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Impact of Urban Forest and Park on Air Quality and the Microclimate in Jinan, Northern China

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Abstract: Though the impact of urban vegetation on air quality and the microclimate has attracted increasing attention, there have been few studies quantitatively assessing this impact in North China, where air pollution is severe. In this study, we investigated the impact of urban forests and urban parks on air quality and the microclimate in Jinan, northern China. Six sites were chosen to represent urban forest, urban park, and downtown areas, respectively. The results indicate that urban forest can effectively reduce $PM_{2.5}$ and ozone (O_3) concentrations in the warm season, when temperatures are higher and plants are lush. The $PM_{2.5}$ and O_3 concentrations in the urban forest areas were 6.3–6.5 μg m^{-3} and 21–23 μg m^{-3} lower than those in downtown areas during the period of 10:00–15:00. In contrast, urban park areas can reduce $PM_{2.5}$ concentrations but have little impact on gaseous pollutants such as nitrogen dioxide and O_3. Furthermore, both urban forest and urban park areas reduced temperatures, by approximately 4.1–6.8 °C and 1.36 °C, respectively, and increased relative humidity, by about 13.4–12.9% and 0.9%, promoting a more comfortable thermal environment for residents. Therefore, this study highlights the crucial role of urban vegetation in improving air quality and creating a comfortable environment for residents.

Keywords: urban forest; urban park; air quality; microclimate; human comfort index

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1. Introduction

To achieve carbon neutrality and improve air quality, the Chinese government has implemented extensive afforestation and greening projects, leading to the expansion of urban forests and urban parks in recent decades. These green spaces are essential green infrastructures in cities, playing critical roles in purifying the air, mitigating urban heat islands (UHIs), providing spaces for recreational activities, and improving human comfort [1–5]. Now, in order to better assist residents in healthy recreational and fitness activities in these green spaces, it is necessary to evaluate the impact of urban forests and urban parks on air quality and the microclimate.

China has faced severe air pollution problems in recent years, with particulate matter (PM) and ozone (O_3) being the primary air pollutants in cities, posing significant threats to human health and ecosystems [6,7]. $PM_{2.5}$ and O_3 have been found to damage the respiratory and cardiovascular systems, increasing the risk of diseases and mortality [8,9]. In response to the escalating air pollution problem, the Chinese government issued the Action Plan on Air Pollution Prevention and Control in 2013, resulting in some improvement in $PM_{2.5}$ concentrations. However, the threat to human health still persists, and surface O_3 pollution has become a serious issue in Chinese cities [10,11].

Previous studies have focused on the impact of urban trees on air quality improvement. Some studies have reported that trees in park or forest areas can remove PM from the atmosphere through dry deposition and interception by the leaves [12–14]. These particles are trapped by the plant surface and eventually deposited on the ground through dry and wet deposition [15,16]. In addition, the concentrations of O_3 in urban forest and urban park areas are influenced by various other factors. On the one hand, urban trees can remove O_3 through processes like canopy stomatal uptake and non-stomatal deposition [17–21], and cooling and humidifying effects can also reduce the photochemical production of O_3 [22]. On the other hand, urban trees can emit biogenic volatile organic compounds (BVOCs) such as isoprene and terpenes, which are important precursors for O_3, potentially leading to the enhancement of O_3 levels [23,24]. In addition, as an important precursor of O_3, the distribution of NO*x* in urban centers is much higher than that in forest areas around cities, resulting in a shift of the formation regime of O_3 from the VOC-limited regime in urban centers to a transitional regime in urban forest areas [22]. Studies have shown varying results regarding whether urban vegetation ultimately increases or decreases O_3 concentrations [25–29]. Fares et al. [25] estimated a total annual removal of 8.4 and 8 kg per hectare for PM_{10} in two urban parks in Rome and Turin, Italy, and the trees in the two urban parks were found to remove 8.1 and 1.42 kg O_3 per hectare. Sicard et al. [26], meanwhile, found that urban trees reduced the O_3 in 2010 by 5.4 g m^{-2} yr^{-1} in 55 US cities and 3.7 g m^{-2} yr^{-1} in 86 Canadian cities. In contrast, Duan et al. [27] found that O_3 concentrations in urban forest areas were higher than those in the urban center, which is in agreement with the findings of Yli-Pelkonen et al. [28] and Grundstrom and Pleijel [29]. Thus, more research is needed to understand whether urban vegetation ultimately increases or decreases O_3 concentrations.

Previous studies on the impact of urban vegetation on $PM_{2.5}$ and O_3 have mainly focused on the removal capacity of vegetation, with few studies investigating the concentration differences inside and outside of urban forests or parks, which is not conducive to guiding residents to carry out leisure activities [22,27]. In addition, most studies in China have focused on megacities such as Beijing, Shanghai, and Shenzhen [27,30,31], while cities in the heavily polluted North China Plain region have not received sufficient attention. As such, we cannot yet quantify the impact of trees in urban forest and urban park areas on air quality and the microclimate for these cities. Jinan is a large city in North China and its vegetation type and forest distribution are representative of the vegetation characteristics of most cities in the central North China Plain. Accordingly, research on Jinan can provide theoretical support for the air pollution control of heavily polluted cities in the center of the North China Plain. Therefore, an accurate assessment of the impact of urban forests and urban parks on $PM_{2.5}$ and O_3 in Jinan is indeed crucial. This will not only improve awareness about the role of urban green spaces in improving air quality but also help mitigate the risks posed by air pollutants to the health of residents.

Furthermore, urban forests and parks have a cooling effect, which helps alleviate the UHI effect and provides residents with comfortable recreational spaces [32–34]. The cooling effect of urban trees is primarily due to evapotranspiration and shading [35]. Through transpiration, urban vegetation evaporates water while consuming solar energy, resulting in temperature reduction and increased relative humidity (RH) [36–38]. Trees also intercept solar radiation and provide shade through their leaves and branches, thereby cooling the air beneath them. Extensive research has been conducted on mitigating the UHI effect through the cooling effects of urban parks and forests [39,40]. Schwaab et al. [38] used satellite land surface temperature (LST) and land cover data from 293 European cities to evaluate the capacities of urban trees to reduce LST. The results showed that urban trees in Southern European and Central European regions can reduce LST by 0–4 K and 8–12 K compared to continuous urban areas. In addition, Zhou et al. [41] selected 276 cities in China with which to evaluate the cooling effects of urban parks, and they found that the park landscape played a dominant role in the cooling effects of parks, with its input greater than those of the surrounding conditions of parks and the local climate. Several studies have also evaluated the cooling and humidifying effects of urban forests and urban parks using direct observational data. Previous studies have shown that clusters of trees can reduced summer temperature by 0.2–3 °C, and they increased RH by 0.2–8% in Beijing [42,43]. However, we found no study using continuously observed surface meteorological parameters to evaluate the cooling and humidifying effects of urban forests and parks in Jinan, nor their influence on human comfort. This has severely hindered the understanding of urban green spaces to date.

Therefore, it is critical to enhance the understanding of the influence of urban forests and urban parks on urban air quality and the microclimate, as well as to help residents engage in more healthful and comfortable recreational activities. In this study, we conducted an analysis using continuous measurement data on air quality and the microclimate in urban, urban forest, and urban park areas in Jinan during May to October 2023. The objective of this study was to investigate the impact of urban forest and urban park areas on $PM_{2.5}$ and O_3 levels, as well as to explore the factors contributing to the dynamic changes in air pollutants. Additionally, we aimed to examine the variations in the microclimate and comfort in urban forests and parks and provide scientific guidance on the leisure activities of residents.

2. Materials and Methods

2.1. Study Area

The study area is located in Jinan, a large city in northern China. Jinan has a substantial population, of over 8.0 million as of 2022, and encompasses an area of 10,244 km^2. The area of forest land accounts for 23.6% of the total area, i.e., 242,315 ha. Furthermore, the coverage of green spaces in the built-up area has reached 41.9% [44]. As Jinan is in a semi-humid continental monsoon climate zone, its average annual temperature is 13.5–15.5 °C, and the average annual precipitation is 600–900 mm.

The urban forest study area is in the southern mountainous area in Jinan, encompassing a total area of 571.39 km^2 [44]. The southern mountainous area is a nature reserve of urban forests, characterized by extensive natural woodland and sparse woodland. The southern mountain area holds great importance as a recreational destination for residents of Jinan and the surrounding cities. It is worth noting that, apart from minimal tourism and residential activities, there are no significant sources of pollution emissions within this region. This characteristic makes it an ideal location in which to assess the impact of urban forests on air quality and the microclimate, as it allows for the isolation of natural influences on these factors without significant confounding inputs from anthropogenic pollution sources.

The urban park study area is focused on Jinan Forest Park, situated in Huaiyin district. The park spans a total area of 69.5 ha, with approximately 60.1 ha dedicated to green spaces (https://english.jinan.gov.cn/, accessed on 31 January 2024). Jinan Forest Park is characterized by its abundance of wetlands and trees, which serve as vital contributors to improving air quality, conserving water, and providing a habitat for various forms of biodiversity. It also serves as a recreational spot for the residents of Jinan, offering a serene and picturesque environment for relaxation and leisure activities.

