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Original Research

Pollution Remediation by Urban Forests: $PM_{2.5}$ Reduction in Beijing, China

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Abstract

We based our research on real-time monitoring data for $PM_{2.5}$ at the Beijing Municipal Environmental Protection Monitoring Center of Haidian Beijing Botanical Garden (a vegetated area), and at Haidian Wanliu (a non-vegetated area). By combining these two data points with the $PM_{2.5}$ and meteorological data from a separate monitoring station in Beijing Botanical Garden's forest interior, we analyzed the daily fluctuation, regional variation, and foliar adsorption characteristics of $PM_{2.5}$ in varied environments (Feb.-Dec. 2013 and Jan.-Feb. 2014). Our results show a double peak and valley pattern of $PM_{2.5}$ daily variation and daytime values greater than nighttime measurements. Average annual $PM_{2.5}$ concentration values at different monitoring stations were Haidian Wanliu (100.61±26.49 $\mu g \cdot m^{-3}$), greater than at the Beijing Botanical Garden forest interior monitoring station (89.72±23.49 $\mu g \cdot m^{-3}$), and both greater than at Haidian Beijing Botanical Garden (77.72±23.37 $\mu g \cdot m^{-3}$). The maximum $PM_{2.5}$ concentrations during 12 months were all in Haidian Wanliu (non-vegetated area), while the minimums were all in Haidian Beijing Botanical Garden (vegetated), Haidian Wanliu being 83.33% of the time higher in $PM_{2.5}$ concentration than Beijing Botanical Garden forest interior. Possibly because of the trees, $PM_{2.5}$ concentrations in the forest area were lower than that in the non-vegetated area. We find an average $PM_{2.5}$ adsorption capacity per unit leaf area of 0.048±0.031 $\mu g \cdot cm^{-2}$ - 0.645±0.034 $\mu g \cdot cm^{-2}$ in May, and 0.058±0.006 $\mu g \cdot cm^{-2}$ - 0.887±0.014 $\mu g \cdot cm^{-2}$ in June for the 10 tree species included in our study. Of these 10, incense *Cedrus deodara* evidences the greatest adsorption and *Sophora japonica* shows the minimum. As a whole, conifers adsorb at 1.32 times the rate of broadleaf tree species, according to our data. $PM_{2.5}$ adsorption capacity was greater in June (0.294±0.227 $\mu g \cdot cm^{-2}$) than in May (0.215±0.184 $\mu g \cdot cm^{-2}$). Daily and annual variation in different regions falls into a pattern where Haidian Wanliu pollution is greater than Beijing Botanical Garden forest interior monitoring station, and both are greater than Haidian Beijing Botanical Garden, which confirms the forest ecosystem's involvement. It appears that the forest has many functions, including atmospheric purification

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by adsorption of $PM_{2.5}$ and other particulates as evidenced by better air quality in forest areas than in non-vegetated sites. Furthermore, forest clearings show better air quality than the forest interior.

Keywords: urban forest, remove function, $PM_{2.5}$, aerosol generator, Beijing nitrification and denitrification, functional bacteria

Introduction

Particulate pollution of the atmosphere is currently the main problem facing urban air quality management [1-2]. Urban vehicles, plus smokestacks and incinerators of industrial zones, discharge large quantities of soot. Long-term exposure of the human body to combustion-related fine particulate air pollution has become a significant risk factor in lung cancer and cardiopulmonary disease mortality [3-4].

Of the urban aerosol mix, $PM_{2.5}$ is most important to human health. The complex chemical composition, small particle size, and prolonged atmospheric retention properties of $PM_{2.5}$ impact the environment significantly, including reducing visibility, altering cloud formation processes [5], damaging forests and crops, and reducing biological diversity [6]. $PM_{2.5}$ contains many toxic and harmful compounds such as acids, polycyclic aromatic hydrocarbons, and heavy metals that have been shown in epidemiological studies to directly impair human health – especially respiratory functions [7-9]. While there are many harmful compounds in pollution, $PM_{2.5}$ is most directly related to adverse human health [10].

