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EFFECT OF SPATIAL DIFFERENTIATION OF PLANT COMMUNITIES ON $PM_{2.5}$ AND O_3 IN URBAN GREEN SPACES IN BEIJING, CHINA

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Highlights:

- the $PM_{2.5}$ concentrations are low in the areas of evergreen coniferous trees (ECP) and/or deciduous broadleaved trees (DBP) are the dominant species of tree-shrub-grass (TSG) and tree-shrub (TS);
- the O_3 concentration of all the plant community areas reaching the level of "low pollution";
- the AQI with $PM_{2.5}$–O_3 value of compound concentration as the main parameter reaches the level of "moderate pollution", and the result that deserves further attention.

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Abstract. Urban green space can improve the air quality of urban human settlements. This study aimed to investigate the spatial differences of air quality among the different plant community structures and types of urban park green spaces. We select 17 sample sites in Beijing Olympic Forest Park, and they are located in different areas of plant community structures and types. The study entailed an analysis of the interrelationships between the plant community structures, types, and $PM_{2.5}$, O_3, and $PM_{2.5}$–O_3 compound data. The results showed that $PM_{2.5}$ was lower in tree-shrub-grass, tree-shrub, and tree-grass than in shrub-grass and grass plant community areas; $PM_{2.5}$ was lower in evergreen coniferous, mixed coniferous and broadleaved, and deciduous broadleaved plant communities than that in grass or shrub ones. In different plant community structures, types areas, O_3 was higher than 100 $\mu g \cdot m^{-3}$, and there were no significant differences among the plant community areas. The air quality index with $PM_{2.5}$–O_3 composite pollution value as the main parameter reached the level of "moderate pollution", and the result that deserves further attention. The research results provide a basic scientific basis for the planning, design, and updating optimization of functional urban green spaces based on evidence-based design.

Keywords: air pollution, landscape architecture, urban green space, $PM_{2.5}$–O_3, spatial differentiation, evidence-based design.

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1. Introduction

As urbanization in China increases and the population density in built-up areas continues to rise, environmental problems such as pollution aggravation have emerged in urban agglomerations such as Beijing-Tianjin-Hebei, Yangtze River Delta, Pearl River Delta, Chengdu-Chongqing, and especially in high-density urban areas such as the Beijing and Tianjin metropolitan region (Chen, 2020; Qi et al., 2017; Wu et al., 2021; Zhao & Xu, 2021; Feng et al., 2021; Liu et al., 2021; Liu et al., 2018; Xiao et al., 2022). In the last decade, major urban areas across China have experienced frequent exceedances of pollutant concentrations, which have seriously affected the health of residents, the quality of the urban microenvironment, and sustainable development (Fan et al., 2021; Li et al., 2022; Liu et al., 2021; Zhao et al., 2022). Fine particulate matter represented by $PM_{2.5}$ and gaseous pollutants represented by O_3 have exceeded the standard concentration. Particularly in recent years, the Beijing-Tianjin-Hebei metropolitan region and other city clusters have shown the characteristics of multiple contamination of $PM_{2.5}$, O_3, and $PM_{2.5}$–O_3 during the autumn–winter seasons (Cai et al., 2022; Chen, 2020; Li et al., 2022; Qin et al., 2019; Qu et al., 2018; Sheng et al., 2019; Wang et al., 2019; Zhao et al., 2018; Feng et al., 2021; Xiao et al., 2022). $PM_{2.5}$ mainly originates from industrial processes such as combustion and transport operations. It occurs mainly in the autumn–winter seasons and usually with significant spatial aggregation and diffusivity (Gao et al., 2020; Wang et al., 2019; Liu et al., 2018; Zhao et al., 2022). O_3 pollution mainly occurs in the summer and autumn. It has a certain homology and correlation with $PM_{2.5}$ pollution, because they share common precursors, nitrogen oxides (NO_x) and volatile organic compounds (VOCs), which produce O_3 through photochemical reactions (Cai et al., 2022; Fishman & Crutzen, 1978). The spatio-temporal distribution features of NO_x and VOCs are different, because the mechanisms are not identical. Among the reduction (dissipation) and regional transmission (spill over) factors for both $PM_{2.5}$ and O_3, larger-scale air movement (wind) and vegetation coverage are considered to be the most effective drivers (more than chemical energy use and population density) (Chen, 2020; Douglas et al., 2019; Qi et al., 2017; Liu et al., 2018; Wang et al., 2021). Previous studies have selected factors from the urban area scale, the street/block scale, and the landscape site scale to explain the underlying mechanisms for dissipating or reducing $PM_{2.5}$–O_3 compound pollution from the perspective of urban blue-green spatial system planning (Cai et al., 2022; Fan et al., 2021; Wu et al., 2021; Xiang et al., 2020), block/street morphology (He et al., 2023; Dai et al., 2020; Wang et al., 2021), and urban green space landscape spatial construction (Cai et al., 2022; Chen et al., 2019; King et al., 2014; Xing & Sun, 2022; Yin et al., 2022; Zhang et al., 2017). Some studies focusing on the plant community or individual scale of the plant landscape have concluded that $PM_{2.5}$ concentration has a significant negative correlation with the amount of tri-dimensional green biomass of local plants (Zhu et al., 2019; Yan & Hong, 2019).