2.2. Observation Sites

The locations of observation sites are depicted in Figure 1. Three air quality monitoring stations were chosen to represent urban forest sites at different altitudes in the southern mountainous area in Jinan. The Paomaling station (PML: 117.22° E, 36.43° N, 768 m a.s.l.) is located in the Paomaling scenic area, approximately 27 km away from the city center. It serves as a background site in Jinan region. The Xiying station (XY: 117.23° E, 36.51° N, 318 m a.s.l.) is located at the Xiying sub-district office, 25 km away from the city center. Similarly, the Liubu station (LB: 117.12° E, 36.45° N, 196 m a.s.l.) is located at the Liubu sub-district office, 26 km away from the city center. Both the XY and LB sites are situated in a mountain valley, where the air quality is predominantly influenced by mountain and valley breezes. These three stations, PML, XY, and LB, provide air quality data representing different altitudes within the urban forest area. As for the urban site, the Jinan Environmental Monitoring Center station (JN: 117.15° E, 36.66° N, 35 m a.s.l.) was selected. It is located in the bustling downtown area of Jinan, with nearby commercial areas, residential areas, and arterial area roads.

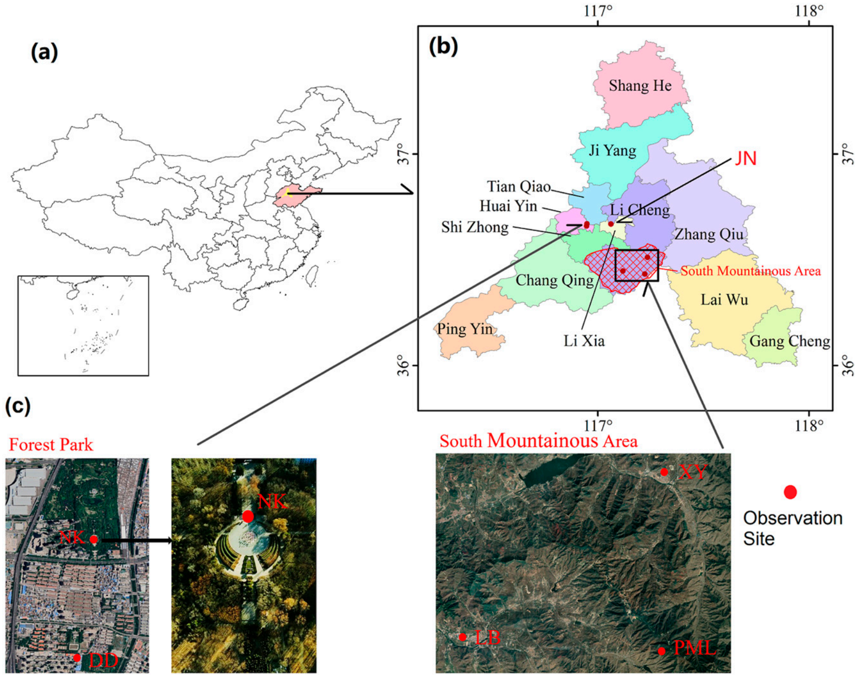

Figure 1. Map of China and Shandong Province (pink area), with yellow area representing the city of Jinan (**a**). Distributions of six observation sites within Jinan (**b**). Map of Jinan Forest Park and South Mountainous Area. JN: Jinan Environmental Monitoring Center Station; NK: Nongkesuo station; DD: Duandian station; XY: Xiying station; LB: Liubu Station; PML: Paomaling Station. The position and topography of observation sites (**c**).

To investigate the impact of urban parks on air quality and the microclimate, two air quality monitoring stations were chosen to represent the urban park sites. The Nongkesuo (NK) station is situated within the Jinan Forest Park, while the Duandian (DD) station is situated approximately 1 km south of the park, proving a comparison point just outside the park boundaries. By choosing these two stations in close proximity to the park, the study aimed to assess the impact of the park vegetation on air quality and the microclimate.

2.3. Observation Data

Hourly average concentrations of O_3, NO_2, $PM_{2.5}$, and micrometeorological parameters (temperature, relative humidity (RH), wind speed) were obtained from the Jinan Ecological and Environmental Bureau (http://jnepb.jinan.gov.cn/; accessed on 20 November 2023). Considering that deciduous broad-leaved trees are the main tree species in the urban forests and parks of Jinan, a time period in the warm season with relatively more leaves was selected for this study. However, there is relatively more precipitation in the warm season. Therefore, to scientifically assess the impact of urban trees on air quality, the data during rainfall were excluded from this study. As a result, all data were collected from 24 May 2023 to 10 October 2023. The monthly mean values of air pollutants and micrometeorological parameters were averaged each month. The values for May and October were only collected for late May (24–31 May) and early October (1–10 October). For O_3, the maximum daily 8 h average ozone (MDA8 O_3) was used to analyze the O_3 levels. The diurnal variations were averaged from hourly data over the time period analyzed. The data used in this study are real-time monitoring data and have not been verified by the

Jinan Ecological and Environment Bureau. To ensure data quality, data quality control was applied to remove unreliable outliers, following the approach taken in previous studies, using the z-score method. This method allows for the identification and removal of data points that deviate significantly from the average, helping to ensure the accuracy and reliability of the dataset used for further analysis [45]. This method has been extensively applied to the data quality control of air quality monitoring stations in China [46,47].

2.4. Human Comfort Index

Urban vegetated spaces have been found to enhance thermal comfort by reducing air temperature and increasing humidity during the summer season [48]. Thus, we analyzed the thermal comfort of each observation site in urban forest and park areas based on the human comfort index (CI) recommended by the Beijing Meteorological Bureau [42,49]. As shown in Equation (1), a CI between 50 and 55 is the most comfortable, with larger or smaller values being more uncomfortable. When the CI value falls between 55 and 70, it is considered within the comfortable range. In this range, the human body is expected to feel comfortable in the given conditions. Meanwhile, if the CI value increases to 70–80, it indicates that the human body will start feeling heat. If the CI value increases to larger than 85, the human body will feel unbearable heat and extremely uncomfortable. This range suggests that the environment has become excessively hot for comfort. This empirical model for thermal comfort prediction has been established since 1997, with air temperature, relative humidity, and wind speed as the input variables. Thus, the difference in CI between urban park or urban forest sites and urban sites represent the improved thermal comfort through vegetation cooling and humidifying effects.

$$\mathrm{CI_i} = 1.8 \times \mathrm{T_i} + 0.0055 \times (100 - \mathrm{RH_i}) - 3.2 \times \sqrt{\mathrm{W_i}} + 32 \tag{1}$$

where i is the ith observation site, and $\mathrm{T_i}$, $\mathrm{RH_i}$, $\mathrm{W_i}$, and $\mathrm{CI_i}$ are the air temperature (°C), relative humidity (%), wind speed (m/s), and human comfort index of the observation site, respectively.

3. Results and Discussion

3.1. Effects of Urban Forest on Air Quality

3.1.1. Monthly Variations

To examine the effects of urban forests on air quality in Jinan, we compared the concentrations of air pollutants between the urban center and urban forest sites. Table 1 and Figure 2 display the observed concentrations of $PM_{2.5}$, O_3, and NO_2 at urban, valley, and ridge sites. At the urban site, the average concentration of $PM_{2.5}$ was 21.4 ± 7.6 μg m^{-3} (mean ± standard deviation), which was higher than those at valley sites (20.7 ± 6.8 μg m^{-3} at XY; 16.6 ± 6.5 μg m^{-3} at LB) and the ridge site (14.5 ± 7.3 μg m^{-3} at PML). The $PM_{2.5}$ values for the four sites did not exceed the national ambient air quality standard (NAAQS) Grade II (GB3095-2012) threshold of 35 μg m^{-3} for $PM_{2.5}$. The higher $PM_{2.5}$ concentration at the XY site indicates that it is more influenced by human activities compared to the LB site, but it is still lower than the $PM_{2.5}$ concentration at the urban site. In addition, the mean $PM_{2.5}$ value at PML was 6.9 μg m^{-3} lower than that at the urban site. Therefore, it seems that urban forests can effectively reduce the concentration of $PM_{2.5}$ in Jinan, which is consistent with the results of previous studies [12,50,51]. The average RH value at the three urban forest sites was 65.3 ± 12.3%, which was higher than that of the urban site (50.0 ± 10.5%). In contrast, the average temperature at the three urban forest sites was 23.2 ± 4.1 °C, which was lower than that of the urban site (28.6 ± 4.4 °C). The cooling and humidifying effects of forest trees contribute to the enhanced removal ability of $PM_{2.5}$. The average wind speed at the PML site was 2.78 ± 1.07 m s^{-1}, which was much higher than at the valley sites (0.93 ± 0.13 m s^{-1} for XY site and 1.58 ± 0.47 m s^{-1} for LB site) and urban site (1.06 ± 0.33). The lower $PM_{2.5}$ level in the forest area was mainly due to lower precursor emissions and the higher removal of $PM_{2.5}$ by vegetation. However, the

$PM_{2.5}$ values in the urban forest area were significantly greater than the $PM_{2.5}$ standard (10 μg m^{-3}) recommended by the World Health Organization (WHO), indicating further efforts are needed to reduce $PM_{2.5}$ levels in the Jinan forest to improve human health.