With rapid economic development, continuous urban expansion, sharp population rise, and accompanying motor vehicles, atmospheric pollution has reached serious levels in Beijing, China's capital [11]. As the environmental load becomes heavier and harmful gases, smoke, and dust increase in the air, $PM_{2.5}$ has gradually become the primary air pollutant [12-13]. At present, the study of particles concentrates on composition and sources of particulate matter, variation in mass concentration, and effects of meteorological factors on particulate matter and particulate monitoring methods [14-16]. However, research on forest filtration of $PM_{2.5}$ combined with vegetation information, meteorological conditions, and particle concentration levels is especially lacking, leading to less-than-comprehensive ecological information available for city forest management and air quality improvement. Therefore, studying forest $PM_{2.5}$ regulation function has become a hot topic for urban ecology and environmental science. In order to improve the city's air quality and its residential environment, it is immediately necessary to treat haze to remove emitted pollutants from the atmosphere and reduce particulate air pollution in Beijing and other ecologically fragile regions [4].

The green plant is a natural enemy of $PM_{2.5}$ fine particles [17]. Hence, urban forest management is accepted as an important control measure due to the strong function of forests in detaining dusts, absorbing pollutants, and reducing dust transportation, thereby purifying the atmosphere [18-19]. Using the foliar surface area of the forest to absorb particulates has become a prominent $PM_{2.5}$ treatment method. In Germany, mixed forests were estimated to reduce atmospheric $PM_{2.5}$ by about 12% [20-21]. For instance, it has been found that coniferous forests and Norway spruce forests have notably changed the sulfur concentration and $PM_{2.5}$ deposition rates in central Japan [22-23]. Hwang et al. [4] chose five tree species to perform a chamber experiment whose results show that the intercept potential of conifers is higher than that of broadleaf trees. Neinhuis et al. [24] have proposed that *Ginkgo biloba* has "self-cleaning" characteristics, so its particle retention ability is poor [25].

Matsuda et al. [22] analyzed sulfate flux of $PM_{2.5}$ in deciduous forests of varied heights during the central Japanese summer, finding that $PM_{2.5}$ concentration at 27 m is significantly higher than at 21 m, which indicates retention and adsorption of pollutants descending the foliage column. As air filters through foliated strata, $PM_{2.5}$ concentration significantly decreases, as well as sulfur concentration and the settlement rate of $PM_{2.5.}$ Wang et al. [26] conjectured that conifers with smaller leaves, more complex stems, and evergreen foliage would more effectively adsorb atmospheric particles, choosing six conifer species for comparison. Their results evidence that the highest density of particles were trapped by Chinese arborvitae *(Platycladus orientalis)*, the second being incense or deodar cedar (*Cedrus deodara)*. He et al. [27] selected 30 landscape tree species form northern zones, and found the best dust removal effects in shrubby cinquefoil *(Potentilla fruticosa)* and rose pea-shrub *(Caragana rosea)*, which are good candidates for greening areas with heavy dust pollution. Previous studies often applied the "water washing method," and a number of studies have focused on the dust removal effect of trees, but research so far lacks innovation and studies on particle absorption by trees of variously-sized particles.

We use real-time $PM_{2.5}$ monitoring data at the Beijing Municipal Environmental Protection Monitoring Center of Haidian Beijing Botanical Garden (vegetated area) and Haidian Wanliu (non-vegetated area), combined with the $PM_{2.5}$ data and meteorological data from the forest interior monitoring station in Beijing Botanical Garden. We applied an aerosol generator to quantify foliar adsorption of $PM_{2.5}$, concentration variation characteristics and $PM_{2.5}$ adsorption capacity of different tree species. Under the time scale in the city forest ecological system and non-vegetated area we carried out these measurements to explore forest ecosystem removal of $PM_{2.5}$, interpret the forest air purification function, and provide reference for urban forest measurement and management.

Study Area

Beijing Botanical Garden forest interior monitoring station and its sampling equipment are located in northwestern Beijing Botanical Garden's Korean pine *(Pinus koraiensis)* grove at the foot of Xishan (Xi Mtn.). The total area of the garden is 4 km^2. It is a display and conservation piece of plant resources, for scientific research, popular science, tourism, and development as one integrated botanical garden. About 18 km from downtown, it is located at 39°48'N, 116°28'E, and the altitude is 76 m, belonging to a temperate continental climate. Annual average temperature here is 11.6ºC and the mean temperature is -3.7ºC in January, 26.7ºC in July. Extreme average annual high temperature is 41.3ºC, while extreme low temperature is -17.5ºC. Average annual rainfall and relative humidity are 634.2 mm and 43%-79%, respectively.

