant compositions of selected plots were recorded during preinvestigation and classified into eight community types as described above. To measure canopy characteristics, CD, canopy porosity (CP), LAI and sky view factor (SVF) were selected to define the community canopy in horizontal, vertical and overall leaf volume dimensions, respectively. Within each community, five measuring points were set at the positions shown in Figure 2. All canopy measurements were conducted on a cloudy day (without strong direct solar radiation) at a 1.5 m-height above each measuring point. The mean of these five measuring points was used to represent the CD, CP, LAI and SVF values of each community.



Figure 2. Schematic diagram of measuring point of CD, LAI and SVF in sample community.

(1) CD measurements: Photos were taken vertically at all measurement points within the plant community using a full-frame single-lens reflex (SLR) camera. Then, these photos were processed by Adobe Photoshop software (PS; Abode Inc., San Jose, CA, USA) and the CD was represented as the mean pixel ratio of the horizontal section of the canopy.

(2) CP measurements: Photos were taken horizontally toward the center of the canopy at all measurement points within the plant community using a full-frame SLR camera. After PS pretreatment, the CP was determined as the mean Photoshop pixel ratio of the vertical section of the canopy.

(3) LAI measurements: LAI values for each plant community were directly obtained using the LAI-2200 Plant Canopy Analyzer (LI-COR Biosciences, Lincoln, NE, USA). To avoid interference from surrounding obstructions, the lens cover with $30-60^{\circ}$ angle was used (depends on the surrounding environment).

(4) SVF measurements: Photos were taken vertically at all measurement points within the plant community by a full-frame SLR camera with a fisheye lens. After PS pretreatment,



example is shown in Figure 3.

photos were imported into RayMan software [47] to further determine SVF values. An

Figure 3. Example of SVF of one sample community in summer.

2.4. Data Analysis

In this study, for each monitoring point, the mean value of round-trip mobile data at the same time represented its observational value at this time. The averages of the six rounds of data monitoring were used to represent daily averages of AT, RH, PM_{10} and $PM_{2.5}$.

One-way ANOVA and multiple comparison (Duncan's method) were carried out to examine the significant differences in microclimates and PM levels among plant communities with different compositions. Groups with identical letters are not significantly different at $\alpha = 0.05$. Pearson correlation was used to examine relationships among canopy parameters, AT, RH and PM concentrations. Relationships among these variables were visualized based on non-linear curve fitting. All statistical analyses were performed using SPSS 22.0 software (IBM Corp., Armonk, NY, USA). A *p*-value < 0.05 was regarded as being statistically significant. Non-linear fitting was performed using Origin 2017 software (OriginLab Corp., Northhampton, MA, USA).

3. Results

3.1. Microclimate and Airborne Particle Levels of Different Community Types

3.1.1. Air Temperature and Relative Humidity

The daily average AT (dAT) of the eight plant community types in summer are shown in Figure 4a with the superscript representing the result of multiple comparisons. The M-TSG community had the lowest dAT (33.58 ± 2.04) °C, followed by B-TSG (33.95 ± 1.91) °C and B-TG (34.49 ± 1.01) °C. C-SG reached the highest dAT of (38.39 ± 1.10) °C, which is dramatically higher than the minimum value of 4.81 °C. ANOVA and Duncan analysis revealed significant differences among the eight plant community types, having a *p*-value of 0.008. As shown in Figure 4b, the maximum dRH was recorded in the B-TSG community ($57.41\% \pm 4.07\%$), followed by M-TSG ($56.52\% \pm 4.76\%$) and B-TG ($53.98\% \pm 3.94\%$) community. The minimum dRH was recorded in the C-SG community ($45.59\% \pm 4.12\%$). The difference between extreme values was 11.81%. There were significant differences among community types (p = 0.012).



Figure 4. Daily average levels of (a) AT, (b) RH, (c) PM₁₀ and (d) PM_{2.5} of different community types.