Table 1. The average concentrations (mean ± standard deviation; unit: μg m^{-3}) of $PM_{2.5}$, MDA8 O_3, NO_2, and the micrometeorological parameters (temperature (T): °C; relative humidity (RH): %; wind speed (WS): m s^{-1}).

Site	Type	$PM_{2.5}$	MDA8 O_3	NO_2	T	RH	WS
JN	Urban	21.4 ± 7.6	179 ± 40	29.5 ± 13.4	28.6 ± 4.4	50.0 ± 10.5	1.06 ± 0.33
XY	Valley forest	20.7 ± 6.8	157 ± 33	10 ± 2.9	23.6 ± 4.2	66.2 ± 10.8	0.93 ± 0.13
LB	Valley forest	16.6 ± 6.5	160 ± 34	9.3 ± 3.3	24.1 ± 4.2	64.8 ± 11.4	1.58 ± 0.47
PML	Ridge forest	14.5 ± 7.3	174 ± 31	7.2 ± 2.9	21.8 ± 4.0	65.0 ± 14.5	2.78 ± 1.07
NK	Inside park	18.3 ± 7.3	166 ± 41	27.1 ± 9.9	26.4 ± 4.4	55.1 ± 10.1	0.54 ± 0.20
DD	Outside park	27.6 ± 6.6	166 ± 40	27.7 ± 10.7	27.9 ± 4.6	54.2 ± 10.2	0.81 ± 0.25

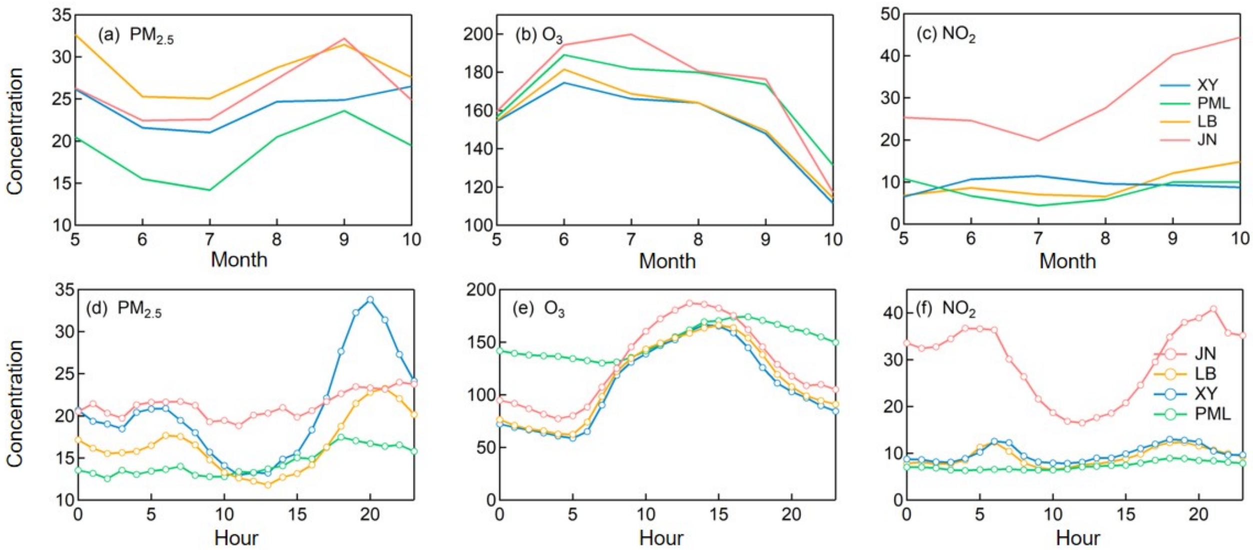

Figure 2. Monthly (**a**–**c**) and diurnal (**d**–**f**) variations in $PM_{2.5}$, O_3, and NO_2 (μg m^{-3}) concentrations at three urban forest sites and one urban site. The monthly mean values for May and October were only collected for late May (24–31 May) and early October (1–10 October). The three urban forest sites are Paomaling (PML), Libu (LB), and Xiying (XY), and the urban site is the Jinan Environment Monitoring site (JN).

Different from the distributions of $PM_{2.5}$, the O_3 concentration at the ridge site was significantly higher than that in the valleys. The mean values of MDA8 O_3 were 174 ± 31 μg m^{-3} at the PML site, 157 ± 33 μg m^{-3} at the XY site, and 160 ± 34 μg m^{-3} at the LB site. Previous studies have also reported higher O_3 levels at ridge sites [52], and the O_3 concentrations increased with altitude from the valley bottom to the summit [53,54]. This can be attributed to the transport of highly concentrated O_3 air masses and their precursors from an urban area to the ridge. In addition, the BVOCs and O_3 from the valleys are transported to the ridge with valley wind during the daytime, resulting in the accumulation of O_3 [55]. Furthermore, the forest canopy cover area was much lower than that in the valley forests, allowing more solar radiation to enter and enhancing the photochemical production rate of O_3. However, despite these factors, the O_3 concentration at PML site was still lower than that at the urban site, especially in July, when the photochemical reaction is strong. During this period, the concentrations of MDA8 O_3 at the JN site and PML site reached approximately 200 μg m^{-3} and 181 μg m^{-3}, respectively. The results of this study are inconsistent with those of Duan et al. [27], who found that the summer MDA8 O_3

concentration at a ridge site in Shenzhen was 86 μg m^{-3}, significantly higher than that in the urban park (51 μg m^{-3}). The discrepancy can be attributed to the large anthropogenic VOCs emissions in the North China Plain, where Jinan is located, while BVOC emissions are relatively small compared to Shenzhen [56,57]. On the one hand, previous studies have proved that Jinan's urban areas emit a large amount of anthropogenic VOCs. In contrast, there are almost no large anthropogenic VOC emission sources in its urban forest areas. In recent years, the large amount of anthropogenic VOC emissions in the North China Plain have led to serious O_3 pollution. VOC emissions from anthropogenic sources in the North China Plain are much higher than those in Shenzhen. On the other hand, forest resources are more abundant in Shenzhen than in Jinan, and its BVOC emissions are higher. Therefore, the O_3 concentration in the urban area of Jinan is higher than that in the urban forest area outside. In Shenzhen, due to the high emissions of BVOCs from urban forests, the O_3 concentration of urban forests is higher than that of the urban center [56,57]. Therefore, the increase in O_3 concentration caused by BVOC emissions in the Jinan urban forest area was not sufficient to exceed the O_3 level observed in the urban area.

The concentration of MDA8 O_3 at the urban site was consistently higher than those at the valley sites, with an average difference of 34 μg m^{-3} and 31 μg m^{-3} higher than the XY and LB sites, respectively, in July. Furthermore, the temperature in the valleys was significantly lower than that in the urban area, while the RH was higher in the valleys compared to the urban area. The cooling and humidifying effects of the forest not only weakened the photochemical reaction but also enhanced the removal capacity of O_3. Furthermore, the average NO_2 concentrations were 29.5 ± 13.4 μg m^{-3}, 10 ± 2.9 μg m^{-3}, 9.3 ± 3.3 μg m^{-3}, and 7.2 ± 2.9 μg m^{-3} at the JN, XY, LB, and PML sites. The decrease in NO_2 concentration from the urban center to the forest parks led to a shift in the O_3 formation mechanism from being VOC-limited to a transitional regime. The significant reduction in NO_2 levels also inhibited the photochemical production of O_3 [58]. Therefore, the combination of reduced precursor emissions and a stronger O_3 removal capacity led to significantly lower O_3 concentrations in urban forest valleys compared to urban centers. We further evaluated the correlations between micrometeorological parameters and air pollutants through Pearson's correlation analysis. The O_3 concentration had a significant positive correlation with the temperature at urban and valley sites. The Pearson correlation coefficients (r) between temperature and O_3 were 0.76, 0.78, and 0.79 at the JN, XY, and LB sites, but the r value was only 0.47 at the PML site. In addition, the RH had a significant negative correlation with O_3, with r values of −0.61, −0.76, and 0.77 at the JN, XY, and LB sites, but the r decreased to 0.20 at the PML site. This indicates O_3 at PML was not dominated by photochemical reactions.

In summary, O_3 pollution in Jinan was severe, especially in summer, with the monthly average MDA8 O_3 concentration exceeding the NAAQS Grade II limit (160 μg m^{-3}) in both the urban center and urban forest areas. However, the urban forests can effectively reduce regional O_3 concentrations in summer, when the temperature is higher and vegetation is relatively lush. The cooling and humidifying effects of the forest, along with the reduction in precursor emissions and enhanced O_3 removal capacity, contribute to the mitigation of O_3 pollution in urban forest areas. In terms of spatial distributions, the $PM_{2.5}$ levels at the ridge site were lower than those in the valley areas, and both were lower than those in urban area. In contrast, the concentrations of MDA8 O_3 at the ridge site were generally higher than those at the valley sites but lower than those in the urban area in Jinan.