There are more than 6,000 kinds of plants in the garden, including 2,000 species of trees and shrubs, 1,620 species of tropical and subtropical plants, 500 kinds of flowers, and 1,900 other species, including fruit trees, aquatic plants, Chinese herbal medicine, and others. The main tree species include *Pinus tabulaeformis*, *Platycladus orientalis*, *Pinus koraiensis*, *Cedrus deodara, Pinus bungeana*, *Eucommia ulmoide Salix babylonica*, *Ginkgo biloba*, and *Sophora japonica*. Significant shrubs include *Ligustrum lucidum*, *Berberis thunbergii*, *Buxus sinica*, *Sabina vulgaris*, *Forsythia suspensa*, and *Jasminum nudiflorum*.

The Environmental Protection Monitoring Center of Haidian Beijing Botanical Garden in Haidian is the same site as the whole botanical garden ecosystem, a "glade" of sorts in an island of vegetation. Haidian Wanliu monitoring station is located in Haidian District near the city center, within the fourth ring road, and is part of a non-vegetated area in which commercial, residential, and shopping districts, plus heavy traffic flourish.

Study Methods

Research Stations

This project is based on forestry standards as found in "Observation Methodology for Long-Term Forest Ecosystem Research" of the People's Republic of China. From the 35 monitoring stations for $PM_{2.5}$, we chose two monitoring sites at Beijing Environmental Protection Monitoring Center, located in Haidian at Beijing Botanical Garden and Wanliu. The Beijing Botanical Garden forest interior monitoring station is located within the *Pinus koraiensis* forest at Beijing Botanical Garden, used to monitor the forest's $PM_{2.5}$ concentration variation. Our $PM_{2.5}$ instrument was manufactured by Thermo (Fisher Scientific Co., USA) with TEOM-1405-D double channel online particle monitor, which records hourly samples around the clock. Beijing Botanical Garden's forest station represents a forest ecosystem site. Haidian Beijing Botanical Garden station represents an entire botanical garden ecosystem, and is located in an open landscape about 200 m from the forest interior monitoring station. Haidian Wanliu station provides an example for non-vegetated sites, located in the city center about 6.2 km from the forest station in Beijing Botanical Garden. Fig. 1 shows the distribution of monitoring stations.

Data Acquisition

$PM_{2.5}$ real-time concentration data for Haidian Wanliu (non-vegetated area) and Haidian Beijing Botanical Garden (open area within vegetated area) were obtained by the Beijing Municipal Environmental Protection Monitoring Center, the $PM_{2.5}$ real-time concentration in forest by the monitoring station in Beijing Botanical Garden's Korean fir grove. We obtained real-time weather data for Beijing Botanical Garden and Haidian Wanliu. Our meteorological data borrow mostly from the China Weather Network (www.weather.com.cn), including temperature, relative humidity, wind speed, rainfall, and other meteorological factors. The "±" symbol means standard deviation, and all data is "mean±SD."

Tree Species

For our study, we selected trees of common species and similar age at Beijing Botanical Garden, five species each of coniferous and deciduous trees: including incense or deodar cedar *(Cedrus deodara)*, a species of juniper *(Juniperus sp.)*, Korean pine *(Pinus koraiensis)*, *Yousong* or Chinese red pine *(Pinus tabulaeformis)*, *Baipisong* or lacebark pine *(Pinus bungeana)*, black locust *(Robinia pseudoacacia)*, ginkgo *(Ginkgo biloba)*, Japanese pagoda tree *(Sophora japonica)*, Siberian apricot *(Prunus sibirica)*, and a lilac species *(Syringa sp.)*.

Leaf Collection Method

On a monthly basis, we cleaned the entire foliage of the sample trees. After cleaning the trees for one month we selected three sample trees (similar in age) from each

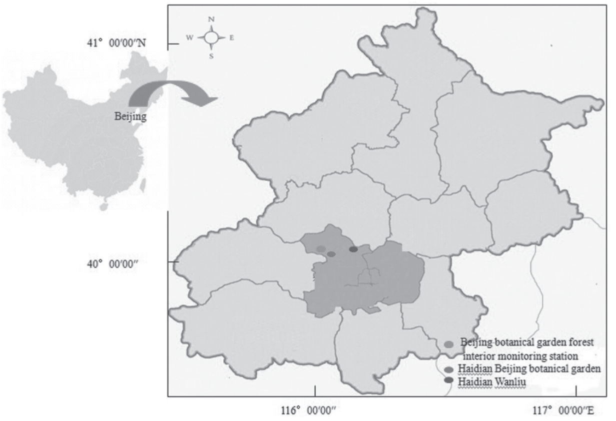

Fig 1. $PM_{2.5}$ monitoring station locations.

of the chosen species and collected sample leaves from the eastern, southern, western, and northern quadrants of the foliage. We transported the sample leaves in sealed, non-static plastic bags to the laboratory for treatment.

