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Article

$PM_{2.5}$ Concentration Differences between Various Forest Types and Its Correlation with Forest Structure

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Abstract: The Plain Forestation Project is an important measure designed to alleviate air pollution in Beijing, the capital of China. Ten commonly cultivated forest types of the Plain Forestation Project were studied at three growth stages of leaves. The particulate matter $(PM)_{2.5}$ concentrations and forest structures were surveyed to analyze the $PM_{2.5}$ concentration differences between different forest types, and establish a linear relationship between forest structures and $PM_{2.5}$ concentration differences. The results suggested that forest ecosystems can block and capture $PM_{2.5}$ from the air. Forests with luxuriant foliage are most effective in removing $PM_{2.5}$ from the air. The average $PM_{2.5}$ mass concentration in the Leaf-on Period (LOP) was the lowest when compared with other periods. The $PM_{2.5}$ concentrations in the forest usually were higher than the control. Correspondingly, $PM_{2.5}$ concentration indexes were negative values during daytime, but this results were reversed at night. Forests can reduce the diffusion rate of $PM_{2.5}$ leading to $PM_{2.5}$ were detained in the forest during daytime, and play an important role in the adsorption or deposition of particulate matter at night. Forest structure was primary reason of the $PM_{2.5}$ concentration difference between different forests. The $PM_{2.5}$ concentration index was positively correlated to canopy density, leaf area index (LAI), and mean diameter at breast height (DBH), and negatively correlated to the average tree height (height), forestland area, grass coverage and height.

Keywords: concentration difference; correlation; forest structure; $PM_{2.5}$

1. Introduction

Forests play an important role in improving the quality of the environment. For example, forests can moderate climate, control rainfall and flooding [1], alleviate the intensity of heat islands [2], conserve energy, carbon dioxide and water, lower noise levels, and reduce air pollution [3–7]. Among the benefits provided by forests, the function that is most significant in Beijing, China is their ability to remove particulate matter (PM) with an aerodynamic diameter of 2.5 microns or less ($PM_{2.5}$) from the air.

Excessive energy consumption caused by rapid urbanization and industrialization has caused a decline in natural forests, forest loss and increasingly severe air pollution in Beijing. Beijing is among the 10 cities of the world with the worst air pollution. Severe air pollution is mainly caused by high concentrations of $PM_{2.5}$. The $PM_{2.5}$ reading in 2014 averaged 85.9 $\mu g \cdot m^{-3}$. In comparison, the national standard is 35 $\mu g \cdot m^{-3}$. $PM_{2.5}$ was found to be the major pollutant on most smoggy days [8]. A high $PM_{2.5}$ concentration has a major effect on air quality, human health, and climate change [9]. In recent years, the Chinese Government has begun various initiatives to reduce the $PM_{2.5}$ pollution in air.

Forests passively scavenge $PM_{2.5}$ and forested areas are characterized by higher rates of dry deposition than other land types [10]. Forests can act as obstacles to dispersal of particulate pollution and thus remove a significant amount of PM from the atmosphere [11]. Leaves and branches can directly capture or retain $PM_{2.5}$ from the air. Vegetation can intercept particulate matter in some regions [12–17]. Trees can also be a source of air pollutants; they emit biogenic volatile organic compounds (BVOCs). BVOCs can react with nitro oxides (NOx) and form O_3 and other aerosol pollutants [18]. Tree pollen is another source of particles that can have serious health effects on people who are allergic to pollen [19].

Forests can be considered a natural lifeform that is similar to a 'living technology' that help maintain a healthy environment and can be used by humans to modify the environment. Many studies have analyzed how forests remove air pollutants [20,21]. Based on these studies, we know that forests can help improve air quality by removing or modifying many different air pollutants or through other tree functions (e.g., air temperature reduction). Consequently, these actions may be beneficial to improving human health. A change in species or locations of trees with respect to each other or buildings and other components of the urban infrastructure can have a major effect on benefits and costs. Several studies have investigated the effectiveness of trees in accumulating airborne particles on foliage [22–24]. Those studies show that broad-leaved species with rough leaf surfaces are more efficient in capturing PM than those with smooth leaf surfaces. Needles of coniferous trees, which produce a thicker epicuticular wax layer, are more effective in PM accumulation than broad-leaved species, and evergreen conifers have the potential to accumulate pollutants throughout the year. These studies only focused on the species and leaves and did not indicate how forest structure affects the ability of trees to reduce $PM_{2.5}$ in air. In addition, this research mostly focuses on the daytime, few studies on the particulate matter in the forests at night. Therefore, whether the $PM_{2.5}$ concentration difference between inside and outside of forests at night is similar to the difference at daytime. What is the relationship between the ability that forests effect the $PM_{2.5}$ concentration and forest structures?

The present study was designed to collect air samples at daytime and night, and provide a more detailed analysis of the correlation between the difference of $PM_{2.5}$ concentration and forest structures. Finally, the linear relationship between forest structures and $PM_{2.5}$ concentration differences was established. The results can be used to maximize the effectiveness of the design of forest structures in reducing $PM_{2.5}$ in the atmosphere.