3.1.2. Particulate Matter Concentrations

PM concentrations shown in Figure 4c reveal that the M-TSG community had the lowest daily average PM₁₀ concentration (dPM₁₀), with a value of merely (37.31 ± 5.98) µg/m³, followed by the (39.67 ± 6.16) µg/m³ B-TSG. The (57.33 ± 6.11) µg/m³ C-SG community featured the highest concentration. The daily average dPM₁₀ of these eight plant community types ranked as follows: M-TSG < B-TSG < C-TSG < M-TG < C-TG < B-TG < B-SG < C-SG, with a range of 20.02 µg/m³ and significant differences among different plant community types (p = 0.035). As for daily average PM_{2.5} levels (dPM_{2.5}) shown in Figure 4d, the difference among all eight plant community types was also significant (p = 0.042). M-TSG had the lowest concentration, with dPM_{2.5} of (15.52 ± 1.55) µg/m³, followed by (15.84 ± 1.69) µg/m³ B-TSG. (18.57 ± 1.36) µg/m³ B-SG and (18.95 ± 1.22) µg/m³ C-SG featured significantly higher concentrations than others, while the difference in extreme values was 3.43 µg/m³.

3.2. Response of Microclimate and Airborne Particle Levels to Plant Community Canopy Characteristics

The canopy characteristics and the daily average AT, RH, PM_{10} and $PM_{2.5}$ values of the nine plant communities in experiment B are, respectively, shown in Tables 4 and 5. To examine the effects of canopy characteristics on microclimate and airborne particle levels, we analyzed the relationships of AT, RH, PM_{10} and $PM_{2.5}$ levels with canopy parameters by calculating Pearson's correlation coefficients (cc) as shown in Table 6.

No.	CD (%)	CP (%)	LAI	SVF (%)
D1	44.879	70.864	1.322	0.476
D2	57.311	57.192	1.506	0.324
D3	67.264	63.336	1.714	0.412
D4	71.369	57.968	2.356	0.238
D5	75.840	54.686	2.268	0.249
D6	77.589	51.036	2.540	0.185
D7	82.392	53.866	2.932	0.147
D8	89.585	43.706	3.294	0.112
D9	92.280	42.213	2.968	0.095

Table 4. Canopy parameters of the sampling community.

No.	dAT (°C)	dRH (%)	dPM ₁₀ (ug/m ³)	dPM _{2.5} (ug/m ³)
D1	31.218	49.666	109.923	44.565
D2	30.977	51.415	107.745	41.593
D3	31.091	50.228	104.441	42.715
D4	30.829	52.922	103.083	39.040
D5	30.286	54.053	105.297	37.943
D6	29.724	53.746	94.929	35.732
D7	30.391	52.569	100.944	38.764
D8	29.540	55.932	98.622	40.678
D9	29.471	54.479	101.549	40.198

Table 5. Daily average level of AT, RH, PM₁₀ and PM_{2.5} within the sampling community.

Table 6. Correlation coefficients between community canopy parameters and microclimate and PM factors.

No.	CI	CD		СР		LAI		SVF	
	сс	sig.	сс	sig.	сс	sig.	сс	sig.	
dAT	-0.874 **	0.002	0.930 **	0.000	-0.867 **	0.002	0.885 **	0.002	
dRH	0.865 **	0.003	-0.917 **	0.001	0.880 **	0.002	-0.902 **	0.001	
dPM ₁₀	-0.769 *	0.015	0.711 *	0.032	-0.788 *	0.012	0.762 *	0.017	
dPM _{2.5}	-0.591	0.094	0.551	0.124	-0.570	0.109	0.671 *	0.048	

Note: cc refers to correlation coefficient; sig. refers to significance, * and ** represent significant level.

3.2.1. Air Temperature and Relative Humidity

Results shown in Table 6 and Figure 5a,b suggest that CD had a strong negative correlation with dAT (cc= -0.874), but was positively correlated with dRH (cc = -0.865). Both correlations reached high significance levels (sig. < 0.01). With increasing CD, dAT gradually decreased, while dRH increased. As CD increased to about 65%, the plant community had a cooling effect, although dAT declined very slightly. Once the CD was over 70%, the decline in dAT was obvious. This indicates that 65%–70% may be a key CD threshold to affect ambient AT. With increasing CD, the change rate of dRH remained stable, showing a quasilinear increase, with no indication of a critical threshold.