3.1.2. Diurnal Variation

To further evaluate the impact of urban forests on $PM_{2.5}$ and O_3, we analyzed the diurnal variation in pollutants during the observation period. As shown in Figure 2, the diurnal variations in $PM_{2.5}$ exhibited distinct patterns among the four sites. At the XY and LB sites, two daily peaks of $PM_{2.5}$ were observed in the morning (5:00–7:00) and evening (20:00). Due to the low boundary layer at night and the unique topography of the valleys, the diffusion of $PM_{2.5}$ is hindered at these sites. As a major pollutant emitted by motor vehicles, the concentration of NO_2 peaked gently at the XY and LB sites during the morning (6:00–7:00) and evening (18:00–19:00). The concentrations of the two peaks were much lower than those observed in the urban area, suggesting that motor vehicle exhaust emissions in the valleys have a minimal contribution to NO_2 levels. Thus, the rapid increase in nighttime $PM_{2.5}$ concentration should be attributed to the combined effects of motor vehicles, human activities, and temperature inversion. Furthermore, the average concentrations of $PM_{2.5}$ between 10:00 and 15:00 were 13.8 ± 0.9 μg m^{-3} for the XY site, 12.8 ± 0.5 μg m^{-3} for the LB site, and 13.5 ± 0.8 μg m^{-3} for the PML site, all of which were lower than that observed at the JN site (19.8 ± 0.6 μg m^{-3}). This indicates that urban forests can effectively reduce $PM_{2.5}$ concentrations when the light is intense, and the air conversion is obvious during daytime. The reductions in $PM_{2.5}$ concentrations amounted to approximately 6.5 μg m^{-3} and 6.3 μg m^{-3} for the valley and ridge sites, respectively. Therefore, visiting urban forests for tourism activities during this period can provide a favorable environment with lower $PM_{2.5}$ levels.

In contrast to the diurnal variation in $PM_{2.5}$, the levels of O_3 started to increase after 4:00, with a concentration of 76 μg m^{-3}, and reached their maximum (188 μg m^{-3}) in the afternoon (13:00–14:00) at the urban site. The diurnal variations in O_3 concentrations at the valley sites exhibited a typical shape similar to that observed at the urban sites in Jinan. The O_3 concentration began to rise from 5:00, reached its peak between 14:00 and 15:00, and gradually decreased until the early morning of the next day. The diurnal variations are generally due to precursor emissions and microclimate parameters, i.e., temperature and RH. Higher temperatures, more intense sunlight, and lower RH promote the photochemical production of O_3. Therefore, the O_3 concentrations increased with the enhancement of temperature and sunlight. Although the amplitude of O_3 concentration increase in the valleys was similar to that observed in the urban area, the underlying reasons were quite different. In the urban area, with high nitrogen oxide (NOx) emissions, the O_3 formation regime tends to be controlled by VOCs. However, in urban forests, the lower concentration of NOx and the higher emissions of BVOCs lead to the O_3 formation regime being controlled by NOx. Therefore, even a small decrease in NO_2 concentration during the daytime in the valleys can result in a sharp increase in O_3 concentration [22].

The O_3 levels between 0:00 and 5:00 (135–142 μg m^{-3}) at the PML site were clearly higher compared to those in the urban and valley sites, and the peak O_3 concentration occurred at 16:00, which was 2–3 h later than the peak at the urban center. These findings are similar to the observations at other mountain sites in the North China Plain [52]. Due to the drop of the boundary layer at night, nitrogen oxide (NO) in the valleys cannot be transported to the mountain ridge. Therefore, during the nighttime, when photochemical production of O_3 does not occur, the O_3 can be directly removed by a NO titration reaction. However, compared to the urban areas, the lower concentrations of NO at PML are not sufficient to react with the high concentrations of O_3, which could restrict the reduction of O_3 during the nighttime. In addition, dry deposition and stomatal absorption by trees can also lead to the loss of O_3. However, the role of these pathways is limited according to previous studies [59,60]. Thus, these pathways did not lead to significant reductions in O_3 concentrations. The PML site exhibited the lowest amplitude of diurnal variation in O_3 concentration (44.6 μg m^{-3}), which was much lower than that observed at the urban (111.6 μg m^{-3}) and valley sites (106.4 μg m^{-3} for LB; 110.1 μg m^{-3} for XY). In addition, the temperature at PML was lower than those at the urban and valley sites, but the RH and wind speed were much higher than at those sites. Therefore, the low diurnal variation suggests that O_3 at the PML site is more susceptible to transport by air masses containing O_3 and its precursors from urban and valley areas, rather than being predominantly influenced by local photochemical processes. In addition, during the period of 10:00-15:00, the O_3 concentrations at the valley (155 ± 9.6 μg m^{-3}) and ridge sites (158 ± 11.9 μg m^{-3}) were lower than that at the urban site (179 ± 10.2 μg m^{-3}).

Therefore, although O_3 pollution was relatively severe in the urban center and urban forest areas, the urban forests effectively reduced the O_3 concentrations by about 23 μg m^{-3}

and 21 μg m^{-3} in the valley and ridge areas, respectively, during the period when a large number of tourists travelled to the southern mountainous area.

3.2. Effects of Urban Parks on Air Quality

The impact of urban parks on air quality was investigated by monitoring air pollutants and micrometeorological parameters inside and outside of Jinan Forest Park. The NK site, located inside the park, and the DD site, located outside the park, were selected for comparison. As shown in Table 1 and Figure 3, the average concentrations of $PM_{2.5}$ at the NK site (inside) and the DD site (outside) were 18.3 ± 7.3 μg m^{-3} and 27.6 ± 6.6 μg m^{-3}, respectively, indicating that the urban park effectively reduced $PM_{2.5}$ concentrations. This result is consistent with previous research in many cities [25,61,62]. Since the monitoring site was not obstructed by the tree canopy, there were no significant difference in temperature or relative humidity observed between the inside and outside of the park. However, deep in the park, the transpiration and respiration of trees, as well as the canopy shielding effect of the tree canopy, enhanced the cooling and humidifying abilities, which can effectively reduce $PM_{2.5}$ levels. In addition, the wind speed inside the park was lower than that outside the park, indicating that the trees acted as a barrier, preventing the entry of external particulates. The lower wind speed also facilitated the dry deposition of particulates. In contrast, the effect of the urban park on the concentrations of gaseous pollutants was weak, and there was little difference in NO_2 and O_3 levels between the inside and outside of the park, which is in agreement with previous studies [63]. Compared to the results of the urban forest impact found before, the differences in $PM_{2.5}$ inside and outside of urban parks revealed a smaller improvement. Therefore, the improvement in urban air quality in urban parks was mainly reflected in the reduction in particulate matter concentration, and there was little impact on gaseous pollutants such as O_3.

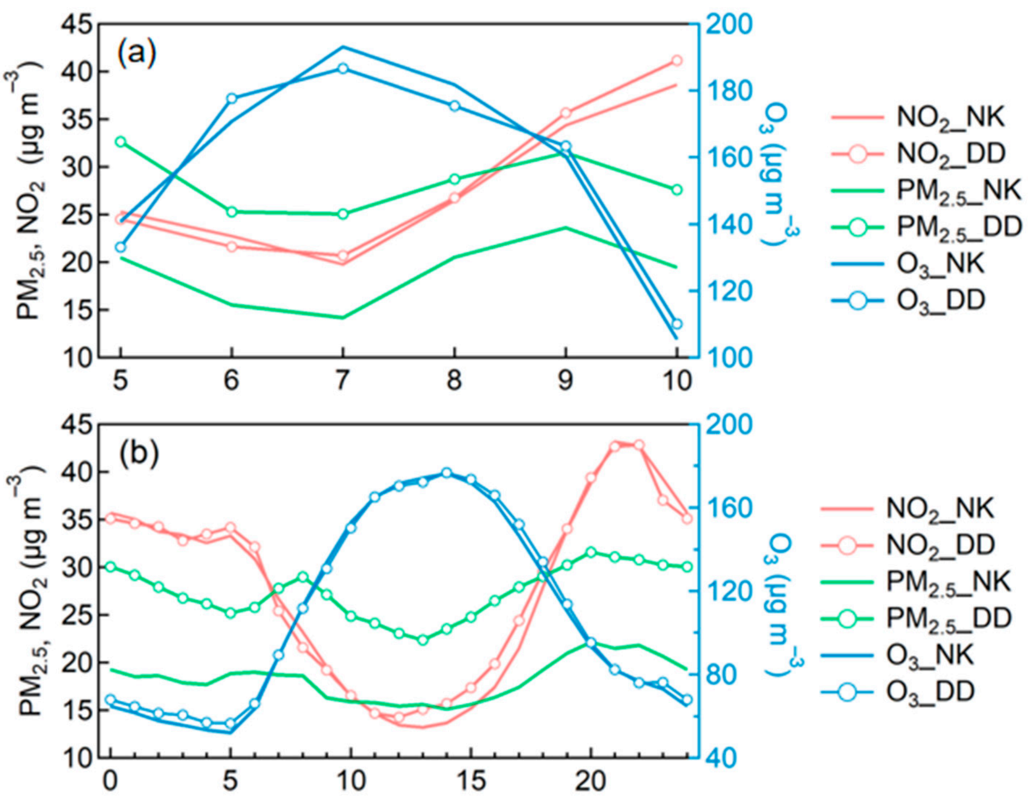

Figure 3. Monthly (**a**) and diurnal (**b**) variations in $PM_{2.5}$, O_3, and NO_2 inside and outside of Jinan Forest Park. The NK site and DD site are located inside and outside the park.