2. Methods

2.1. Sampling Site

The Plain Forestation Project, a demonstration zone developed in 2012 where a million acres of forest have been planted in the plain area with dense population and serious pollution, is located in the Fangshan District in Beijing, China. This demonstration area covers about 140,000 m^2, and includes 15 kinds of trees. The demonstration area is on the south side of the cropland, on the north side of the Yangfumazhuang village, on the east side of newly planted forest land (the main tree species were *Ginkgo biloba* (Ginkgo) *Pinus tabulaeformis* (Chinese Pine), *Koelreuteria paniculata* (Goldenrain) and so on) on the west side of the cropland and woodland that about 300 m wide from the railway to the demonstration area. The control site represents non-forest land or grassland. This grassland was belong to the demonstration area and next to the most of woodlands. The grassland area about 2000 m^2 was large enough to compare with other woodlands so that the background conditions including meteorological conditions and management measures of control site are similar to other woodlands. Broad-leaved forests were selected as study areas that were in good condition and healthy. These forests covered an area of about 3000 m^2 including *Malus micromalus* (Crabapple), *Cerasus pseudocerasus* (Cherry), *Prunus davidiana Franch* (Peach), *Ailanthus altissima* (Ailanthus), *Sophora japonica* (Scholar), *Catalpa bungei* (Catalpa), *Fraxinus chinensis* (White wax), *Robinia pseudoacacia* (Black locust), Goldenrain, and Ginkgo. Figure 1 shows the distribution of forests in the demonstration zone. No shrubs grow in these forests. The standard sample of 20 m × 20 m was set up in the center of the forest. Investigation route according to the S type along the contour line. Three kinds of forest (Crabapple, Cherry, and Peach) were measured 49 trees, and other forests were measured 25 trees. We measured the forest structures including average diameter at breast height (DBH), average height, canopy density, leaf area index (LAI), forestland area, herb height, and herb cover at Leaf Expansion Period (LEP, May), Leaf-on Period (LOP, August), and Deciduous Period (DP, October). DBH: The diameter ulnar was used to measure the diameter of every trees in the standard sample at 1.3 m height. Average height: The telescope dendrometer was used to measure each tree height within standard plots. LAI: The leaf area index was measured using the LAI-2200C plant canopy analyzer (li-cor, Lincoln, NE). We measured the LAI in every 5 × 5 m sample, then calculate the mean value. Grassland survey: We selected four little samples (5 × 5 m) in the standard sample, and set up three herbage plots (1 × 1 m) within each little sample. Herbaceous cover is the ratio between the area of herb cover and the area of herbage plot, and calculated according to the following Equation:

$$c = \sum_{i=1}^{n} c_i \tag{1}$$

where c is the herb cover, c_i is the herb cover of one kind herb. Herb height is calculated according to the following Equation:

$$h = \sum_{i=1}^{n} \frac{h_i \times c_i}{c} \tag{2}$$

where c is the herb cover, c_i is the herb cover of one kind herb, h_i is the herb height of one kind herb.

Figure 1. Inset map shows the layout of the sample experimental field. The larger map shows the site vicinity southwest of Beijing. Sources: Google Earth.

Table 1 shows the results. The field studies did not involve endangered or protected species and no specific permits were required for the described field studies.

Table 1. Stand structure characteristics.

	Stages	Control	Crabapple	Cherry	Peach	Ailanthus	Scholar	Catalpa	White Wax	Black Locust	Goldenrain	Ginkgo
DBH (cm)	LEP	0	2.55	5.50	5.65	8.00	7.45	5.86	7.07	8.62	7.55	6.80
	LOP	0	2.68	5.93	6.03	8.60	8.03	6.17	7.44	9.23	7.82	7.15
	DP	0	2.70	6.00	6.15	8.60	8.10	6.22	7.50	9.33	7.99	7.15
Height (m)	LEP	0	1.66	2.49	3.00	4.20	5.11	3.30	5.00	5.20	5.40	7.25
	LOP	0	1.75	2.79	3.11	4.10	5.59	3.51	5.55	6.04	5.79	7.72
	DP	0	2.05	3.09	3.41	4.40	5.89	3.81	5.85	6.34	6.09	8.02
Canopy Density	LEP	0	0.10	0.25	0.58	0.11	0.20	0.15	0.38	0.65	0.45	0.16
	LOP	0	0.15	0.39	0.83	0.20	0.40	0.23	0.57	0.90	0.68	0.19
	DP	0	0.10	0.20	0.42	0.10	0.18	0.16	0.25	0.40	0.34	0.15
LAI	LEP	0	0.90	2.40	3.00	1.00	2.34	1.40	2.60	3.25	2.76	0.80
	LOP	0	1.17	3.18	4.12	1.52	2.78	1.92	3.71	4.62	3.54	0.97
	DP	0	0.78	1.63	2.08	0.76	1.25	1.34	1.63	2.05	1.77	0.77
Forestland Area (m^2)		1901	2098	1898	1699	4162	4076	3596	2664	3197	3197	3303
Herb Height (m)	LEP	0.28	0.33	0.10	0.10	0.27	0.32	0.45	0.44	0.38	0.38	0.42
	LOP	0.60	0.50	0.20	0.10	0.40	0.50	0.65	0.60	0.55	0.55	0.60
	DP	0	0	0.05	0.05	0	0	0	0	0	0	0.05
Herb Cover	LEP	70%	30%	5%	5%	41%	37%	52%	49%	48%	48%	50%
	LOP	90%	35%	5%	8%	50%	45%	65%	60%	55%	55%	60%
	DP	0%	0%	5%	8%	0%	0%	0%	0%	0%	0%	5%
Number of Tree		0	49	49	49	25	25	25	25	25	25	25