CP was found to be positively correlated with dAT, but negatively correlated with dRH, with cc values of 0.930 and -0.917, respectively (sig. < 0.01, Table 6). The dAT changed less dramatic when CP fell below 48% (Figure 5c), while dramatic AT changes were found between 50%–60% CP, suggesting that plant communities with CP in this interval had marked cooling effects. However, when the community canopy became too porous in the horizontal direction, with CP larger than 60%, the cooling effect was extremely limited. The correlation between CP and dRH shown in Figure 5d is quasilinear. With increasing CP, the reduction in dRH decreased (CP around 57%), although a critical threshold was not apparent.

The dAT decreased while the dRH increased significantly with increasing LAI, as indicated by the results shown in Table 6 and Figure 5e,f. Both parameters were correlated at a high level of significance (sig. < 0.01), with cc values of -0.905 and 0.867, respectively. With increasing LAI, the reduction in dAT changed slightly. In contrast, the dRH increased in a steady quasilinear trend. No thresholds were apparent for AT and RH related to this canopy characteristic.

In contrast, a significant positive relationship between SVF and dAT was observed (cc = 0.885, sig. < 0.01). Lower SVF led to lower dAT. This trend suggests that when the SVF increased within the range 0.10–0.25, the increment in dAT was slightly higher than that when SVF was over 0.25. However, this threshold was not well defined. Meanwhile, the dRH decreased significantly with increasing SVF (cc = -0.902, sig. < 0.01). The relationship between SVFs and dRH was also quasilinear.



Figure 5. Non-linear fitting relationship between: (**a**) canopy density and daily average AT; (**b**) canopy density and daily average RH; (**c**) canopy porosity and daily average AT; (**d**) canopy porosity and daily average RH; (**e**) leaf area index and daily average AT; (**f**) leaf area index and daily average RH; (**g**) sky view factor and daily average AT; (**h**) sky view factor and daily average RH.

3.2.2. Particulate Matter Concentrations

The results in Table 6 and Figure 6a show that the dPM_{10} was negatively correlated with CD (cc = -0.769, sig. < 0.05). With increasing CD, the dPM_{10} decreased significantly without obvious fluctuation. However, when CD increased to 60%–75%, the dPM_{10} reduction increased significantly. Once the CD exceeded 80%, the reduction slowed down again. Interestingly, no significant relationship was detected between CD and $dPM_{2.5}$ (sig. > 0.05). From Figure 6b, the $dPM_{2.5}$ first showed an obvious decrease, but as CD increased to around 78%, $dPM_{2.5}$ increased instead. This indicates that high canopy density is not necessarily conducive to reducing $PM_{2.5}$. From the fitting trend in Figure 6b, 75% was identified as the key CD threshold for effective $PM_{2.5}$ reduction.



Figure 6. Non-linear fitting relationship between: (a) canopy density and daily average PM_{10} ; (b) canopy density and daily average $PM_{2.5}$; (c) canopy porosity and daily average PM_{10} ; (d) canopy porosity and daily average $PM_{2.5}$; (e) leaf area index and daily average PM_{10} ; (f) leaf area index and daily average $PM_{2.5}$; (g) sky view factor and daily average PM_{10} ; (h) sky view factor and daily average $PM_{2.5}$.

The dPM₁₀ values showed a significant positive correlation with CP (sig. < 0.05), with a cc value of 0.711 (Table 6). With increasing CP, dPM₁₀ increased (Figure 6c). The response of dPM₁₀ to the change in CP did not fluctuate significantly. With higher canopy porosity in the horizontal direction, the interception and filtration effects on PM₁₀ became weaker. There was no obvious inflection point to this fitting trend. The correlation between dPM_{2.5} and CP was insignificant (sig. > 0.05). As CP gradually increased, the dPM_{2.5} slightly increased (Figure 6d). Once CP reached 55%, the growth rate of dPM_{2.5}, but once the CP exceeds 55%, the sparse canopy cannot effectively reduce fine particles.