The study of $PM_{2.5}$–O_3 compound pollution at the national, regional, and city scales has mainly used measured data and spatial interpolation methods to describe the heterogeneity of $PM_{2.5}$–O_3 spatial distribution from a quantitative perspective, thus contributing to the formulation of joint prevention and control policies for cities and urban physical space planning. Studies at the landscape and urban green space scales have focused on the factors affecting $PM_{2.5}$–O_3 concentrations, thus providing a scientific basis for incremental urban spatial planning and urban regeneration based on functional green space design that reduces the intensity and scope of $PM_{2.5}$–O_3 pollution. However, in-depth quantitative studies on the spatial differentiation characteristics of $PM_{2.5}$–O_3 within larger urban green spaces are still relatively limited.

We continuously and dynamically monitored the microenvironment effects (such as reduction of airborne fungi and bacteria, cooling and humidification, and negative air ions) of the Beijing Olympic Forest Park from 2005 to 2022. Moreover, we have been monitoring $PM_{2.5}$–O_3 concentrations at regular intervals since 2013.

2. Study area and research methodology

2.1. Study area

The Beijing Olympic Forest Park (BOFP) is located in the Chaoyang District of Beijing, China, and covers a total area of 680 hm^2 (Figure 1); 450 hm^2 of the park is covered by more than 200 species of indigenous plants, forming a human-made near-natural forest system. Due to its large area and lush vegetation, the park plays a vital role in improving the urban microenvironment.

2.2. Research methods

2.2.1. Sample site setup

The chessboard sampling method was used to select 17 measured sample sites in BOFP (Figure 1). And the locations of the sample sites were carefully selected to ensure that they represent the air quality of typical environments (the sample sites of G, H and I are close to the urban road), and the others away from large areas of human activity (urban roads, squares, etc.) and to ensure representative vegetation types. 2–3 sample sites were tested for plant community structure, type, and typical landscape environment (Table 1).

Two comparison sample sites were selected, one 1 km from the south gate of BOFP (near the underground commercial plaza of the Olympic Park) and the other at the north side square of the North Fourth Ring Road (near the "Bird's Nest" National Stadium, where there is a large amount of pavement, less green space, and activities involving dense crowds). Two comparison sample sites were not within the field of view of Figure 1.

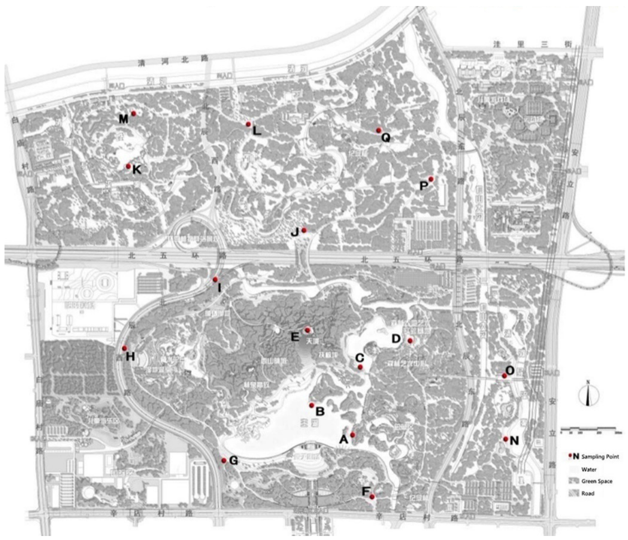

Figure 1. Location of BOFP and 17 experimental sample sites in it

2.2.2. Test method

The test instrument comprised six outdoor air-quality testers (SWEMA TF-9, Sweden), which, in addition to $PM_{2.5}$ and O_3 measurements, could simultaneously collect and record PM_{10} and CO_2 concentrations, air temperature, and relative humidity data (see Table 2 for information on instrument parameters). The experiment was conducted over 3 days during the period 10–25 August 2022, under a clear sky (no more than 30% cloud cover), with calm wind (within 3–4 $m \cdot s^{-1}$), while avoiding rainfall (in the event of rainfall, the experiment was postponed for 3 days). The biological characteristics of the plant community in the sample site area, such as Plant Height, Diameter at Breast Height, Crown Width, Forest Canopy, and Canopy Density of the Dominant Species in the quadrate were obtained by field research in the initial phase. A CI-110 Plant Canopy Im-