$PM_{2.5}$ Absorption Rate per Unit of Leaf Surface

We developed and used our own aerosol generator (QRJZFSQ-I, China) to assay the absorption capacity of total foliar $PM_{2.5}$ and other particles. Based on the wind erosion principle, leaves were added to the materials box of the aerosol generator, and they were stirred and blown to remove static electricity so that the particles on the leaves could make aerosol. We then used a Dustmate (Cp2x/430, html, Britain) handheld $PM_{2.5}$ monitor to measure the mass of the aerosolized $PM_{2.5}$. We performed this protocol for each selected sample species three times. To find the total surface area of all leaf material in the box, we then used a leaf area scanner and leaf area software (EPSON Perfection V700, Japan). The $PM_{2.5}$ adsorption capacity per unit leaf area was determined using the following formula (1):

$$m = m_1 / S \tag{1}$$

…where m is $PM_{2.5}$ adsorption capacity of the unit leaf area ($\mu g \cdot cm^{-2}$), m_1 is the $PM_{2.5}$ adsorption capacity of leaves inside the aerosol generator (g), and S is leaf area (cm^2).

Results and Analysis

Different Time Scales of $PM_{2.5}$ Dynamic

Daily Fluctuation

Fig. 2 illustrates the daily $PM_{2.5}$ variation from three separate monitoring stations. In order to avoid the influence of typical weather and the degree of pollution, we chose a day (3 July 2013) with sun and excellent air quality ($PM_{2.5}$ concentration under $60 \mu g \cdot m^{-3}$). In Fig. 2, $PM_{2.5}$ appears as a typical double peak curve at the three monitoring stations. Haidian Wanliu increased from $41 \mu g \cdot m^{-3}$ at 07:00 to $54 \mu g \cdot m^{-3}$ at 10:00, then began to decline, the lowest value ($21 \mu g \cdot m^{-3}$) occurring at 16:00, reaching a second afternoon peak of $47 \mu g \cdot m^{-3}$ at 18:00 and then declining continually. Beijing Botanical Garden's forest interior monitoring station began at 04:00, rising to a peak of $38 \mu g \cdot m^{-3}$ at 10:00 in the morning, then declining sharply to its lowest value of $8 \mu g \cdot m^{-3}$ at 13:00. From 13:00, the concentration continued to rise toward the maximum day's value at 18:00 during the afternoon at $42 \mu g \cdot m^{-3}$, then declined to the low of $11 \mu g \cdot m^{-3}$ at 23:00. Haidian Beijing Botanical Garden revealed the same trend, where from 06:00 in the morning $PM_{2.5}$ started to increase, and reached the maximum value of $28 \mu g \cdot m^{-3}$ at 11:00, then declined to $14 \mu g \cdot m^{-3}$ at 14:00, rising to a peak of $18 \mu g \cdot m^{-3}$ at 16:00 and reaching the lowest value of $9 \mu g \cdot m^{-3}$ at 19:00.

Wanliu's $PM_{2.5}$ concentration ($36.79 \pm 9.20 \mu g \cdot m^{-3}$) was greater than Beijing Botanical Garden's forest interior monitoring station ($22.04 \pm 9.35 \mu g \cdot m^{-3}$), and both were greater than Beijing Botanical Garden ($15 \pm 5.39 \mu g \cdot m^{-3}$) on the same day. Daily values flux occurred from 06:00-18:00, with a parallel event overnight. Again, $PM_{2.5}$ concentrations at Wanliu ($39.23 \pm 9.80 \mu g \cdot m^{-3}$) registered higher than Beijing Botanical Garden's forest interior monitoring station ($22.38 \pm 9.68 \mu g \cdot m^{-3}$), and both exceeded Beijing Botanical Garden ($18.23 \pm 5.21 \mu g \cdot m^{-3}$) on that day. Evening tallies show Wanliu ($33.91 \pm 7.48 \mu g \cdot m^{-3}$) above Beijing Botanical Garden's forest interior monitoring station ($21.64 \pm 8.93 \mu g \cdot m^{-3}$), and both above Beijing Botanical Garden ($11.18 \pm 2.12 \mu g \cdot m^{-3}$). The daily variation at different monitoring stations is: Wanliu by day ($39.23 \pm 9.80 \mu g \cdot m^{-3}$) was greater than at night ($33.91 \pm 7.48 \mu g \cdot m^{-3}$), Beijing Botanical Garden's forest interior monitoring station by day ($22.38 \pm 9.68 \mu g \cdot m^{-3}$) was also higher than night ($21.64 \pm 8.93 \mu g \cdot m^{-3}$), and Beijing Botanical Garden yielded similarly higher day ($18.23 \pm 5.21 \mu g \cdot m^{-3}$) than night values ($11.18 \pm 2.12 \mu g \cdot m^{-3}$).