2.2. Sampling

The $PM_{2.5}$ concentration was measured using the total suspended particle measurement in the flow of an intelligent sampler TH-150C model (Westernization instrument (Beijing) Technology Co., Ltd., Beijing, China). $PM_{2.5}$ was collected on glass fiber filters (MK360, Munktell & Filtrak GmbH, Sweden) at a flow rate of 100 $L \cdot min^{-1}$. The samplers were calibrated with a flow meter. A weighing method was used to calculate the $PM_{2.5}$ concentration [25,26].

The Micro-quartz fiber filters, T293 (retention 90 mm) (Munktell, Sweden) used for the analysis were first dried for 240 min at 60 °C in a DHG-9123A drying chamber (Biocotek, Shanghai, China) and then left in the weighing room to stabilize the humidity of the hygroscopic paper filters before weighing.

After a further 24 h, the first weighing was a determination of the mass of a clean filter (without dust on the filter, m1), the second step, weighing a filter with dust content (m^2). A XS105DU balance (Readability: 0.01 mg/0.1 mg) (Mettler-Toledo International Inc., Greifensee, Switzerland) was used to weigh the filters. Repeat weighing of unexposed substrates over several days is a better guide to true performance. The weighed filter papers were placed in sealed plastic containers for field sampling. Each sample was labeled so that it could be uniquely identified and sealed with its protective cover to prevent contamination.

One unused loaded sampler from each batch of ten prepared was retained as a blank; a minimum of three blanks were always kept. These were treated as far as possible in the same manner as those actually used for sampling, regarding transport to and from the sampling site but did not have air drawn through them. The samples were transported to the laboratory in a container designed to prevent damage in transit, and labeled to ensure proper handling, then left in the weighing room with the conditioning procedure described above repeated before re-weighing. At the same time, weighed filter blanks had mass ($b = m_{b2} - m_{b1}$). The concentration of $PM_{2.5}$ in the air was calculated according to the following Equation:

$$x = \frac{1000 \times (m_2 - m_1 - b)}{v} \quad (3)$$

where x ($\mu g \cdot m^{-3}$) is the dust concentration; m_2, m_1 (μg) are the filter mass before and after sampling; b (μg) is the blank filter mass; and v (m^3 at standard state) is the air sample volume calculated as the product of volumetric intensity of uptake air flow and sampling time.

Air samples were collected at 10 forests and at a control site (Figure 1). Sampling locations were located in the center of each forest at a height of 1.6 m above the ground (human respiration level). Background conditions of outside forests have little influence on the $PM_{2.5}$ concentration in the center of forest compared with the edge of forest. The $PM_{2.5}$ concentration difference between the center of forest and control can represent the ability that forests adjust particulate matter concentration. The experiment was conducted two times during each leaf stage and for three consecutive days (without rain, or heavy wind), with results given as the mean of replicate measurements. Sampling times were chosen as follows: LEP (in the spring when the leaves are growing): 2 to 4 May, and 26 to 28 May. LOP (in the summer when the leaves mature): 17 to 19 July, 10 to 12 August. DP (in the autumn when the leaves are dropping): 20 to 22 October, 11 to 13 November. LEP (1 to 30 May: in the spring when the leaves are growing), LOP (15 July to 15 August: in the summer when the leaves mature), and DP (15 October to 15 November: in the autumn when the leaves are dropping). The daytime sampling time was from 8:00

to 17:00, and the nighttime sampling time was from 20:00 to the next day at 5:00. The total pollutant collection was calculated according to the following Equation:

$$x = \frac{(m_1 - m_0 - b_m) + (n_1 - n_0 - b_n)}{v_m + v_n} \quad (4)$$

where x (μg·m^{-3}) is the total pollutant collection; m_1 n_1 (μg) are the filter mass after sampling at daytime and night; n_0, m_0 are the filter mass before sampling at daytime and night; b_m, b_n (μg) is the blank filter mass at daytime and night; and v_m, v_n (m^3 at standard state) is the air sample volume at daytime and night calculated as the product of volumetric intensity of uptake air flow and sampling time. The tested species were randomized within test fields that were in a relatively small area. Thus, variations in the environment within the locations of forests should not significantly influence the results.

A meteorological observation site was set up in the center of the control site at a height of 1.6 m above the ground. Meteorological data including temperature, wind speed, humidity and barometric pressure were obtained by a Kestrel 4500-pocket weather tracker (Nielsen-Kellerman Boothwyn, PA, USA).