The dPM₁₀ concentration was negatively correlated with LAI (sig. < 0.05, cc = -0.788). As LAI increased, the dPM₁₀ decreased, with no obvious fluctuation. Once LAI exceeded 2.8, still to increase, the decline in dPM₁₀ slowed. Therefore, a LAI value of 2.8 may be the threshold for community canopy to effectively reduce PM₁₀. There was no significant correlation between dPM_{2.5} and LAI (sig. > 0.05). With increasing LAI, dPM_{2.5} had a U-shaped trend, first decreasing and then increasing, yielding a critical threshold of around 2.50.

SVF had a significant positive effect on dPM_{10} (Table 6), with a cc value of 0.762 (sig. < 0.05). Higher SVF lead to higher dPM_{10} , with an quasilinear trend (Figure 6g). The positive relationship between $dPM_{2.5}$ and SVF was also significant (sig. < 0.05, cc = 0.671). The trend showed a V-shape with the ascending segment obviously larger than the descending one, and the valley located around 0.18. As SVF decreased from a higher level, the $dPM_{2.5}$ decreased rapidly. Once SVF dropped to 0.18, the $dPM_{2.5}$ started to rise again. This indicates that although low SVF enhances the diffusion and attenuation of fine particles, high SVF sustains fine particles under the canopy.

4. Discussion

The effects of different plant community compositions and canopy characteristics on AT, RH and air particle levels have received increasing attention recently because the cooling, humidifying and particle-detaining abilities differ greatly among tree species [48,49]. This means that plant communities, comprised of different plant species, have variable potentials to regulate heat and pollution. Meanwhile, the regulatory effects of plant communities on environmental factors do not equal a simple superposition of the regulatory capacities of individual plants. Instead, the canopy structures, reflecting the overall leaf volume and geometric shape of the plant community, have important impacts on energy conversion and airflow beneath the canopy, affecting microclimate and airborne particle levels [50]. Based on this, our investigation focused on the effects of community composition and canopy structure on microclimate and airborne particle levels.

4.1. Effects of Plant Community Composition on Microclimate and Airborne Particle Levels

Some previous studies have found that there are differences between conifers and broad-leaved plants in regulating microclimate [51,52]. Compared with plant communities composed solely of coniferous or broad-leaved plants, mixed-composition plant communities have better cooling and humidifying effects. The coniferous communities perform remarkably well at shading and cooling, while the broad-leaved communities often produce an excellent humidifying effect. In addition to species composition, the hierarchical structure of the plant community also affects the overall biomass and canopy characteristics of the community. Zhu et al. [53] reported that the cooling and humidifying effects of turf communities are not significant. In contrast, tree-shrub-grass communities have a large leaf area, and can provide a remarkable microclimate effect. Tree–grass communities also maintain strong permeability under sufficient leaf amount, which is conducive to the air circulation under their canopies, especially in breezy weather, demonstrating an outstanding cooling effect. In this study, the daily average AT and RH of the different community types were significantly different. The cooling and humidifying effects of the M-TSG and B-TSG communities were excellent compared with the other types. This is precisely because these two community types have more leaves and higher canopy coverage, resulting in stronger transpiration, and a greater capacity to intercept and absorb solar radiation. Previous researchers have drawn similar conclusions [54,55].

Similarly, for airborne particles, the composition of the plant community determines its regulatory effect on different-sized PM. There are reports of conifers having smaller leaf area but denser canopies which may intercept airborne particles effectively. Moreover, some pine species secrete mucus, making it difficult for adhering particles to re-enter the atmosphere [55,56]. Apparently, trees are the main agents for removal of air particles in green spaces, given their dense canopies and large total leaf areas, which enhance their dust retention capacities [23,57,58]. In this study, we found that the M-TSG community, with abundant leaves and a mixed structure, reduced PM_{10} most greatly. However, as for $PM_{2.5}$, although plant communities with scarce leaves were not conducive to the absorption of fine particles, outward diffusion of $PM_{2.5}$ was hindered when the hierarchical structure was too complex and dense. In addition, some studies have found that some organic volatiles released by conifers can be converted into secondary aerosols, forming $PM_{2.5}$ and other fine particles [59]. Therefore, having sufficient leaf area, internal airflow permeability and moderate coniferous components make the M-TG community the most efficient at reducing $PM_{2.5}$. Differences in dPM_{10} among the eight community types were more pronounced than those for $dPM_{2.5}$, indicating that community composition has a greater influence on coarse particles than on fine particles.