The diurnal variations in air pollutant concentrations inside and outside of urban park are shown in Figure 3. Two peaks of NO_2 were observed at the DD site, occurring around 5:00 and 21:00–22:00, with concentrations of approximately 34.2 μg m^{-3} and 42.7 μg m^{-3}, respectively. The significant increase in NO_2 levels in the morning was primarily attributed to the conversion of NO to NO_2 during the morning rush hour, as well as the accumulation of NO_2 resulting from weak photochemical reactions. Following sunrise, the concentration of NO_2 decreased rapidly, and the O_3 levels started to rise. The strong traffic flow and human activities during morning rush hour contributed to an increase in $PM_{2.5}$ concentration from 5:00 until the first peak at 8:00, reaching 29.0 μg m^{-3}. The NO_2 concentration reached its lowest level at noon, when solar radiation is strongest. After that, the lowest concentrations of $PM_{2.5}$ were observed at 13:00 (22.3 μg m^{-3}), and the maximum levels of O_3 appeared at 14:00 (177 μg m^{-3}). Subsequently, with the decrease in solar radiation and temperature and the increase in RH, the concentrations of NO_2 and $PM_{2.5}$ began to increase, while the O_3 concentration started to decline. The evening rush hour in downtown Jinan typically occurred between 17:00 and 20:00, emitting a significant amount of NO. Consequently, the concentrations of $PM_{2.5}$ and NO_2 increased during this period, reaching their maximum at 20:00 (31.6 μg m^{-3}) and 22:00 (42.8 μg m^{-3}), respectively. The titration reactions of NO with O_3 resulted in reduced O_3 levels and increased NO_2 levels. Then, there was a gradual decrease in NO_2, $PM_{2.5}$, and O_3 concentrations during the night, mainly due to the absence of photochemical processes and low convection under the nighttime inversion layer.

The $PM_{2.5}$ concentrations inside the park were relatively lower compared to those outside the park, with two peaks of the differences observed at 9:00 and 17:00, showing differences of 10.8 μg m^{-3} and 10.5 μg m^{-3}, respectively. Previous studies have indicated that the green spaces in urban parks can effectively remove $PM_{2.5}$, and arbors and shrubs are the best vegetation species [12,64,65]. The trees in the urban park in Jinan are dominated by arbors, so it has a strong removal efficiency. In contrast, the O_3 concentrations inside the park were only around 4–5 μg m^{-3} lower than those at the outside sites during the morning and evening rush hours. In addition, the O_3 concentration inside park was even higher than those at the outside site during 8:00–14:00. This can be attributed to the lower wind speed inside the park, which results in weaker diffusion of gaseous pollutants. As a result, the NO titration reaction inside the park is less susceptible to the interference from the gases outside the park [22].

3.3. Effects of Urban Trees on the Microclimate and Human Comfort Index

3.3.1. Effects of Urban Forest

Urban trees cannot only improve air quality but also reduce the temperature and increase the humidity through cooling and humidifying effects. As shown in Figure 4, the average temperatures at the valley and ridge sites within the urban forests were 4.1 ± 1.6 °C and 6.8 ± 4.5 °C lower, respectively, than that at urban site. In contrast, the average RH values at the valley and ridge sites were 13.4 ± 6.6% and 12.9 ± 10.1% higher, respectively, than that at urban site. This indicates that the high density of forest canopy in the valley contributes to a more significant humidifying effect compared to at the ridge site. However, it is important to note that the lower temperature at the PML site is primarily due to its higher elevation. In terms of diurnal variations, all four sites showed a similar pattern. However, the temperature at the valley sites was 3.4 ± 0.1 °C lower than that at urban site during 10:00–15:00. In contrast, the difference was 7.1 ± 0.5 °C for the ridge site and urban site. As a ridge site, PML showed a small amplitude of diurnal variations in temperature and RH, and it maintained a lower temperature and higher RH and WS during the daytime.

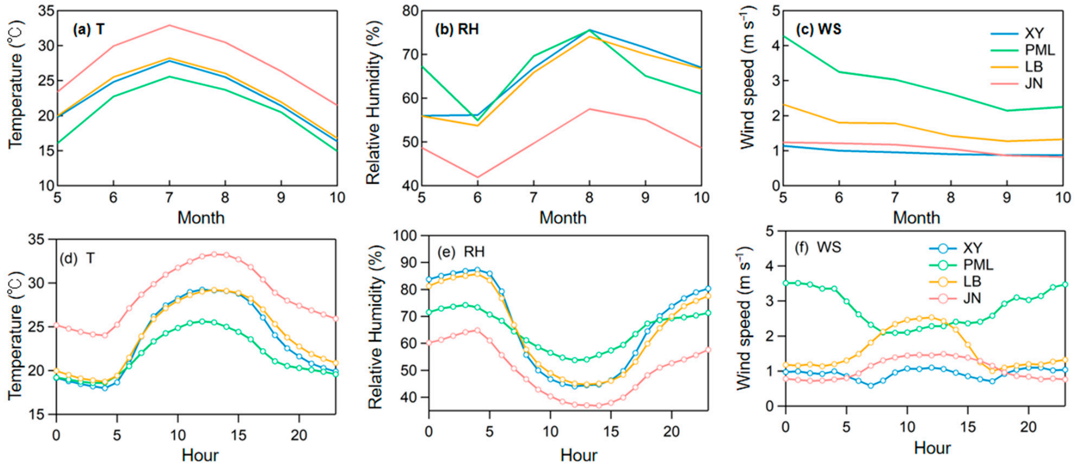

Figure 4. Monthly (**a**–**c**) and diurnal (**d**–**f**) variations in micrometeorological parameters (temperature: °C; relative humidity; wind speed: m s^{-1}) at urban and urban forest sites.

Furthermore, we compared the differences in human comfort index between the urban site and the urban forest sites. A CI value greater than 70 indicates discomfort due to excessive heat, and a larger CI value corresponds to a more uncomfortable feeling for the human body. As shown in Figure 5, the average values of CI at the JN site exceeded 80 from late May to September, except in early October. During the hours of 10:00–15:00, the CI values even exceeded 87, indicating the highest level of discomfort in downtown Jinan throughout the observation period. As such a time, the human body might feel unbearable heat and extremely uncomfortable. In contrast, the average CI value at the PML site was 69 ± 7.7, much lower than those at the urban and valley sites. This suggests that PML was the most comfortable locations for human beings during the observed period compared with urban and valley sites. As shown in Figure 5d, the PML site reduced the human CI by 6.1–12.8 during the hours of 10:00–15:00, resulting in a more comfortable thermal environment. Similarly, the XY and LB sites also improved human comfort by reducing the CI by 5.9–8.8 and 4.8–7.6, respectively. Therefore, we suggest that people in downtown Jinan can experience a more comfortable feeling by visiting the urban forests in the southern mountainous area. The urban forests provide relief from the discomfort caused by high CI values in the urban areas, offering a more pleasant and comfortable thermal environment.

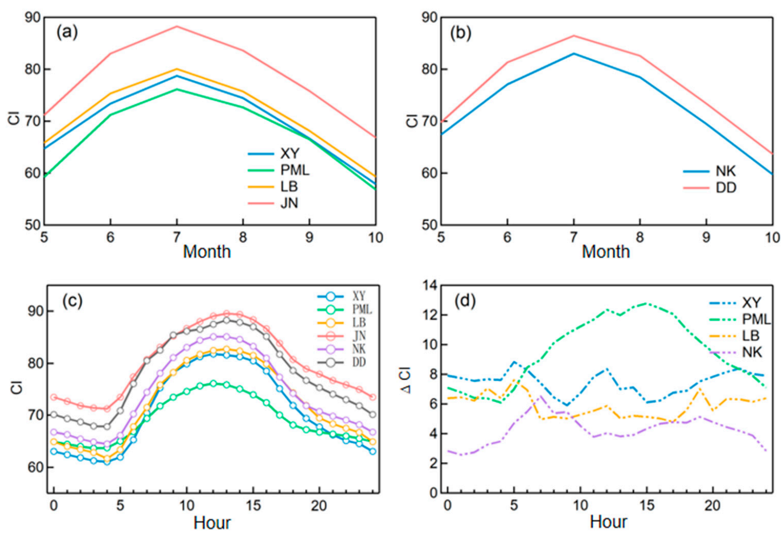

Figure 5. Monthly (**a**,**b**) and diurnal variations (**c**) of human comfort index (CI) at the six observation sites. Differences in CI values (ΔCI) between the urban forest (XY, PML and LB) and urban center (JN) and between inside (NK) and outside (DD) the urban park (**d**).