2.3. Analysis

Data were subjected to one- and multi-way analysis of variance using Statistical Product and Service Solutions (SPSS). Values presented on bar charts are means, while values on dot charts are individual values with a trend line and correlation coefficients.

The $PM_{2.5}$ concentration index used to estimate the difference between forests and control was calculated according to Equation:

$$I = \frac{x_0 - x_i}{x_0} \times 100 \quad (5)$$

where I is the $PM_{2.5}$ concentration index, x_0 is the $PM_{2.5}$ concentration of the control, and x_i is the $PM_{2.5}$ concentration of the studied forest site.

The applicability of the Spearman Rank Correlation Coefficient is better than the other corresponding parameter methods used to determine whether the two random variables have a trend of change. Meanwhile, the nonparametric analysis method can reliably obtain the conclusion when the overall distribution is not clear and the overall information is lacking. Therefore, the correlation between forest structure and $PM_{2.5}$ concentration index is determined by the Spearman Rank Correlation Coefficient.

3. Results and Discussion

3.1. $PM_{2.5}$ Concentration Differences at Different Times

Figure 2 shows the observed mean $PM_{2.5}$ concentration of 10 forests and the control site varied during an entire day and between stages of leaf growth. A significant difference in the mean $PM_{2.5}$ concentration was observed between daytime, nighttime and different leaf stages. The average $PM_{2.5}$ mass concentration in LOP (48.09 μg·m^{-3}) was lower than during the LEP (72.53 μg·m^{-3}) and DP (68.97 μg·m^{-3}) in the daytime. Meanwhile, the average $PM_{2.5}$ mass concentration in DP (163.70 μg·m^{-3}) was higher than during the LEP (117.80 μg·m^{-3}) and LOP (79.86 μg·m^{-3}) at night.

The influence of seasonal differences in the concentration of particles was mainly affected by topography and climatic conditions. Topographically, the city of Beijing is located in the northwest edge of the North China Plain. There is a western and northern mountainous hilly area as well as central and eastern plains. The terrain tilts from the northwest to the southeast. The hilly areas to the north and northeast of Beijing to the west of Beijing are surrounded by three small plains of hilly areas within Beijing city. The landscape has an area of clear relief in a valley that is surrounded by mountains, forming a funnel that allows the winds to increase in speed significantly, and pollutants can be exhausted from the area by a large outlet [27]. The climatic conditions in spring in Beijing include the monsoon, drought, and more days with high winds and blowing sand conditions. The sand weather brings a lot of particles. The particle matter will accumulate at the plain area leading to the raise of the $PM_{2.5}$ concentration. In autumn, cool weather dominates with less wind, and winner becomes cool and dry. Thus, atmospheric situations in the surface layer is stable. This climate conditions were not conducive to reduce the $PM_{2.5}$ concentration.

The reason for the differences between daytime and night air pollution is that the higher temperatures and lighter daytime winds are conducive to the diffusion and deposition of $PM_{2.5}$. In addition, the $PM_{2.5}$ concentration may be reduced by wet deposition of dew in the morning. Furthermore, the ground temperature is higher than the air temperature in the daytime, forming a temperature inversion that is not conducive to the diffusion of $PM_{2.5}$, and allows easy resuspension of $PM_{2.5}$ [28–30].