4.2. Critical Thresholds of Plant Community Canopy's Regulating Effects on Microclimate and Airborne Particle Levels

Canopy characteristics affect the thermal and airborne-particle regulation service of a plant community. Based on remote sensing data and field survey, Hardin [33] found that the cooling effect of urban forests was significantly positively correlated with LAI. Srivanit and Hokao [35] pointed out that CD is an important factor affecting the cooling effect related to urban forests. Peters and Mcfadden [34] also advocated that the AT within plant communities was significantly related to community CD and LAI. Similar conclusions were drawn in this study. The dAT within the community was significantly negatively correlated with CD and LAI, but positively correlated with CP and SVF. In contrast, dRH showed the reverse trends with these attributes. Generally, the density of the plant community canopy in the vertical direction (CD, SVF) determines the amount of solar radiation intercepted and absorbed, while the porosity (CP) in the horizontal direction affects the air exchange between the plant community and its surroundings. When the community canopy became too dense in the horizontal direction, it hindered air circulation under the canopy and slowed down heat loss. LAI reflects the total leaf amount of the community, which determines the amount of transpiration and shade cast. These all affect the heat and water conversion inside and outside the community, and therefore affect AT and RH. Hence, plant communities with high CD and LAI but low CP and SVF resulted in greater cooling and humidifying effects.

In our study, several specific inflection points were found in non-linear responses between some canopy characteristics and dAT and dRH. Plant communities with CD over 65%–70% and CP below 60% had outstanding cooling effects. As a plant community's humidification effects mainly depend on transpiration, its relations with canopy characteristics were basically linear. As CD and LAI increased, and CP and SVF decreased, RH increased steadily, showing no critical threshold. A few scholars have recently attempted to explore critical thresholds of vegetation canopy attributes affecting microclimate. Zhu et al. [53] found that when CD ranged from 10% to 31%, the community had a slight cooling and humidifying effect. This effect became significant once values exceeded 44%, and stabilized at 67%. Tang et al. [39] advocated that the cooling intensity of a plant community was linearly and positively correlated with CD. Every 10% increase in CD caused the cooling intensity to increase by 0.5°C. In contrast, there was a non-linear positive correlation between LAI and the cooling intensity of the community. Once LAI increased within the range of 0.23–2.30, the cooling intensity increased rapidly. There is still much to explore in this field and more research is needed.

The dPM₁₀ and dPM_{2.5} had variable relationships with community CD, CP, LAI and SVF. Generally, when air carrying PM passes through the community canopy, large-sized particles are more likely to be intercepted and deposited on the surfaces of branches, leaves and stems [60]. Therefore, when communities have higher CD and LAI, but lower CP and SVF values, this creates a canopy structure with a larger amount of branches and leaves in both horizontal and vertical directions, allowing it to intercept more coarse particles like PM₁₀. In contrast, Liu et al. [37] found that PM_{2.5} level was positively correlated with CD, LAI and average tree diameter (DBH), but negatively correlated with average tree height, forest land area, herbaceous coverage and height. In this study, most responses of dPM_{2.5} to community canopy structure were non-linear, with critical inflection points, resulting in few significant correlations. This may be related to the dependence of the attenuation of fine particles on outward diffusion dilution. Therefore, when the community canopy is too sparse, it is not conducive to the interception and absorption of PM_{2.5}.

dense canopies will not only hinder the diffusion of $PM_{2.5}$ into the upper atmosphere along with turbulent air flow, but weaken the Brownian motion of particles under low temperature and high humidity conditions, which could even increase their concentration due to the moisture absorption and condensation of fine particles. Compared with dPM_{10} , the response of $dPM_{2.5}$ to community canopy structure is more complex. Janhäll [30] mentioned that vegetation barriers were suggested to be dense enough to provide a large depositional surface area, but porous enough to ensure air infiltration and upward diffusion of particles. Similar conjectures can be made based on the results of this study.