3.3.2. Effects of Urban Parks

We further investigated the cooling effect of urban parks and the thermal comfort inside and outside parks. The results revealed that the temperature inside the studied urban park was 1.36 °C lower compared to outside the park (Figure 6). This finding is similar to the results observed by Amani-Beni et al. in the Beijing Olympic Park, where the temperature inside the park was found to be 1.12 °C lower than that of the bare area [42]. In addition, the urban park was found to increase air humidity by 1.04% and decrease wind speed by 0.39 m s^{-1} during the hours of 10:00–15:00. As a result, the urban park contributed to a decrease in the CI by approximately 2.35–4.25, providing a more comfortable thermal environment throughout the observation period. This result aligns with the findings observation in the Beijing Olympic Park, where the CI was reduced by 2.43 [42].

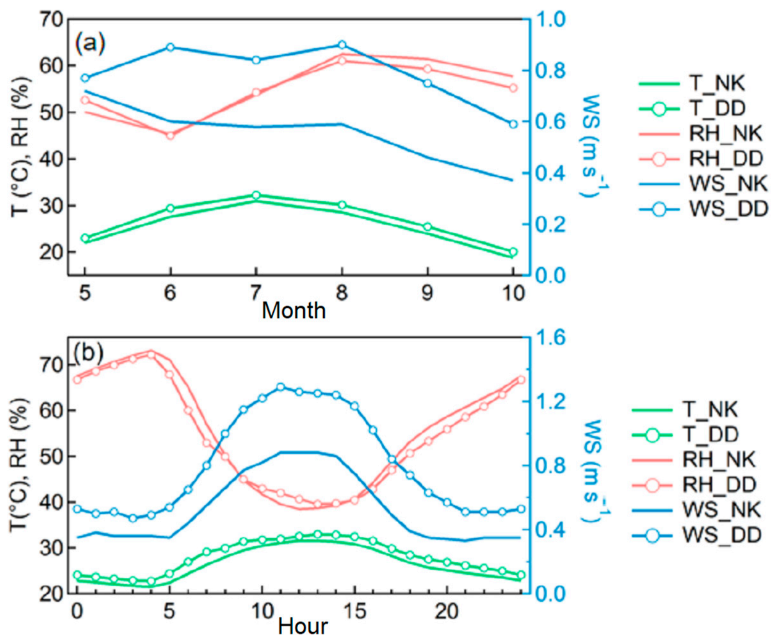

Figure 6. Monthly (**a**) and diurnal (**b**) variations in micrometeorological parameters (temperature: °C; relative humidity; wind speed: m s^{-1}) inside and outside of Jinan Forest Park.

The diurnal variation analysis showed that starting from 4:00, the temperature and wind speed increased while humidity decreased. Therefore, the CI value reached its maximum at 12:00 and then began to decline. As a result, the ΔCI values showed that the first peak occurred at 7:00, which is in the morning rush hour, and the second weak peak occurred at 17:00 during the evening rush hour. As shown in Figure 6b, in the morning rush hour, the temperature inside the park was 2.85 °C lower than that of the outside site, the RH was 4.07% higher, and the wind speed was 0.25 m s^{-1} lower than at the outside site. Thus, the ΔCI values reached the first peak at 7:00. In the evening rush hour, the temperature, RH, and wind speed inside the park showed −1.66 °C, +2.04%, and −0.35 m s^{-1} differences compared to the outside site. Therefore, in the morning and evening rush hour, people feel the greatest difference in comfort in the park and outside the park, which suggests that if outdoor activities are needed in the morning and evening, they should be located away from the downtown area, choosing a more comfortable environment (such as in the park) for outdoor activities. The ΔCI ranged from 3.8 to 5.5 during 10:00–15:00. Consequently, the urban park effectively reduced the CI during the daytime, promoting a more comfortable thermal environment for human beings. These findings highlight the positive impact of urban parks in mitigating heat and improving thermal comfort, contributing to a more pleasant and comfortable outdoor environment.

4. Conclusions

To explore the impacts of urban trees on air quality and the microclimate, continuous measurement data were obtained from urban, urban forest, and urban park areas in Jinan, eastern China, in May–October 2023. The major findings are summarized as follows.

Three urban forest sites and one urban downtown site were analyzed for their impacts on air quality. Both the valley sites and the ridge site showed lower concentrations of $PM_{2.5}$ and O_3 compared to the urban site. This reduction was primarily attributed to the combination of fewer precursor emissions and the stronger removal capacity resulting from the cooling and humidifying effects of forest trees. Although the BVOCs emitted by forests are important precursors of O_3 and SOA, their emissions are much lower than those of anthropogenic VOCs in urban areas. Consequently, the concentrations of $PM_{2.5}$ and O_3 are lower in urban forest areas. Urban forests effectively reduce regional $PM_{2.5}$ and O_3 concentrations in the summer when temperatures are higher and vegetation is more abundant. However, the O_3 pollution in Jinan remains severe, especially from June to August, when the monthly average MDA8 O_3 concentrations in both the urban center and urban forest areas exceeded 160 $\mu g\ m^{-3}$. Therefore, to effectively control regional O_3 pollution, we recommend promoting the planting of low-BVOC-emission tree species and rationally planning the urban forest layout. In terms of diurnal variations, we focused on analyzing the O_3 and $PM_{2.5}$ concentrations during the 10:00–15:00 period, which is the peak time for tourist activities. During this period, the $PM_{2.5}$ and O_3 concentrations in the urban forest areas were 6.3–6.5 $\mu g\ m^{-3}$ and 21–23 $\mu g\ m^{-3}$ lower than those in urban areas.

To explore the impact of urban parks on air quality, we selected the NK and DD sites as locations inside and outside the Jinan Forest Park, respectively. The results showed that the urban park effectively reduced the average $PM_{2.5}$ concentrations by about 9.3 $\mu g\ m^{-3}$ during the May–October period. However, urban park trees had little impact on gaseous pollutants such as NO_2 and O_3. The $PM_{2.5}$ concentrations inside the park were 10.5–10.8 $\mu g\ m^{-3}$ during the morning and evening rush hours, but the O_3 concentrations inside the park were only 4–5 $\mu g\ m^{-3}$ lower than those at the site outside. In addition, the O_3 concentrations inside the park were even higher than those at the site outside during 8:00–14:00.

Urban trees not only improve air quality but also reduce temperatures and increase humidity through cooling and humidifying effects. The urban forest reduced the temperature by about 4.1 °C and 6.8 °C and increased the RH by about 13.4% and 12.9% in the valley and ridge areas, respectively. Similarly, the urban park reduced the temperature by about 1.36 °C and increased the RH by about 0.9%. As such, we found that both urban forests and urban parks promote a more comfortable thermal environmental for human beings, reducing the CI by 4.8–7.8 and 6.1–12.8 at the valley and ridge sites in the forest areas and 3.8–5.5 in the urban park areas. In sum, this study has evaluated the impact of urban forests and parks on air quality and human comfort in Jinan based on direct observational data, contributing to the scientific understanding of the critical role of urban vegetation in improving air quality and enhancing human comfort.

Author Contributions: Conceptualization, K.L. and L.S.; methodology, K.L., J.L. and L.S.; investigation, J.L. and X.Y.; validation and formal analysis: K.L., J.L. and X.Y.; writing—original draft preparation: K.L. and J.L.; writing—review and editing, L.S., C.X. and G.Y.; visualization, X.Y. and L.S.; supervision, L.S. and C.X.; project administration, L.S. and G.Y.; funding acquisition, L.S. and C.X. All authors have read and agreed to the published version of the manuscript.