Table 1. Biological characteristics of sample sites in BOFP

Sample site	Plant community structure	Plant community type	Typical environ-ment	Dominant species	Plant Heigh/m	Diameter at Breast Height/cm	Crown Width/m	Forest Canopy/m	Canopy Den-sity/%
CK 1	–	–	–	–	–	–	–	–	–
CK 2	–	–	–	–	–	–	–	–	–
A	TG	DBP	DPC	*Populus tomentosa*	10~12	25~30	2.0~2.5	5.0~6.0	65
B	–	–	SPC	*Salix matsudana cv.pendula*	4.5~5.5	20~25	4.0~4.5	2.0~2.5	25
C	TSG	DBP	MPC	*Salix matsudana cv.pendula*	5.5~6.0	20~25	3.5~4.0	3.0~3.5	75
D	TSG	CBP	MPC	*Sabina chinensis, Sophora japonica*	3.5~4.0/ 5.5~6.0	20~25	2.0~2.5/ 4.5~5.0	1.5~2.0/ 2.5~3.0	85
E	T	CP	SPC	*Pinus tabulaeformis*	3.0~3.5	10~15	3.5~4.0	1.5~2.0	35
F	TG	DBP	DPC	*Salix matsudana*	7.0~8.0	20~25	4.5~5.0	3.0~4.0	85
G	SG	S	DPC	*Syringa oblata*	2.5~3.0	–	2.0~2.5	1.5~2.0	75
H	SG	S	DPC	*Caryopteris×clandonensis 'Worcester Gold'*	0.5~1.0	–	–	–	45
I	SG	S	DPC	*Euonymus japonicus*	0.5~1.0	–	–	–	45
J	SG	CP	DPC	*Pinus tabulaeformis)*	4.5~5.0	10~15	2.5~3.0	2.0~2.5	55
K	SG	DBP	DPC	*Amygdalus triloba*	3.0~3.5	–	2.0~2.5	1.0~1.5	75
L	G	G	SPC	*Lawn and ground-cover*	–	–	–	–	75
M	TS	CP	DPC	*Pinus tabulaeformis*	3.5~4.0	10~15	2.5~3.0	1.5~2.0	95
N	TSG	CBP	MPC	*Populus tomentosa*	9.5~10.0	25~30	2.5~3.0	5.0~6.0	90
O	TSG	DBP	MPC	*Sophora japonica*	6.5~7.0	20~25	4.0~4.5	2.5~3.0	90
P	TG	DBP	DPC	*Ginkgo biloba*	4.5~5.0	15~25	2.5~3.0	2.0~2.5	75
Q	TG	DBP	DPC	*Sophora japonica, Fraxinus chinensis*	3.5~4.0	15~20	3.0~3.5/ 5~6	2~3/3~4	75

Note: (1) The sample site E is located in the "Heavenly Realm", which is 85 m above sea level, compared to other parkland sample sites at 43 m; (2) Plant community structures: tree-shrub-grass (TSG), tree-shrub (TS), tree-grass (TG), shrub-grass (SG), and grass/ground cover (G); plant community types: evergreen coniferous plant community (ECP), coniferous and broadleaved mixed plant community (CBP), deciduous broadleaved plant community (DBP), shrub (S), and grass/ground cover (G); typical environments: tree-shrub- grass multi-layer plant Community (MPC), tree-shrub, tree-grass, and shrub-grass double-layer plant community (DPC), grass/ground cover single-plant community (SPC), waterfront plant community (WPC), and waterfront square (WS); CK denotes the comparison sample.

age Analyzer was used to measure the leaf area index and other plant community quantification parameters.

Table 2. Test instrument parameters

Instrument	Items	Range of value	Accuracy
Outdoor air quality testers (SWEMA TF-9, Sweden)	$PM_{2.5}$	0–1000 ug·m^{-3}	±10% readout values
	O_3	0–1200 ug·m^{-3}	±20 ug·m^{-3}+10% of readout values
	PM_{10}	0–2000 ug·m^{-3}	±10% readout values
	CO_2	350–2000 PPM	±50 PPM+3% readout values
	Tempe-rature	–20–50 °C	<±0.5 °C
	Relative Humidity	0–99%	<±3.5%

2.2.3. Data analysis methods

1) Statistical methods. The instrument automatically recorded and stored the measurement data from the sample sites. Measurements were taken from 8:00–18:00 (at 10 min intervals). Instantaneous value measurement, meanwhile, were taken in the morning, noon, and afternoon at the following times: 8:50–9:10 (at 5 min intervals), 13:20–13:40, and 17:20–17:40. The arithmetic mean of the five times taken in each period was used as the value for morning, noon, and afternoon, respectively. The comparison sample data indicate the $PM_{2.5}$–O_3 composite pollution concentration of the ambient background.