To summarize, the $PM_{2.5}$ concentration shows double peaks (morning and evening – "morning peak and afternoon valley") and daily variation with daytime values greater than at night. We feel these events closely relate to commuting city traffic rush hours as well as increased business-hours for industrial production, which causes more pollutants. Early morning conditions included ground radiation of heat, rapid cooling, and temperature inversion, so that the near-surface atmospheric convection was weak and not conducive to the spread of particles, possibly increasing concentration. Temperature was the highest at noon – potentially accelerating photochemical processes in the atmosphere, which was at the time also unstable, with strong turbulence and thus full convection, enabling the dissipation of pollutants. As production ceased for the night, so did the pollution sources.

From the different monitoring stations, the $PM_{2.5}$ concentrations in botanical garden monitoring stations were all lower than those in non-vegetated areas, averaging 40.77-59.91% lower. $PM_{2.5}$ concentration in Haidian Wanliu was greater during 100% of sample time than in Haidian Beijing Botanical Garden, and 83.33% of the time greater than Beijing Botanical Garden's forest interior monitoring station during the day. Therefore, $PM_{2.5}$ concentrations in the vegetated areas were lower than those in non-vegetated areas, indicating the forest's strong ability to absorb $PM_{2.5}$. Forests can prevent, detain, and absorb dust and degrade pollutants, and their large crowns provide numerous ecological benefits. Trees are plentiful in the botanical garden, and vegetation cover rate is high, enhancing forest biological activity. At the same time, these vegetated areas are away from the city center, where factory sources play a smaller role in total pollutants, making pollution lighter in forested areas. In addition, $PM_{2.5}$ concentration inside the forest was greater than in a "glade" within the forest ecological system. Seventy-five percent of the sampled time the concentration in *Pinus koraiensis* forest interior was greater than that in the open

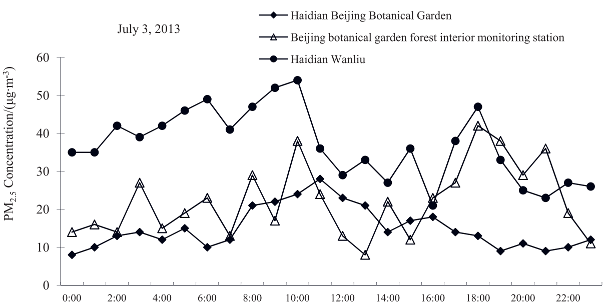

Fig. 2. Diurnal variation of $PM_{2.5}$ concentrations at three monitoring stations.

in Beijing Botanical Garden during the day. Under the same pollution conditions, the forest interior, with low temperature, high humidity and low wind speed, did not dissipate proliferated particles but instead accumulated them, which made the $PM_{2.5}$ concentration inside higher than in the open. The principle factor causing this is the absorption and accumulation effect of forests, their great numbers, and adsorption potential, which traps more pollutants and causes them to move to the interior. Thus the PM2.5 concentration is lower in open areas within vegetated surroundings.