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References

1. Endreny, T.A. Strategically growing the urban forest will improve our world. *Nat. Commun.* **2018**, *9*, 1160. [CrossRef] [PubMed]
2. Manes, F.; Marando, F.; Capotorti, G.; Blasi, C.; Salvatori, E.; Fusaro, L.; Ciancarella, L.; Mircea, M.; Marchetti, M.; Chirici, G.; et al. Regulating Ecosystem Services of forests in ten Italian Metropolitan Cities: Air quality improvement by PM_{10} and O_3 removal. *Ecol. Indic.* **2016**, *67*, 425–440. [CrossRef]
3. Nowak, D.J.; Hirabayashi, S.; Bodine, A.; Hoehn, R. Modeled $PM_{2.5}$ removal by trees in ten U.S. cities and associated health effects. *Environ. Pollut.* **2013**, *178*, 395–402. [CrossRef] [PubMed]
4. Grote, R.; Samson, R.; Alonso, R.; Amorim, J.H.; Cariñanos, P.; Churkina, G.; Fares, S.; Le Thiec, D.; Niinemets, Ü.; Mikkelsen, T.N.; et al. Functional traits of urban trees: Air pollution mitigation potential. *Front. Ecol. Environ.* **2016**, *14*, 543–550. [CrossRef]
5. Xu, C.; Dong, L.; Yu, C.; Zhang, Y.; Cheng, B. Can forest city construction affect urban air quality? The evidence from the Beijing-Tianjin-Hebei urban agglomeration of China. *J. Clean. Prod.* **2020**, *264*, 121607. [CrossRef]
6. Guan, Y.; Xiao, Y.; Wang, Y.; Zhang, N.; Chu, C. Assessing the health impacts attributable to $PM_{2.5}$ and ozone pollution in 338 Chinese cities from 2015 to 2020. *Environ. Pollut.* **2021**, *287*, 117623. [CrossRef] [PubMed]
7. Xiao, Q.; Geng, G.; Xue, T.; Liu, S.; Cai, C.; He, K.; Zhang, Q. Tracking $PM_{2.5}$ and O_3 Pollution and the Related Health Burden in China 2013–2020. *Environ. Sci. Technol.* **2022**, *56*, 6922–6932. [CrossRef] [PubMed]
8. Han, C.; Xu, R.; Ye, T.; Xie, Y.; Zhao, Y.; Liu, H.; Yu, W.; Zhang, Y.; Li, S.; Zhang, Z.; et al. Mortality burden due to long-term exposure to ambient $PM_{2.5}$ above the new WHO air quality guideline based on 296 cities in China. *Environ. Int.* **2022**, *166*, 107331. [CrossRef] [PubMed]
9. Zhang, Y. All-Cause Mortality Risk and Attributable Deaths Associated with Long-Term Exposure to Ambient $PM_{2.5}$ in Chinese Adults. *Environ. Sci. Technol.* **2021**, *55*, 6116–6127. [CrossRef]
10. Hu, Y.; Yao, M.; Liu, Y.; Zhao, B. Personal exposure to ambient $PM_{2.5}$, PM_{10}, O_3, NO_2, and SO_2 for different populations in 31 Chinese provinces. *Environ. Int.* **2020**, *144*, 106018. [CrossRef] [PubMed]
11. Lyu, Y.; Wu, Z.; Wu, H.; Pang, X.; Qin, K.; Wang, B.; Ding, S.; Chen, D.; Chen, J. Tracking long-term population exposure risks to $PM_{2.5}$ and ozone in urban agglomerations of China 2015–2021. *Sci. Total Environ.* **2023**, *854*, 158599. [CrossRef] [PubMed]
12. Han, D.; Shen, H.; Duan, W.; Chen, L. A review on particulate matter removal capacity by urban forests at different scales. *Urban For. Urban Green.* **2020**, *48*, 126565. [CrossRef]
13. Kwak, M.J.; Lee, J.; Kim, H.; Park, S.; Lim, Y.; Kim, J.E.; Baek, S.G.; Seo, S.M.; Kim, K.N.; Woo, S.Y. The Removal Efficiencies of Several Temperate Tree Species at Adsorbing Airborne Particulate Matter in Urban Forests and Roadsides. *Forests* **2019**, *10*, 960. [CrossRef]
14. Perini, K.; Ottelé, M.; Giulini, S.; Magliocco, A.; Roccotiello, E. Quantification of fine dust deposition on different plant species in a vertical greening system. *Ecol. Eng.* **2017**, *100*, 268–276. [CrossRef]
15. Zhang, Z.; Liu, J.; Wu, Y.; Yan, G.; Zhu, L.; Yu, X. Multi-scale comparison of the fine particle removal capacity of urban forests and wetlands. *Sci. Rep.* **2017**, *7*, 46214. [CrossRef] [PubMed]
16. Liu, J.; Liu, J.; Zhu, L.; Wang, H.; Yang, Y.; Liu, J.; Qiu, D.; Ma, W.; Zhang, Z.; Liu, J. Dry deposition of particulate matter at an urban forest, wetland and lake surface in Beijing. *Atmos. Environ.* **2016**, *125*, 178–187. [CrossRef]
17. Nowak, D.J.; Hirabayashi, S.; Doyle, M.; McGovern, M.; Pasher, J. Air pollution removal by urban forests in Canada and its effect on air quality and human health. *Urban For. Urban Green.* **2018**, *29*, 40–48. [CrossRef]
18. Selmi, W.; Weber, C.; Rivière, E.; Blond, N.; Mehdi, L.; Nowak, D. Air pollution removal by trees in public green spaces in Strasbourg city, France. *Urban For. Urban Green.* **2016**, *17*, 192–201. [CrossRef]
19. Kitao, M.; Komatsu, M.; Hoshika, Y.; Yazaki, K.; Yoshimura, K.; Fujii, S.; Miyama, T.; Kominami, Y. Seasonal ozone uptake by a warm-temperate mixed deciduous and evergreen broadleaf forest in western Japan estimated by the Penman–Monteith approach combined with a photosynthesis-dependent stomatal model. *Environ. Pollut.* **2014**, *184*, 457–463. [CrossRef] [PubMed]
20. Wang, H.; Zhou, W.; Wang, X.; Gao, F.; Zheng, H.; Tong, L.; Ouyang, Z. Ozone uptake by adult urban trees based on sap flow measurement. *Environ. Pollut.* **2012**, *162*, 275–286. [CrossRef]
21. Sicard, P.; Agathokleous, E.; De Marco, A.; Paoletti, E. Ozone-reducing urban plants: Choose carefully. *Science* **2022**, *377*, 585. [CrossRef] [PubMed]
22. Fitzky, A.C.; Sandén, H.; Karl, T.; Fares, S.; Calfapietra, C.; Grote, R.; Saunier, A.; Rewald, B. The Interplay Between Ozone and Urban Vegetation—BVOC Emissions, Ozone Deposition, and Tree Ecophysiology. *Front. For. Glob. Chang.* **2019**, *2*, 50. [CrossRef]

23. Gao, Y.; Ma, M.; Yan, F.; Su, H.; Wang, S.; Liao, H.; Zhao, B.; Wang, X.; Sun, Y.; Hopkins, J.R.; et al. Impacts of biogenic emissions from urban landscapes on summer ozone and secondary organic aerosol formation in megacities. *Sci. Total Environ.* **2022**, *814*, 152654. [CrossRef] [PubMed]
24. Matsumoto, J. Measurements of total ozone reactivity in a suburban forest in Japan. *Atmos. Environ.* **2021**, *246*, 117990. [CrossRef]
25. Fares, S.; Conte, A.; Alivernini, A.; Chianucci, F.; Grotti, M.; Zappitelli, I.; Petrella, F.; Corona, P. Testing Removal of Carbon Dioxide, Ozone, and Atmospheric Particles by Urban Parks in Italy. *Environ. Sci. Technol.* **2020**, *54*, 14910–14922. [CrossRef] [PubMed]
26. Sicard, P.; Sicard, P.; Agathokleous, E.; Araminiene, V.; Carrari, E.; Hoshika, Y.; De Marco, A.; Paoletti, E. Should we see urban trees as effective solutions to reduce increasing ozone levels in cities? *Environ. Pollut.* **2018**, *243*, 163–176. [CrossRef] [PubMed]
27. Duan, W.; Wang, C.; Pei, N.; Zhang, C.; Gu, L.; Jiang, S.; Hao, Z.; Xu, X. Spatiotemporal Ozone Level Variation in Urban Forests in Shenzhen. *China For.* **2019**, *10*, 247. [CrossRef]
28. Yli-Pelkonen, V.; Setälä, H.; Viippola, V. Urban forests near roads do not reduce gaseous air pollutant concentrations but have an impact on particles levels. *Landsc. Urban Plan.* **2017**, *158*, 39–47. [CrossRef]
29. Grundström, M.; Pleijel, H. Limited effect of urban tree vegetation on NO_2 and O_3 concentrations near a traffic route. *Environ. Pollut.* **2014**, *189*, 73–76. [CrossRef] [PubMed]
30. Zhai, C.; Bao, G.; Zhang, D.; Sha, Y. Urban Forest Locations and Patch Characteristics Regulate $PM_{2.5}$ Mitigation Capacity. *Forests* **2022**, *13*, 1408. [CrossRef]
31. Zhang, B.; Xie, Z.; She, X.; Gao, J. Quantifying the Potential Contribution of Urban Forest to $PM_{2.5}$ Removal in the City of Shanghai, China. *Atmosphere* **2021**, *12*, 1171. [CrossRef]
32. Lu, J.; Li, Q.; Zeng, L.; Chen, J.; Liu, G.; Li, Y.; Li, W.; Huang, K. A micro-climatic study on cooling effect of an urban park in a hot and humid climate. *Sustain. Cities Soc.* **2017**, *32*, 513–522. [CrossRef]
33. Yang, A.-S.; Juan, Y.-H.; Wen, C.-Y.; Chang, C.-J. Numerical simulation of cooling effect of vegetation enhancement in a subtropical urban park. *Appl. Energy* **2017**, *192*, 178–200. [CrossRef]
34. Jay, O.; Capon, A.; Berry, P.; Broderick, C.; de Dear, R.; Havenith, G.; Honda, Y.; Kovats, R.S.; Ma, W.; Malik, A.; et al. Reducing the health effects of hot weather and heat extremes: From personal cooling strategies to green cities. *Lancet* **2021**, *398*, 709–724. [CrossRef] [PubMed]
35. Hathway, E.A.; Sharples, S. The interaction of rivers and urban form in mitigating the Urban Heat Island effect: A UK case study. *Build. Environ.* **2012**, *58*, 14–22. [CrossRef]
36. Kong, F.; Yan, W.; Zheng, G.; Yin, H.; Cavan, G.; Zhan, W.; Zhang, N.; Cheng, L. Retrieval of three-dimensional tree canopy and shade using terrestrial laser scanning (TLS) data to analyze the cooling effect of vegetation. *Agric. For. Meteorol.* **2016**, *217*, 22–34. [CrossRef]
37. Alkama, R.; Forzieri, G.; Duveiller, G.; Grassi, G.; Liang, S.; Cescatti, A. Vegetation-based climate mitigation in a warmer and greener World. *Nat. Commun.* **2022**, *13*, 606. [CrossRef]
38. Schwaab, J.; Meier, R.; Mussetti, G.; Seneviratne, S.; Bürgi, C.; Davin, E.L. The role of urban trees in reducing land surface temperatures in European cities. *Nat. Commun.* **2021**, *12*, 6763. [CrossRef] [PubMed]
39. Masoudi, M.; Tan, P.Y.; Fadaei, M. The effects of land use on spatial pattern of urban green spaces and their cooling ability. *Urban Clim.* **2021**, *35*, 100743. [CrossRef]
40. Gao, Z.; Zaitchik, B.F.; Hou, Y.; Chen, W. Toward park design optimization to mitigate the urban heat Island: Assessment of the cooling effect in five U.S. cities. *Sustain. Cities Soc.* **2022**, *81*, 103870. [CrossRef]
41. Zhou, Y.; Zhao, H.; Mao, S.; Zhang, G.; Jin, Y.; Luo, Y.; Huo, W.; Pan, Z.; An, P.; Lun, F. Studies on urban park cooling effects and their driving factors in China: Considering 276 cities under different climate zones. *Build. Environ.* **2022**, *222*, 109441. [CrossRef]
42. Amani-Beni, M.; Zhang, B.; Xie, G.-D.; Xu, J. Impact of urban park's tree, grass and waterbody on microclimate in hot summer days: A case study of Olympic Park in Beijing, China. *Urban For. Urban Green.* **2018**, *32*, 1–6. [CrossRef]
43. Wu, Z.; Chen, L. Optimizing the spatial arrangement of trees in residential neighborhoods for better cooling effects: Integrating modeling with in-situ measurements. *Landsc. Urban Plan.* **2017**, *167*, 463–472. [CrossRef]
44. Jinan Statistics Bureau. Jinan Statistical Yearbook. 2022. Available online: https://jntj.jinan.gov.cn/col/col27523/index.html (accessed on 31 January 2024).
45. Lu, X.; Hong, J.; Zhang, L.; Cooper, O.R.; Schultz, M.G.; Xu, X.; Wang, T.; Gao, M.; Zhao, Y.; Zhang, Y. Severe Surface Ozone Pollution in China: A Global Perspective. *Environ. Sci. Technol. Lett.* **2018**, *5*, 487–494. [CrossRef]
46. He, J.; Gong, S.; Yu, Y.; Yu, L.; Wu, L.; Mao, H.; Song, C.; Zhao, S.; Liu, H.; Li, X.; et al. Air pollution characteristics and their relation to meteorological conditions during 2014–2015 in major Chinese cities. *Environ. Pollut.* **2017**, *223*, 484–496. [CrossRef] [PubMed]
47. Song, C.; Wu, L.; Xie, Y.; He, J.; Chen, X.; Wang, T.; Lin, Y.; Jin, T.; Wang, A.; Liu, Y.; et al. Air pollution in China: Status and spatiotemporal variations. *Environ. Pollut.* **2017**, *227*, 334–347. [CrossRef] [PubMed]
48. De Quadros, B.M.; Mizgier, M.G.O. Urban green infrastructures to improve pedestrian thermal comfort: A systematic review. *Urban For. Urban Green.* **2023**, *88*, 128091. [CrossRef]
49. Li, D.; Mu, H.; Gao, Y.; Lu, M.; Liu, C. A GIS-Based Analysis of the Carbon-Oxygen Balance of Urban Forests in the Southern Mountainous Area of Jinan, China. *Sustainability* **2022**, *14*, 16135. [CrossRef]