2) Air-quality evaluation method. According to the Ambient Air Quality Standards (GB 3095-2012, Chinese National Standards) (*Announcement on the Release of the Revision of Ambient Air Quality Standards (GB 3095-2012)*, 2018), released by the Ministry of Ecology and Environment in February 2012, the air-quality index (AQI) is a numerical value used to quantitatively describe the air quality: "excellent" (AQI ≤ 50), "good" (50 < AQI ≤ 100), "low pollution" (100 < AQI ≤ 150), "moderate pollution" (150 < AQI ≤ 200), "heavy pollution" (200 < AQI ≤ 300), and "severe pollution" (AQI > 300). This air-quality assessment is based on data recorded automatically at 10-min intervals for 10 consecutive hours from 8:00 to 18:00 (total of 76 recordings). The $PM_{2.5}$ and O_3 concentration values in this revised list can be used to evaluate the air-quality levels of the different plant communities in BOFP (Table 1). The formula for calculating the AQI is as follows:

$$AQI = \frac{AQI_{high} - AQI_{low}}{C_{high} - C_{low}}(C - C_{low}) + AQI_{low}, \quad (1)$$

where: C is the daily average of $PM_{2.5}$ and O_3 concentrations; I_{low} corresponds to the index limit of C_{low} (constant); I_{high} corresponds to the index limit of C_{high} (constant); C_{low} is less than or equal to the mass concentration limit of C (constant); and C_{high} is greater than or equal to the mass concentration limit of C (constant).

2.2.4. Data processing

EXCEL 2019 was employed for organizing and conducting calculations about the average of $PM_{2.5}$ and O_3 concentrations, to facilitate subsequent comparisons. For significance analysis and one-way analysis of variance, SPSS 26 was utilized. Additionally, Origin 2023 was used to generate correlation bar charts and standard curves.

3. Results

3.1. Spatial differentiation of $PM_{2.5}$ pollution

1) $PM_{2.5}$ concentration and AQI within different plant community structure areas

Figure 2a shows the instantaneous $PM_{2.5}$ value in the morning, noon, and afternoon within different plant community areas in BOFP. During the Morning period, the value of the grass/ground cover (G) plant community area was the highest (above 50 μg·m^{-3}). The tree-shrub (TS) are was below 50 μg·m^{-3} (air quality "excellent"), with the lowest value. The $PM_{2.5}$ concentrations in the tree-shrub-grass (TSG) and the tree-shrub (TS) structure areas remained stable and decreased from noon to afternoon. However, the $PM_{2.5}$ concentrations in the other plant community structure areas gradually increased, and all were higher than 50 μg·m^{-3}. Figure 2b compares the AQI values regarding $PM_{2.5}$ concentrations in the different plant community structure areas. The $PM_{2.5}$ concentrations in the areas with tree-shrub-grass (TSG), tree-grass (TG), and tree-shrub (TS) structures were below 50 μg·m^{-3} (air quality "excellent"), while the air quality in these areas with other community structures was just as high.

2) $PM_{2.5}$ concentration and AQI within different plant community type areas

Figure 3a shows the instantaneous $PM_{2.5}$ value in the morning, noon, and afternoon within different plant community type areas. The comparison between the three instantaneous values shows a slow increase in $PM_{2.5}$ concentrations from morning to afternoon. The three instantaneous values of $PM_{2.5}$ in the evergreen coniferous plant community (ECP), coniferous and deciduous broadleaf plant community (CBP, DBP) areas were all below 50 μg·m^{-3} (air quality "excellent"), while the instantaneous values at noon and afternoon in the shrub (S) area and the three instantaneous values in the grass/ground cover (G) area were above 50 μg·m^{-3}. Figure 3b compares AQI values within different plant community types areas. The $PM_{2.5}$ concentrations in the evergreen coniferous (ECP), mixed coniferous and broadleaved (CBP), and deciduous broadleaf plant community (DBP) areas were below 50 μg·m^{-3}, and the air quality was assessed as "excellent".

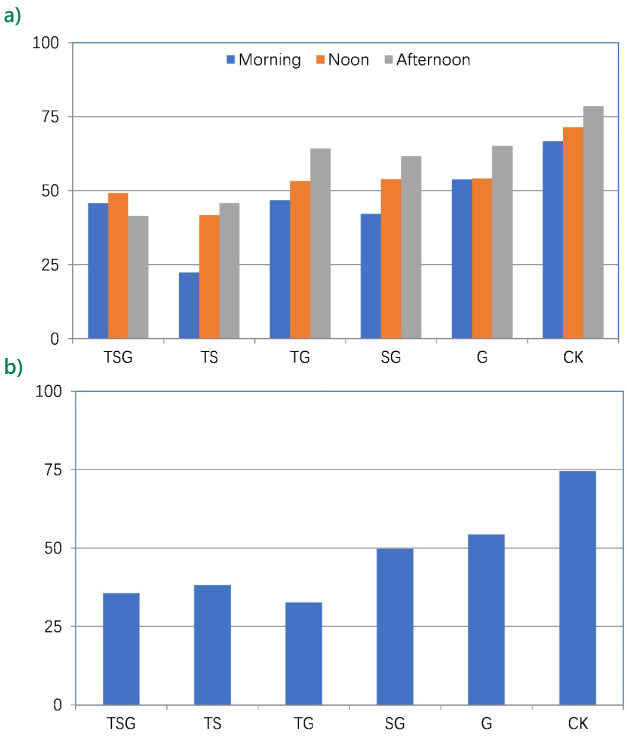

Figure 2. $PM_{2.5}$ instantaneous values (ug·m^{-3}) and AQI in different plant community structure areas