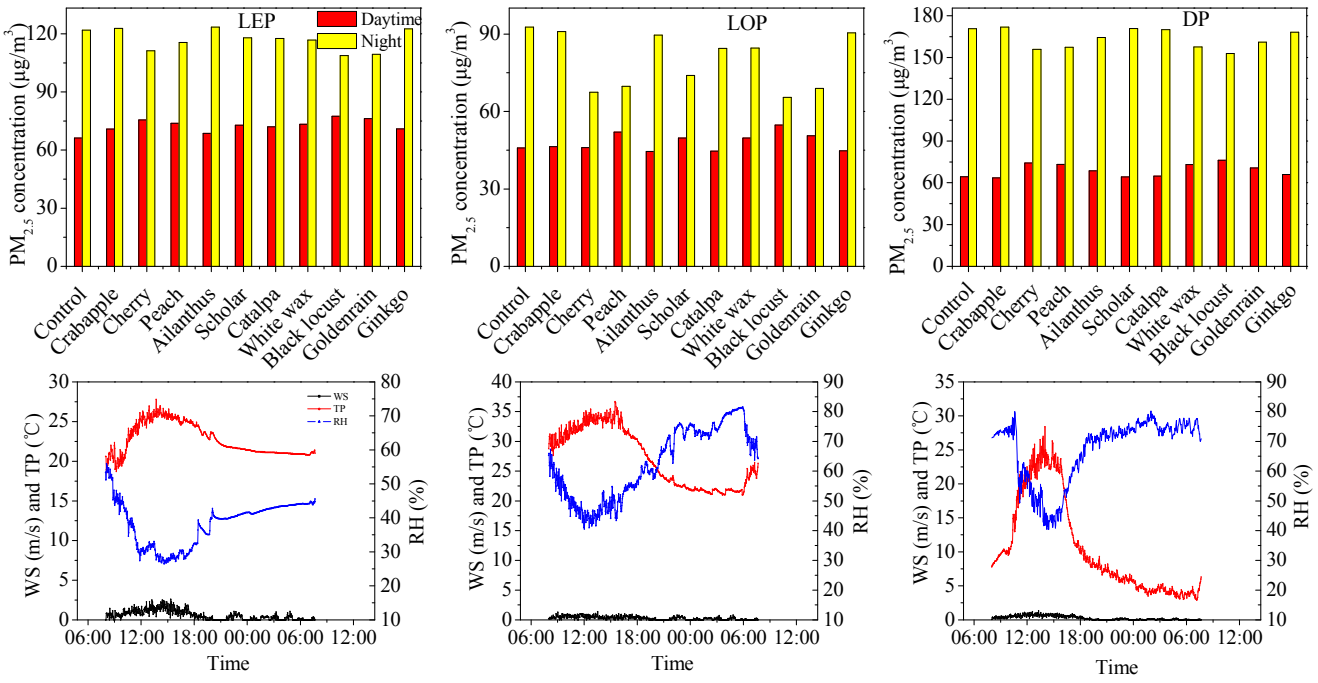

Figure 2. Average $PM_{2.5}$ concentration of 10 forest types and the control area in three leaf growth periods and differing climatic conditions.

Table 2 shows the $PM_{2.5}$ concentration index in different forests. The $PM_{2.5}$ concentration in most of the forests usually was higher than that of the control. Correspondingly, the $PM_{2.5}$ concentration index was negative value during daytime, but this phenomenon was reversed at night (Figure 2 and Table 2). In addition, the absolute value of the $PM_{2.5}$ concentration index in the daytime was higher than at night in the LEP and DP; however, the opposite was true in the LOP. This may occur because the $PM_{2.5}$ spreads

more slowly in forests than in the control area, and $PM_{2.5}$ accumulated in forests. In addition, breezes may lead to $PM_{2.5}$ resuspension on leaves, and trees emit BVOCs that can react with NOx and O_3 to form aerosols during the daytime [16,17]. In contrast, photosynthesis stops and most stomata close at night. The woodland usually had the higher relative humidity than the control area. Plant respiration and higher relative humidity may be more conducive to the deposition of $PM_{2.5}$.

Table 2. Particulate matter $(PM)_{2.5}$ concentration index in different forests.

	Leaf Expansion Period			Leaf Flourish Period			Deciduous Period		
	Daytime	**Night**	**Total**	**Daytime**	**Night**	**Total**	**Daytime**	**Night**	**Total**
Crabapple	−7.04	−0.70	−2.93	−1.07	1.85	0.89	1.10	0.66	0.79
Cherry	−14.04	8.81	0.77	−0.31	11.02	7.27	−15.34	8.96	2.32
Peach	−11.43	5.28	−0.60	−13.36	13.92	4.89	−13.89	8.84	2.63
Ailanthus	−3.64	−1.20	−2.06	2.96	3.28	3.18	−6.66	4.76	1.64
Scholar	−9.98	3.30	−1.37	−8.44	20.17	10.70	0.14	-0.68	−0.45
Catalpa	−8.70	3.61	−0.72	2.66	8.87	6.82	−0.68	0.75	0.36
White wax	−10.71	4.29	−0.99	−8.39	8.73	3.07	−13.64	8.20	2.23
Black locust	−17.00	10.80	1.01	−19.37	29.37	13.24	−18.48	9.44	1.81
Goldenrain	−15.12	10.28	1.34	−10.43	25.60	13.68	−10.00	6.48	1.98
Ginkgo	−7.20	−0.47	−2.84	2.46	2.41	2.43	−2.72	2.54	1.10

3.2. Differences in the $PM_{2.5}$ Concentration Index between the Different Forests

Table 2 records the significant differences between forest types. A positive value indicates the forest $PM_{2.5}$ concentrations were lower than in the control; a negative value indicates that the forest $PM_{2.5}$ concentrations were higher than in the control. As Table 2 shows, the absolute values of the $PM_{2.5}$ concentration index at day or night in Black locust and Goldenrain were higher than in other forests during all three leaf stages. Another notable result is that the $PM_{2.5}$ concentration difference between most species and the control is obvious except for with Crabapple, Ailanthus, and Ginkgo.

The effects of plant species on $PM_{2.5}$ concentration depended on four main factors: deposition, absorption, retardation and released $BVOC_S$. The deposition and absorption of $PM_{2.5}$ in the forests as a whole are mainly affected by the shape of the forest, the structure of the leaves, and the changes in meteorology over time. Retardation is usually affected by a complex forest structure, such as canopy density, LAI, and degree of transparency. The spatial structure of branches and twigs and the shape of leaves also play an important role in the PM filtration properties of a plant. Considering individual leaves, deposition and absorption may be increased or reduced by different surface structures [15].