Annual Variation of $PM_{2.5}$ at Various Monitoring Stations

Fig. 3 portrays the annual variation in $PM_{2.5}$ concentrations at three different monitoring stations, from March 2013 to February 2014. $PM_{2.5}$ concentrations varied widely at different monitoring stations. Wanliu has the widest range, Beijing Botanical Garden's forest interior monitoring station second, and Beijing Botanical Garden last. In 100% of the 12 sampled months, $PM_{2.5}$ concentrations in [Haidian] Wanliu and Beijing Botanical Garden's forest interior monitoring stations registered higher levels than Haidian Beijing Botanical Garden, and 83.33% of the time Wanliu was more polluted than Beijing Botanical Garden's forest interior monitoring station. In Haidian Wanliu, the $PM_{2.5}$ concentration average was 66.76 $\mu g \cdot m^{-3}$-162.24 $\mu g \cdot m^{-3}$, with a mean value of 100.6±26.49 $\mu g \cdot m^{-3}$, while at Beijing Botanical Garden's forest interior monitoring station, concentration averaged 63.58 $\mu g \cdot m^{-3}$-150.71 $\mu g \cdot m^{-3}$, with a mean of 89.72±23.49 $\mu g \cdot m^{-3}$, and Beijing botanical Garden averaged 51.81 $\mu g \cdot m^{-3}$-138.45 $\mu g \cdot m^{-3}$, while the mean was 77.72±23.37 $\mu g \cdot m^{-3}$.

Over these months, the three monitoring stations' maximum points were all in February 2014, while the minimums occurred in August 2013 in both Haidian Wanliu and Haidian Beijing Botanical Garden, and Beijing Botanical Garden's forest interior monitoring station saw its minimum in February 2013. There were differences among other months, but the variability was low. Three occurrences of heavy pollution in Beijing in February 2014 left only six days of first- and second-grade air quality. The third episode persisted for eight days (20-27 February) with heavy pollution. $PM_{2.5}$ concentrations at Haidian Wanliu, Haidian Beijing Botanical Garden and Beijing Botanical Garden's forest interior monitoring station reached 567 $\mu g \cdot m^{-3}$, 464 $\mu g \cdot m^{-3}$, and 900$\mu g \cdot m^{-3}$, respectively, under seriously polluted conditions. Additionally, February is coal-burning season in Beijing, another emissions source and a factor in the year's worst pollution event. The average $PM_{2.5}$ concentration at Beijing Botanical Garden's forest interior monitoring station was higher than that at Haidian Wanliu and Haidian Beijing Botanical Garden in both July and August. The $PM_{2.5}$ concentration at Beijing Botanical Garden's forest interior monitoring station (80.32±21.54 $\mu g \cdot m^{-3}$) was again higher than at Haidian Wanliu (75.59±25.02 $\mu g \cdot m^{-3}$), and the lowest was Haidian Beijing Botanical Garden (58.04±19.68 $\mu g \cdot m^{-3}$) in July. During August the pattern was repeated: Beijing Botanical Garden's forest interior monitoring station (82.22±18.65 $\mu g \cdot m^{-3}$), more than Haidian Wanliu (66.76±33.85 $\mu g \cdot m^{-3}$), and the least in Haidian Beijing Botanical Garden (51.81±25.91 $\mu g \cdot m^{-3}$). We conclude that monsoonal weather and more intense heat during July and August in Beijing created special conditions. With temperatures up to 38°C and a mean temperature of 27.36°C, these "sauna days" of high temperature and high humidity create stagnant and retentive conditions within the forest, leading to $PM_{2.5}$ concentrations in a forest interior more than that in non-vegetated areas. Within the forest ecosystem of Beijing Botanical Garden, $PM_{2.5}$ concentration was still lower than that in non-vegetated areas, yet the $PM_{2.5}$ concentration was greater than in the open area of the botanical garden.

Above all, lack of vegetation cover and adsorption of pollution by trees, coupled with the accumulation of people, traffic flow, and accompanying emissions lead to higher $PM_{2.5}$ concentrations in non-vegetated areas. The forest interior and "glade" areas mimic forest ecosystems. Due to plant cover, a portion of pollutants are adsorbed by foliage. In addition, its location at the edge of the city experiences less traffic flow and emissions so that $PM_{2.5}$ concentrations are generally low in the forest ecosystem. The forest interior is relatively windless, decreasing diffusion, increasing humidity, and decreasing convection, with stable conditions magnified by the coolness of shade,