50. Zhu, C.; Przybysz, A.; Chen, Y.; Guo, H.; Chen, Y.; Zeng, Y. Effect of spatial heterogeneity of plant communities on air PM_{10} and $PM_{2.5}$ in an urban forest park in Wuhan, China. *Urban For. Urban Green.* **2019**, *46*, 126487. [CrossRef]
51. Popek, R.; Fornal-Pieniak, B.; Chyliński, F.; Pawełkowicz, M.; Bobrowicz, J.; Chrzanowska, D.; Piechota, N.; Przybysz, A. Not Only Trees Matter—Traffic-Related PM Accumulation by Vegetation of Urban Forests. *Sustainability* **2022**, *14*, 2973. [CrossRef]
52. Sun, L.; Xue, L.; Wang, T.; Gao, J.; Ding, A.; Cooper, O.R.; Lin, M.; Xu, P.; Wang, Z.; Wang, X.; et al. Significant increase of summertime ozone at Mount Tai in Central Eastern China. Atmos. *Chem. Phys.* **2016**, *16*, 10637–10650.
53. Guo, H.; Ling, Z.H.; Cheung, K.; Jiang, F.; Wang, D.W.; Simpson, I.J.; Barletta, B.; Meinardi, S.; Wang, T.J.; Wang, X.M.; et al. Characterization of photochemical pollution at different elevations in mountainous areas in Hong Kong. *Atmos. Chem. Phys.* **2013**, *13*, 3881–3898. [CrossRef]
54. Ezcurra, A.; Benech, B.; Echelecou, A.; Santamaría, J.; Herrero, I.; Zulueta, E. Influence of local air flow regimes on the ozone content of two Pyrenean valleys. *Atmos. Environ.* **2013**, *74*, 367–377. [CrossRef]
55. Ghirardo, A.; Xie, J.; Zheng, X.; Wang, Y.; Grote, R.; Block, K.; Wildt, J.; Mentel, T.; Kiendler-Scharr, A.; Hallquist, M.; et al. Urban stress-induced biogenic VOC emissions and SOA-forming potentials in Beijing. *Atmos. Chem. Phys.* **2016**, *16*, 2901–2920. [CrossRef]
56. Li, L.; Yang, W.; Xie, S.; Wu, Y. Estimations and uncertainty of biogenic volatile organic compound emission inventory in China for 2008–2018. *Sci. Total Environ.* **2020**, *733*, 139301. [CrossRef] [PubMed]
57. Li, M.; Zhang, Q.; Zheng, B.; Tong, D.; Lei, Y.; Liu, F.; Hong, C. Persistent growth of anthropogenic non-methane volatile organic compound (NMVOC) emissions in China during 1990–2017: Drivers, speciation and ozone formation potential. *Atmos. Chem. Phys.* **2019**, *19*, 8897–8913. [CrossRef]
58. Wang, T.; Xue, L.; Feng, Z.; Dai, J.; Zhang, Y.; Tan, Y. Ground-level ozone pollution in China: A synthesis of recent findings on influencing factors and impacts. *Environ. Res. Lett.* **2022**, *17*, 063003. [CrossRef]
59. Cape, J.N.; Hamilton, R.; Heal, M.R. Reactive uptake of ozone at simulated leaf surfaces: Implications for 'non-stomatal' ozone flux. *Atmos. Environ.* **2009**, *43*, 1116–1123. [CrossRef]
60. Wittig, V.E.; Ainsworth, E.A.; Long, S. To what extent do current and projected increases in surface ozone affect photosynthesis and stomatal conductance of trees? A meta-analytic review of the last 3 decades of experiments. *Plant Cell Environ.* **2007**, *30*, 1150–1162. [CrossRef] [PubMed]
61. Su, T.-H.; Lin, C.-S.; Lu, S.-Y.; Lin, J.-C.; Wang, H.-H.; Liu, C.-P. Effect of air quality improvement by urban parks on mitigating $PM_{2.5}$ and its associated heavy metals: A mobile-monitoring field study. *J. Environ. Manag.* **2022**, *323*, 116283. [CrossRef] [PubMed]
62. Chen, M.; Dai, F.; Yang, B.; Zhu, S. Effects of neighborhood green space on $PM_{2.5}$ mitigation: Evidence from five megacities in China. *Build. Environ.* **2019**, *156*, 33–45. [CrossRef]
63. Knight, T.; Price, S.; Bowler, D.; Hookway, A.; King, S.; Konno, K.; Richter, R.L. How effective is 'greening' of urban areas in reducing human exposure to ground-level ozone concentrations, UV exposure and the 'urban heat island effect'? An updated systematic review. *Environ. Evid.* **2021**, *10*, 12. [CrossRef]
64. Popek, R.; Fornal-Pieniak, B.; Dąbrowski, P.; Chyliński, F. The Role of Spontaneous Flora in the Mitigation of Particulate Matter from Traffic Roads in an Urbanised Area. *Sustainability* **2023**, *15*, 7568. [CrossRef]
65. Popek, R.; Mahawar, L.; Shekhawat, G.S.; Przybysz, A. Phyto-cleaning of particulate matter from polluted air by woody plant species in the near-desert city of Jodhpur (India) and the role of heme oxygenase in their response to PM stress conditions. *Environ. Sci. Pollut. Res.* **2022**, *29*, 70228–70241. [CrossRef] [PubMed]