Plants play an important role in filtering ambient air by adsorbing $PM_{2.5}$ onto leaf surfaces. Forests with a large total leaf area index are considered to be the most effective type of vegetation for this purpose [10]. The structure of tree crowns leads to turbulent air movements, which increases $PM_{2.5}$ deposition and absorption on leaves [31,32]. Some species-specific leaf features *i.e.*, trichrome and the chemical composition and structure of epicuticular waxes may enhance this air filtration process [24,33]. The BVOC emissions and quality have not been confirmed in different kinds of forest. However, the high LAI of forests often allowed for greater amounts of emissions [34,35]. At daytime, the $PM_{2.5}$ was blocked in the forest by forests. Relatively, the $PM_{2.5}$ concentration in the control would be reduced. At

night, the forests have a larger area of the adsorption particles than the non-forest land, because the leaves can absorb a large amount of particulate matter. In addition, the humidity of the forest is larger, it is more prone to condensation of water vapor, which is favorable for the wet deposition of particles. These results showed that forests affect the diffusion rate of particulate matter during daytime and play an important role in the adsorption or deposition of particulate matter at night.

3.3. Effect of Climatic Conditions on $PM_{2.5}$ Concentration

The removal of $PM_{2.5}$ by forests is influenced by a variety of factors. These include not only the forest structure, such as the size and shape of leaves, the trunk, canopy density, LAI, and the nature of the herb layer; $PM_{2.5}$ removal is also affected by meteorological factors such as temperature, relative humidity and wind speed, which all play an important role. These have considerable influence on the speed, the amounts of $PM_{2.5}$ deposition and forest filtration performance.

Wind speed and mixing depth have a strong effect on particulate matter [36]. High wind speed results in dispersion of $PM_{2.5}$ mass concentrations outside the forest; meanwhile, stagnation leads to the accumulation of $PM_{2.5}$ in the forest, thereby changing the $PM_{2.5}$ pollution situation. Temperature usually has a negative correlation with $PM_{2.5}$ [37]. An increase in temperature causes a decrease in airborne nitrate particulates [36,38] and the formation of higher sulfate particulate concentrations because of faster SO_2 oxidation [39,40]. In addition, temperature can also affect the ability of leaf stomata to capture $PM_{2.5}$. The effect of relative humidity on $PM_{2.5}$ is mainly reflected in the processes of nucleation and coagulation. The fundamental effect of humidity on deposition is because particles are mainly hygroscopic, and their size varies as a result of the absorption or discharge of water [30,41,42]. An increase in relative humidity causes an increase in the airborne $PM_{2.5}$ concentration. However, the total amounts of aerosols would decrease when relative humidity increased to a certain degree.

In this study, the $PM_{2.5}$ collection times were analyzed based on data collected during the day without rain, with light wind, and with stable air pressure. Therefore, temperature and relative humidity were the main meteorological factors that influenced $PM_{2.5}$ concentrations. Based on Figure 2, the variation of $PM_{2.5}$ concentration during an entire day can be explained as follows: the lower $PM_{2.5}$ concentration during the daytime is caused by the higher temperature, low relative humidity, and strong wind. In addition, the woodland usually had the lower temperature and wind speed as well as a higher relative humidity than the control. These conditions were conducive to the volatilization of BVOCs, and formation of secondary aerosols during the day. However, these meteorological conditions were propitious to the deposition of $PM_{2.5}$. The meteorological difference between woodland and the control was changed with the variations of forest structures so that the forest structure was primary reason of the $PM_{2.5}$ concentration difference. These results showed that the $PM_{2.5}$ concentration differences between the woodland and control were significant in any forest type with luxuriant foliage compared with in sparse forest types.

3.4. Correlation between the $PM_{2.5}$ Concentration Index and Forest Structure

The $PM_{2.5}$ concentration index has been correlated with forest structure to discover any possible association between the ability of a forest to capture $PM_{2.5}$ and forest structure.

Table 3 shows the correlation of the $PM_{2.5}$ concentration index with forest structure at each stage of leaf growth and the total. Obviously, the correlation between the $PM_{2.5}$ concentration index and height, forestland area, herb height, and herb cover is not prominent. The DBH is uncorrelated with the $PM_{2.5}$ concentration index during the daytime and the LEP, and the other correlation is significant (a = 0.05). However, the correlation between canopy density, LAI and the $PM_{2.5}$ concentration index is almost significant (a = 0.01). These results indicated that the ability of a forest to reduce the concentration of $PM_{2.5}$ is significantly correlated with canopy density, LAI, and DBH, while it is weakly correlated to height, forestland area, herb height, and herb cover. Therefore, the reduction of airborne $PM_{2.5}$ by forests mainly depended on the leaves and trunks.

Table 3. Spearman Rank Correlation Coefficients between the $PM_{2.5}$ concentration index and forest structures.