Figure 3. $PM_{2.5}$ instantaneous values (ug·m^{-3}) and AQIin different plant community type areas

3) $PM_{2.5}$ concentration and AQI within typical landscape environment areas

Figure 4a shows the instantaneous $PM_{2.5}$ value in the morning, noon, and afternoon in the typical landscape environment of BOFP. The comparison of the three instantaneous values shows a slow increase from morning to afternoon in most areas, with only areas of the multi-layer plant community (MPC) showing an increase followed by a decrease. The $PM_{2.5}$ concentrations in all landscape areas were below 50 μg·m^{-3} in the morning and below 50 μg·m^{-3} in the multi-layer (MPC) and waterfront plant community (WPC) areas (air quality "excellent"). In a combined comparison, the $PM_{2.5}$ concentrations in BOFP were significantly lower than in the comparison sample sites. Figure 4b compares $PM_{2.5}$ concentrations at the sample sites. The air quality of the single-layer (SPC) environment was rated as "good." In contrast, the other typical environments were rated as "excellent". On balance, the air quality indices in BOFP were better than those in the comparison samples.

3.2. Spatial differentiation of O_3 pollution

1) O_3 concentration and AQI within different plant community structure areas

Figure 5a shows the O_3 concentrations in the morning, noon, and afternoon in BOFP. The comparison between the three periods shows that the O_3 concentrations in all plant community structure areas exhibited an increasing trend from morning to afternoon, with large increase from the morning to noon and a minor increase from noon to the afternoon. O_3 concentrations in all areas of the plant community structure were below 100 μg·m^{-3} in the mornings and above 100 μg·m^{-3} at noon and in the afternoons. Figure 5b shows a comparison of the O_3 concentration in the different community structure areas. The difference in O_3 concentration between the different community structures areas in BOFP is insignificant. O_3 concentration is slightly lower than in the comparison sample sites, but not significantly different. All areas have "low pollution."

2) O_3 concentration and AQI within different plant community type areas

Figure 6a shows the O_3 concentrations in the Morning, Noon, and Afternoon of the different plant community types areas in BOFP. The comparison between the three instantaneous values shows that O_3 concentrations tended to increase from morning to afternoon, with higher initial values (above 100 μg·m^{-3}) in the morning for evergreen coniferous (ECP), mixed coniferous and broadleaved (CBP) and deciduous broadleaf plant communities (DBP) and a slow increase from morning to afternoon; lower initial values (below 100 μg·m^{-3}) in the morning for the two community types of shrub (S) and grass/ground Cover (G), and a large increase from morning to noon and a minor increase from noon to afternoon. Collectively, there were no significant differences between the Noon and Afternoon values of the O_3 concentrations in all plant community types. Figure 6b shows a comparison of O_3 concentrations in the different plant community types areas. Overall, no significant differences were found between the air quality of the different plant community types in BOFP. Although the air quality of BOFP is slightly higher than in the comparison sample sites (CK), there is still no significant difference, and the air quality is assessed as "low pollution."

3) O_3 concentration and AQI within the typical landscape environment

Figure 4. $PM_{2.5}$ instantaneous values (ug·m^{-3}) and AQI in typical landscape environment areas

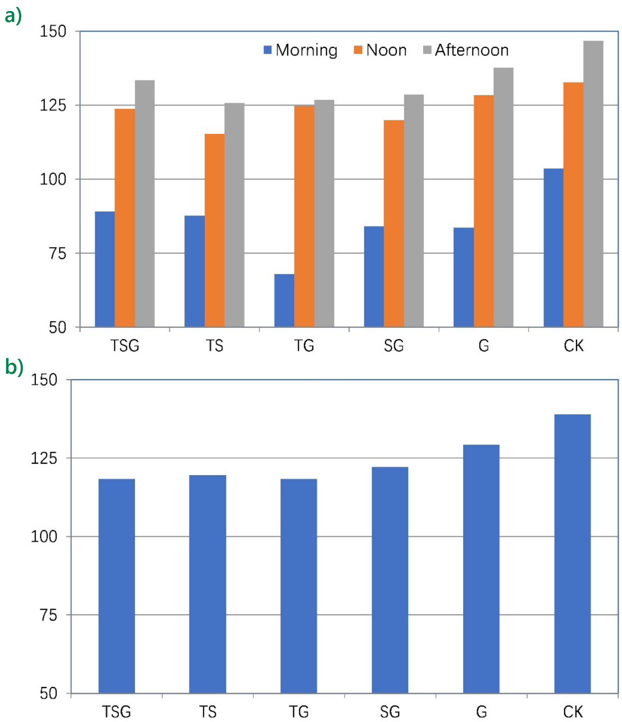

Figure 5. O_3 instantaneous values (ug·m^{-3}) and AQIin different plant community structure areas

Figure 7a shows the O_3 concentrations in the morning, noon, and afternoon in the typical landscape environment area of BOFP. The comparison between the three instantaneous values shows that O_3 concentrations in the typical landscape environment areas exhibited an increasing trend from morning to afternoon. However, the initial value concentrations were lower (below 100 μg·m^{-3}) in the areas of the multi-layer (MPC), double-layer (DPC), and single-layer plant communities (SPC), with a large increase from the morning to noon and a minor increase from noon to afternoon. The noon and afternoon values of the O_3 concentrations were above100 μg·m^{-3} in all areas of the landscape environment. A comparison of the air quality assessment values, in terms of O_3 concentrations, for the sample sites in typical landscape environments is shown in Figure 7b. There is no significant difference in air quality between the typical environmental areas. The air quality within BOFP is slightly higher than in the comparison sample sites, but not significantly different, all being "low pollution."