To date, only a few scholars have reported critical thresholds of plant community canopy characteristics affecting air particle levels. Yin et al. [56] considered that the best CD and CP values for plant communities to reduce total suspended particulates (TSP) were 70%–85% and 25%–33%, respectively. In our study, communities with CD values above 65%–70% and LAI values below 2.8 had higher reduction effects on PM_{10} . For $PM_{2.5}$, the greatest reductions occurred for CD, CP, LAI and SVF values of 75%–78%, 55%, 2.30–2.50 and 0.18, respectively. Our results clearly have some overlap with Yin's conclusions.

Canopy structure is an important factor affecting the thermal and air particle regulatory services of plant communities. A previous study recorded strong associations between air pollutants and UHI effect during certain seasons (i.e., winter and autumn) [32]. Therefore, constructing plant communities with good regulatory effects on both microclimate and air particle pollution is an economical and effective way to improve urban environments. In this study, mixed TSG and TG communities with CD, CP, LAI and SVF values of 75%, 55%, 2.5 and 0.18, respectively, produced noticeable positive effects on both microclimate and air particle levels.

In general, this work focused on the impacts of the composition and canopy characteristics of plant communities on microclimate and airborne particles in Beijing and quantified the critical thresholds of plant community canopy characteristics. This research may guide future urban green spaces' construction aiming to improve the thermal environment and reduce air pollution. However, this study also has some limitations. Firstly, although the study area and selected plant communities are typical in urban green-space in Beijing, limited by the monitoring conditions, the number of samples is limited. Secondly, it must be noted that the critical thresholds of canopy structure reported here may only be applicable to our study area, and could not be validated as general conclusions. Future research is urgently needed to support and corroborate our results in future.

5. Conclusions

In summer, significant differences existed in daily AT, RH, PM_{10} and $PM_{2.5}$ levels among eight plant community types. The M-TSG community had the strongest cooling and PM_{10} reduction effects; the B-TSG community had the best humidifying effect; and the M-TG community was most effective in reducing $PM_{2.5}$. dAT and dPM_{10} were significantly negatively correlated with CD and LAI, while positively related with CP and SVF, while these correlations were opposite for dRH. The response of $dPM_{2.5}$ to various canopy structures was complex, featuring multiple non-linear relations. Critical thresholds were found in some cases. Plant communities with CD greater than 65%–70% and CP below 60% had a significant cooling effect. No critical threshold was found for the humidifying effect. Plant communities with CD ranging 60%–75% and LAI close to but no more than 2.8 had excellent PM_{10} reduction effects. Plant communities featuring 75%–78%, 55%, 2.30–2.50 and 0.18 CD, CP, LAI and SVF, respectively, had pronounced $PM_{2.5}$ reduction effect. Overall, mixed TSG or TG communities with about 75% CD, 55% CP, 2.5 LAI and 0.18 SVF perform most noticeably both microclimate and air particle regulation services.

Author Contributions: Conceptualization, S.F., L.D.; funding acquisition, L.D.; project administration, L.D.; data acquisition, S.F.; formal analysis, S.F., M.Z., Y.L., K.L.; drafting the manuscript, S.F., L.D.; revising the manuscript critically for important intellectual content, S.F., L.D. All authors have read and agreed to the published version of the manuscript. **Funding:** This work was supported by Beijing Municipal Science and Technology Project (D171100 007117001).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This research was funded by Beijing Municipal Science and Technology Project: Establishing Evaluation System for Ecological Function of Multi-scale Green Spaces in the Northern Urban Area (D171100007117001). We would like to thank Sijia Wu, Yilun Li, Kun Li, Mengyuan Zhang, Jing Han, Rui Jing and Fan Wu for their support in the field work and data processing. We sincerely thank the anonymous reviewers for their valuable comments.

Conflicts of Interest: The authors declare no conflict of interest.

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