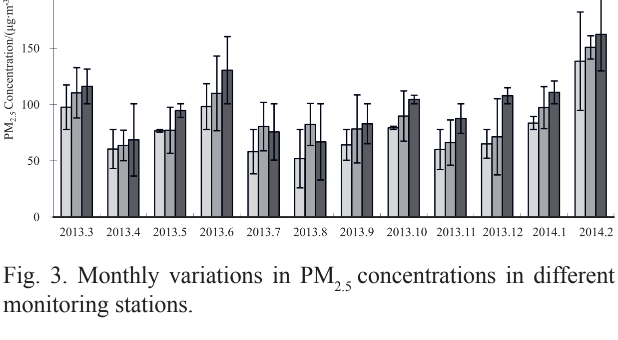

Fig. 3. Monthly variations in $PM_{2.5}$ concentrations in different monitoring stations.

all of which encourage particulate concentration relative to open areas [28-29]. On the other hand, the large number of trees in the forest interior provides heightened and continuous adsorption and accumulation by foliage, making pollutants penetrate the forest interior so that $PM_{2.5}$ concentration was reduce reduced in the open "glade" station.

$PM_{2.5}$ Absorption Feature Variation between Tree Species

According to time-relative $PM_{2.5}$ analysis, $PM_{2.5}$ concentrations in forest areas are far lower than in non-vegetated areas, but this is not enough to describe the powerful $PM_{2.5}$ removal function of the forest ecosystem. Tree leaves can adsorb a large amount of pollution particles and play a vital role air purification, but how this can be embodied in terms of scientific data and quantifying the $PM_{2.5}$ absorption capacity of a forest has not been addressed. Therefore, we calculated the $PM_{2.5}$ adsorption amount of different tree species per unit of leaf area, and analyzed the $PM_{2.5}$ absorption rates of 10 tree species.

Fig. 4 charts the actual $PM_{2.5}$ adsorption amount per unit of leaf area for various tree species. Because deciduous species in our list are dormant in Beijing annually from January to April, we selected two months in May and June to analyze the $PM_{2.5}$ adsorption capacity of the 10 tree species. Results show different trees with high adsorption capacity. The $PM_{2.5}$ adsorption capacity per unit leaf area for the 10 species were 0.048±0.031 $\mu g \cdot cm^{-2}$-0.645±0.034 $\mu g \cdot cm^{-2}$ in May. The top three performers were *Cedrus deodara, Juniperus spp.*, and *Robinia pseudoacacia,* while the bottom two were *Ginkgo biloba* and *Sophora japonica.* The greatest $PM_{2.5}$ adsorption capacity per unit leaf area (*Cedrus deodara* 0.645±0.034 $\mu g \cdot cm^{-2}$) is 13.42 times above the smallest (*Sophora japonica* 0.048±0.041 $\mu g \cdot cm^{-2}$). Average $PM_{2.5}$ adsorption capacity of unit leaf area for the different species was (0.058±0.006) $\mu g \cdot cm^{-2}$-(0.887±0.014) $\mu g \cdot cm^{-2}$ in June; and the top three were *Cedrus deodara, Pinus bungeana*, and *Pinus tabulaeformis* while the bottom two were *Siberian Apricot* and *Sophora japonica*. The largest $PM_{2.5}$ absorption capacity of unit leaf area (*Cedrus deodara* 0.887±0.014 $\mu g \cdot cm^{-2}$) was 15.19 times greater than the smallest (*Sophora japonica* 0.058±0.006 $\mu g \cdot cm^{-2}$). Consequently, the highest $PM_{2.5}$ absorption capacity in conifers per unit leaf area appears to be *Cedrus deodara*, which is consistent with research results of Beckett, et al. in a British park [30]. Their results place pine (195 $mg \cdot m^{-2}$) over Cypress (61 $g \cdot m^{-3}$) for $PM_{2.5}$ adsorption capacity.