3.3. Spatial differentiation of $PM_{2.5}$–O_3 compound pollution

Figure 8a to 8c compares the $PM_{2.5}$–O_3 compound pollution AQI values of the structure and type of green space plant communities and typical landscape environments. The results show that the $PM_{2.5}$ concentrations are low (below 50 μg·m^{-3}) (air quality "excellent") and the O_3 concentrations are high (close to or above 100 μg·m^{-3}) in each plant community structure, type, and typical landscape environment area. Thus, the $PM_{2.5}$–O_3 concentration, as an air quality index, reached or exceeded 150 μg·m^{-3}, reaching the level of "low pollution" or even "moderate pollution." This result deserves further attention. In addition, the AQI ($PM_{2.5}$–O_3 compound pollution) is relatively low in the areas of tree-shrub-grass (TSG), multi-layer (MPC), tree-shrub (TS), tree-grass (TG), double-layer (DPC), and waterfront plant communities (WPC).

4. Discussion

4.1. Spatially divergent correlations between green space plant communities and $PM_{2.5}$

In Figure 2a, 3a, and 4a, the slow increase in $PM_{2.5}$ concentration during the three instantaneous periods of morning, noon, and afternoon. This increase in concentration may originate from the increase in dust and urban air pollutants caused by human activities, such as construction and transport operations, which are either direct or indirect sources of $PM_{2.5}$ (e.g., NOx and VOCs, precursors of $PM_{2.5}$). Changes in climatic factors in the urban area during the test time, such as a gradual increase in air temperature and decrease in relative humidity, also simultaneously lead toan increase in $PM_{2.5}$ concentrations. This result further validates some scholars' similar yet different findings, and so further research is needed (Cai et al., 2022; Xiao et al., 2022; Zhang et al., 2017; Zhao et al., 2014). In Figure 2a and 4a, $PM_{2.5}$ concentrations in the area of the tree-shrub-grass plant community (TSG) increase and then decrease. This phenomenon is significant in the context of increasing $PM_{2.5}$ concentrations. It is probably due to the more extensive leaf area index and tri-dimensional green biomass of the complex plant space of tree-shrub-grass

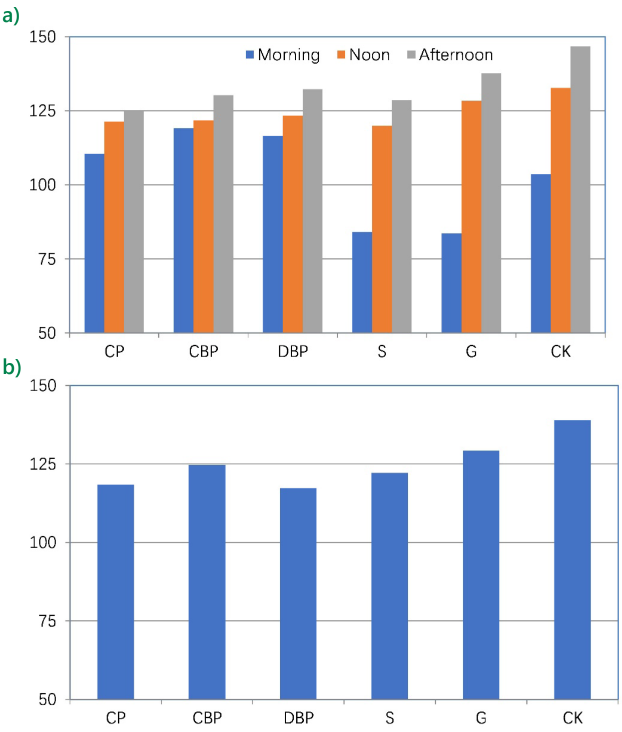

Figure 6. O_3 instantaneous values (ug·m^{-3}) and AQI in different plant community type areas