		DBH	Height	Canopy Density	LAI	Forestland Area	Herb Height	Herb Cover
LEP	Daytime	−0.427	−0.427	−0.936 **	−0.918 **	0.223	0.316	0.088
	Night	0.264	0.255	0.855 **	0.855 **	−0.360	−0.330	−0.084
	Total	0.155	0.055	0.573 *	0.609 *	−0.351	−0.223	0.042
LOP	Daytime	−0.245	−0.255	−0.791 **	−0.773 **	0.383	0.416	0.325
	Night	0.609 *	0.509	0.909 **	0.836 **	0.096	−0.475	−0.297
	Total	0.621 *	0.491	0.773 **	0.691 *	0.232	−0.393	−0.261
DP	Daytime	−0.304	−0.247	−0.665 **	−0.628 **	0.289	0.216	0.183
	Night	0.385 *	0.255	0.861 **	0.853 **	−0.170	0.135	0.179
	Total	0.381 *	0.268	0.616 **	0.554 **	−0.050	0.233	0.250
Total	Daytime	−0.323	−0.247	−0.665 **	−0.628 **	0.289	0.216	0.144
	Night	0.377 *	0.246	0.848 **	0.832 **	−0.184	0.105	0.147
	Total	0.356 *	0.263	0.583 **	0.517 **	−0.053	0.226	0.218

** Correlation is significant at the 0.01 level; * Correlation is significant at the 0.05 level.

Another notable result is that the Spearman Rank Correlation Coefficient during the LOP is higher than other foliage-related periods. This result may occur because physiological activities of trees are very strong during the LOP. The leaves and trunks can adsorb a large quantity of $PM_{2.5}$. However, the stronger physiological activities mean the trees release additional BVOC emissions. The effects of the herb layer are small, but they cannot be ignored. The herb layer can reduce the source of $PM_{2.5}$ by covering the ground surface [43]. The herb layer can reduce dust pollution caused by wind erosion that carries PM into the air [27]. This result indicate that forests have the greatest influence on the $PM_{2.5}$ concentration at mature stage.

Figure 3 shows the linear relationships between DBH, canopy density, LAI and the $PM_{2.5}$ concentration index including three stages of leaf growth. Figure 3a–c show the $PM_{2.5}$ concentration index has a weakly negative correlation (r = −0.323) with DBH during the daytime and a positive association (a = 0.05) at night (r = 0.377) and total (r = 0.356; Table 3). About 18% of the variance in the $PM_{2.5}$ concentration index in the day and at night and 8% of the variance during an entire day can be explained by its linear relationship with DBH. A higher DBH leads to a significant difference in the $PM_{2.5}$ concentration between forests and the control. This indicates that the PM absorption of trunks should not be ignored.