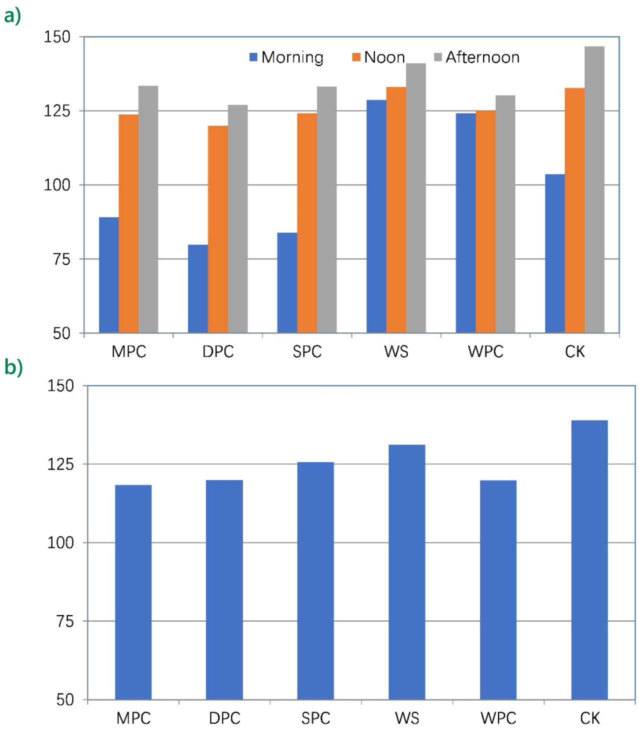

Figure 7. O_3 instantaneous values (ug·m^{-3}) and AQIin typical landscape environment areas

(TSG), which improves the urban microclimate conditions, for example, by increasing the horizontal and vertical air eddy and turbulence in the tree canopy, flushing fine particles into the canopy and further increasing the adhesion of fine particles to the plant leaf surface and facilitating plant. This may also be why the $PM_{2.5}$ of urban green space was significantly lower than at the comparison sites (Cai et al., 2022; Fan et al., 2021; Niu et al., 2022; Sheng et al., 2019; Liu et al., 2021). Figure 2b, 3b and 4b show that the double-layered plant community (DPC) structure of tree-grass (TG), tree-shrub (TS) structure and evergreen coniferous (ECP), mixed coniferous and broadleaved (CBP) and deciduous broadleaf plant communities (DBP) as well as the waterfront plant community (WPC) areas can ensure turbulence between the forests, promoting horizontal and vertical air flow with canopy cover in the upper layers and enhancing the $PM_{2.5}$ abatement effect of the tree canopy (Fan et al., 2021; Fishman & Crutzen, 1978; Jiang & Hong, 2021). The plants of evergreen coniferous (ECP) and mixed coniferous plant community (CBP) in BOFP are still small, but the $PM_{2.5}$ in these areas can be maintained within a certain concentration range, and the abatement effect of this community type deserves further attention (it is probably due to the dense branches and leaves, which are more conducive to promoting the dry deposition process of $PM_{2.5}$). A layer of cover ensures turbulence in the forest, promoting horizontal and vertical airflow and further exerting the $PM_{2.5}$ abatement effect of the tree canopy (Fan et al., 2021; Jiang & Hong, 2021).

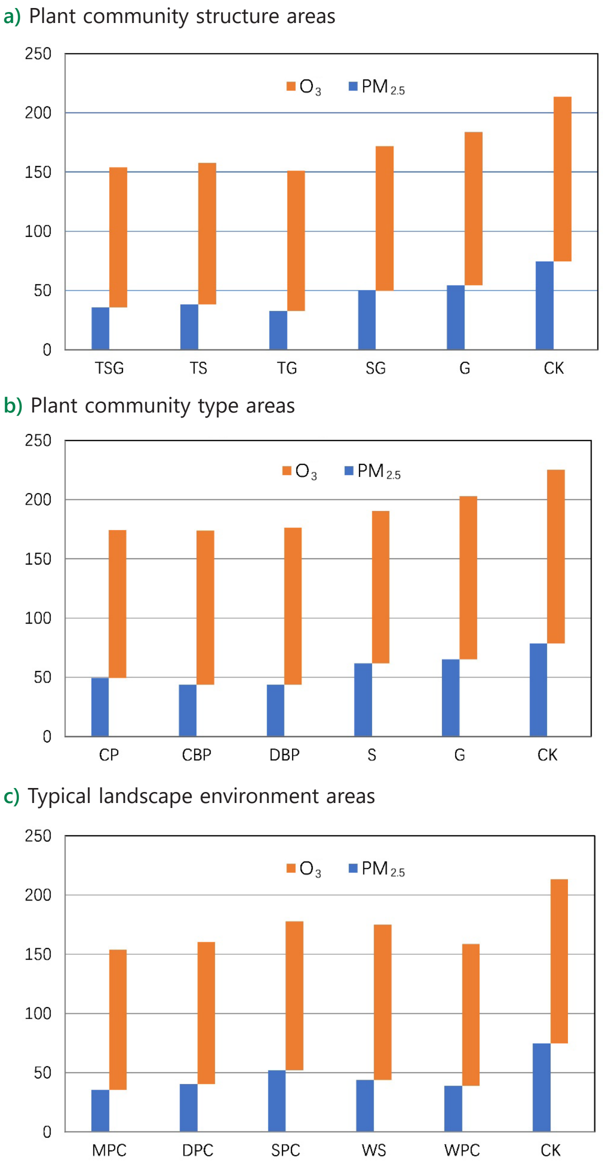

Figure 8. AQI ($PM_{2.5}$–O_3 combined concentration)

4.2. Spatially divergent correlations between green space plant communities and O_3

In Figure 5a, 6a, and 7a, O_3 concentrations increased in the Morning, Noon, and Afternoon instantaneous for different plant community structures, types, and typical landscape environments. This increase was probably due to the gradual increase in solar radiation and the increased concentration of O_3 precursor compounds (NOx and VOCs), which favoured the production of higher O_3 concentrations. O_3 starting concentrations were low in all three periods. However, the increase in concentration was greater from morning to noon, while the increase tapered off from noon to afternoon. In the first period, O_3 concentrations increased rapidly because the intensity of solar radiation increased rapidly to the highest value (O_3-producing conditions), and O_3 precursor concentrations also reached a particularly high value (O_3-producing feedstock). In the second period, O_3 concentrations increased to the highest value on the measurement day. Hence, the increase in concentration slowed. In Figure 5b, 6b, and 7b, there is no significant difference in air quality between the different structures, types of plant communities, and landscape environments (all reach the level of "low pollution"), probably because the green field plant communities themselves produce some amount of O_2 through photosynthesis, but have no abatement on O_3. In Figure 7a, the morning O_3 concentrations in the typical waterfront environment (WS, WPC) were higher than those in the typical plant community area and even higher than those in the comparison sample sites, probably because this environment is more favourable to O_3 production due to the intense light in the morning (side shading only) (Fan et al., 2021). This result can be investigated in future studies (Cai et al., 2022; Qi et al., 2017).

4.3. Spatially divergent correlations between green space plant communities and $PM_{2.5}$–O_3 compound pollution

As shown in Figure 8a to 8c, the spatial variation of $PM_{2.5}$ concentrations was significant for different plant community structures, types, and typical landscape environments in the urban green spaces. However, O_3concentrations did not show significant spatial variation and were high (all above 100 $\mu g \cdot m^{-3}$). Based on the results above, the air quality was assessed as "moderate pollution" because of the high contribution of O_3 to the $PM_{2.5}$–O_3 compound pollution (over 70%). Most researchers now believe that $PM_{2.5}$ pollution and O_3 pollution are similar and homogenous (Fan et al., 2021; Gao et al., 2020). Air movement (wind) is considered the most effective mechanism for abatement both, followed by factors such as green vegetation. However, it can be inferred from the results of this study that green vegetation areas can abate $PM_{2.5}$ to varying degrees, but no significant abatement of O_3 was observed. Some scholars therefore believe that regional coordination, joint prevention, and control mechanisms should be adopted for $PM_{2.5}$–O_3 compound pollution. The control and reduction of $PM_{2.5}$ and O_3 precursors (industrial processes and fossil energy-using urban traffic) and the creation of mechanisms for the abatement and rapid dispersion of $PM_{2.5}$–O_3 pollution (improvement and optimization of the neighbourhood wind environment and the formation of "Urban Wind Corridors" in general planning) are central to this joint prevention and control strategy (Li et al., 2022; Dai et al., 2020; Feng et al., 2021; Wang et al., 2021; Xiao et al., 2022).

5. Conclusions

This study aimed to provide a scientific basis for the renewal and optimization of urban green spaces. The results allow us to draw the following conclusions:

- The $PM_{2.5}$ concentrations are low in the areas of evergreen coniferous trees (ECP) and/or deciduous broadleaved trees (DBP) are the dominant species of tree-shrub-grass (TSG) and tree-shrub (TS).
- The O_3 concentration of all the plant community areas reaching the level of "low pollution".
- The AQI with $PM_{2.5}$–O_3 value of compound concentration as the main parameter reaches the level of "moderate pollution", and the result that deserves further attention.

The findings may not be universal, however, due to the study's significant spatial and temporal heterogeneity. In particular, given the openness and complex system of urban green spaces, we modelled the spatial composition of green space plant communities but may have overlooked or ignored the heterogeneous information that has an impact on the results. Furthermore, three instantaneous concentration measurements from the morning, noon, and afternoon were used as the daily average concentrations, whereas the data underlying the air-quality evaluation were taken at 08:00. The data were automatically recorded at 10 min intervals for 10 consecutive hours from 08:00 to 18:00, and there may be some differences in accuracy between the two. The conclusions are therefore tentative and should be subject to more reviews and test.

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Author contributions

Jianbin Pan: conceptualization, methodology, software, validation, formal analysis, resources, data curation, visualization, supervision, project administration, funding acquisition; Shuyu Chen: methodology, software, validation, investigation, resources, data curation, writing-original draft preparation, writing-review and editing, visualization, funding acquisition; Nuo Xu: validation, formal analysis, data curation, writing-original draft preparation, writing-review and editing; Meijing Cheng: investigation; Xian Wang: investigation; Jingwen Lan: investigation; Rui Wang: data curation; Yajie Wang: data curation. All authors have read and agreed to the published version of the manuscript.

Disclosure statement

The authors declare no conflict of interest.

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