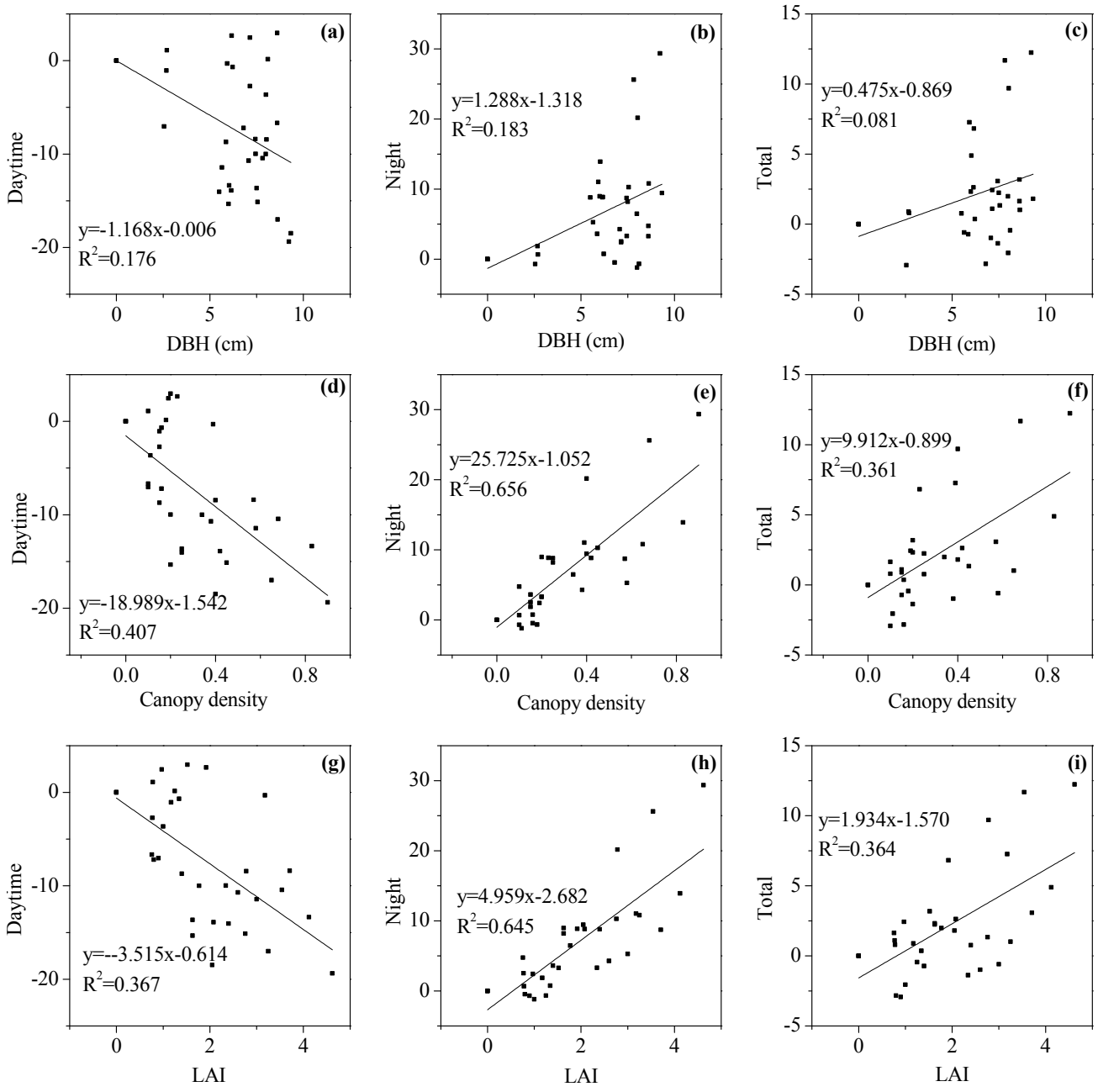

Figure 3. Effects of DBH, canopy density, and LAI on the $PM_{2.5}$ concentration index during daytime and night. (**a**–**c**) The linear relationships between DBH and the $PM_{2.5}$ concentration index; (**d**–**f**) The linear relationships between canopy density and the $PM_{2.5}$ concentration index; (**g**–**i**) The linear relationships between LAI and the $PM_{2.5}$ concentration index at daytime, night, and whole day—three diurnal time periods.

The forest canopy density represents the degree of canopy cover ground. Figure 3d shows that the $PM_{2.5}$ concentration index had a significant ($a = 0.01$) correlation with forest canopy density ($r = -0.665$) during the daytime. The regression line shows that 40.7% of the variation in the $PM_{2.5}$ concentration index was associated with canopy density. Figure 3e shows that the $PM_{2.5}$ concentration index was positively significantly correlated ($a = 0.01$; $r = 0.848$) with forest canopy density at night. About 65.6% of the variation in the $PM_{2.5}$ concentration index may be explained by its linear relationship with forest

canopy density. Figure 3f shows that a positive correlation exists ($a = 0.01$; $r = 0.583$) between the $PM_{2.5}$ concentration index and forest canopy density during an entire day with 36.1% of the variation in the $PM_{2.5}$ concentration index caused by forest canopy density.

The forest canopy density and leaf area index mainly depend on the degree of luxuriant foliage. The leaf area index (LAI) is a dimensionless quantity that characterizes plant canopies [44]. Therefore, the linear relationship between the $PM_{2.5}$ concentration index and the leaf area index is consistent with forest canopy density. Figure 3g shows that a negative correlation ($r = -0.628$) exists between the $PM_{2.5}$ concentration index and LAI during the daytime with 36.7% of the variation in the $PM_{2.5}$ concentration index caused by the LAI. The $PM_{2.5}$ concentration index has a statistically significant correlation ($r = 0.832$) with LAI at night and a good correlation ($r = 0.517$) during an entire day. About 64.5% of the variance in the $PM_{2.5}$ concentration index at night and 36.4% of the variance during an entire day can be explained by its linear relationship with LAI. The forest canopy density and LAI represent the luxuriant dense of forest canopy, so these results indicate that the ability of forests to affect $PM_{2.5}$ concentration mainly depend on the forest canopy.

4. Conclusions and Recommendations for Application

This study attempts to characterize the differences in the $PM_{2.5}$ concentrations in different forest types and their correlation with forest structure. The average $PM_{2.5}$ mass concentration was lowest in the LOP. Meanwhile, the different forests had markedly different $PM_{2.5}$ concentrations. The $PM_{2.5}$ concentrations in the forest usually were higher than the control. Correspondingly, $PM_{2.5}$ concentration indexes were negative values during daytime, but this results were reversed at night. The main air pollution-related function of forests is to prevent the spread of $PM_{2.5}$ caused the retention of $PM_{2.5}$ in the forest during daytime, and absorb or deposit $PM_{2.5}$ lead to the reduction of $PM_{2.5}$ concentrations at night. All forests are most effective at removing $PM_{2.5,}$ when the leaves are fully developed. Forest structure was primary reason of the $PM_{2.5}$ concentration difference between different forests. Among forest structures, canopy density and LAI show a significant correlation to the $PM_{2.5}$ concentration index, and DBH shows a weak correlation to the $PM_{2.5}$ concentration index; therefore, the sequestration of $PM_{2.5}$ by forests from air mainly depended on the canopy. Although herb height and herb cover were not correlated to the $PM_{2.5}$ concentration index, this layer can help reduce dust pollution caused by wind erosion that carries PM back into the air.

In terms of application, results from this study suggest that in a high $PM_{2.5}$ emission area, especially around factories and roads, tree species with faster growth should be chosen for afforestation, and some appropriate herbs should be planted. These measures should be aimed at blocking the diffusion of $PM_{2.5}$ and removing $PM_{2.5}$ in the forest.

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Author Contributions

Xuhui Liu and Xinxiao Yu conceived and designed the experiment. The paper was written by Xuhui Liu with a significant contribution by Zhenming Zhang.

Conflicts of Interest

The authors declare no conflict of interest.

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