Their given reasoning suggests a feature of leaf surface characteristics leading to atmospheric particle retention capacity. Surface roughness and density of villi on pine needles are higher than on cypress scales. Villi were found to cause particle adhesion, thereby possibly strengthening the adsorption effect. *Sophora japonica* yielded the lowest numbers for deciduous species in May and June. $PM_{2.5}$ adsorption capacity per unit leaf area yielded conifers (0.213±0.207 $\mu g \cdot cm^{-2}$) greater than broadleaf species (0.113±0.063 $\mu g \cdot cm^{-2}$) in May. June showed conifer (0.450±0.225 $\mu g \cdot cm^{-2}$) greater than broadleaf (0.138±0.063 $\mu g \cdot cm^{-2}$). The adsorption rate of conifers appears to be 1.32 times that of broadleaf trees, the reason being that conifer trees have much more villus and leaf lipide. Conifers in general exude highly viscous oils and resins (terpenoids), plus they are mostly evergreen (*Larix spp.* being one exception), meaning that they can perform purification year-round. During spring, $PM_{2.5}$ adsorption ability per unit leaf area in June (0.294±0.227 $\mu g \cdot cm^{-2}$) was greater than in May (0.215±0.184 $\mu g \cdot cm^{-2}$), and average $PM_{2.5}$ adsorption capacity per unit leaf area for our species group in June was 1.38 times that in May. We feel the reason is particle accumulation over time. Pollutant accumulation time was long in June compared to May. On the other hand, our results do correlate to $PM_{2.5}$ concentrations. For example, the atmospheric $PM_{2.5}$ concentration in June was (109.89±33.20) $\mu g \cdot m^{-3}$, which was greater than in May at (77.10±20.45) $\mu g \cdot m^{-3}$. Adsorption rates were 1.42 times higher in June than in May, suggesting that leaves absorb more pollutants in June than in May.

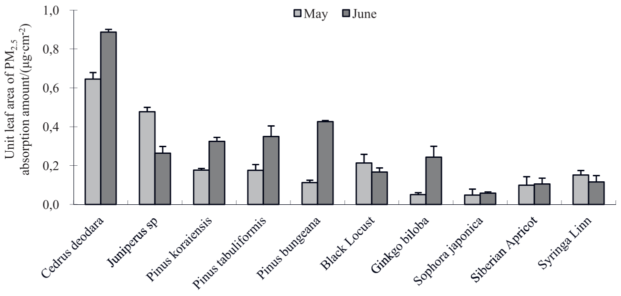

Fig. 4. Unit leaf area of $PM_{2.5}$; actual absorption quantity by species.

Discussion

$PM_{2.5}$ Temporal Variation

Daily fluctuation of $PM_{2.5}$ concentration was higher by day than night, as was degree of variation, which is the combined result of pollutant emission and meteorological conditions. People's production activities decrease at night, as well as the pollution sources. Around dawn, human activities gradually increase, and pollutant emissions as well. Moreover, conditions not conducive to particulate dissipation prevail in the morning: ground radiation, rapid cooling, and temperature inversion producing weak near-surface convection. A "morning peak, noon valley" of pollution change pattern appears over the days. The peak value occurred between 06:00-10:00, closely related to work time, intensive traffic, high exhaust emissions and road dust. The second peak was at 16:00-19:00, but not as marked as for the main peak (except severe pollution). The peaks and valleys form due to human rush hours and atmospheric inversion layers. In the morning and evening, due to the inversion layer, rush hour automobile exhaust pollutants do not readily dissipate. After 23:00, with reduced human activities, $PM_{2.5}$ concentration decreases until 07:00 the following morning.

The largest $PM_{2.5}$ annual concentrations between the three monitoring stations all fall in February 2014 and June 2013. While the minimum at Haidian Wanliu and Haidian Beijing Botanical Garden were both in August with mean values of 66.76±33.85 $\mu g \cdot m^{-3}$ and 51.81±25.91 $\mu g \cdot m^{-3}$, respectively, the lowest at Beijing Botanical Garden's forest interior monitoring station falls in April, at 63.58±13.55 $\mu g \cdot m^{-3}$. For the period from March 2013 to February 2014, seasonal variations of $PM_{2.5}$ concentration in Haidian Wanliu was: winter (126.91±25.01 $\mu g \cdot m^{-3}$) > spring (93.04±19.43 $\mu g \cdot m^{-3}$) > autumn (91.55±9.28 $\mu g \cdot m^{-3}$) > summer (90.93±28.17 $\mu g \cdot m^{-3}$), and Haidian Beijing Botanical Garden's pattern was winter (95.64±31.20 $\mu g \cdot m^{-3}$) > spring (78.18±15.21 $\mu g \cdot m^{-3}$) > summer (69.31±20.51 $\mu g \cdot m^{-3}$) > autumn (67.75±8.27 $\mu g \cdot m^{-3}$). Beijing Botanical Garden's forest interior monitoring station pattern was winter (106.37±33.10 $\mu g \cdot m^{-3}$) > summer (90.80±13.50 $\mu g \cdot m^{-3}$) > spring (83.68±19.65 $\mu g \cdot m^{-3}$) > autumn (78.03±9.62 $\mu g \cdot m^{-3}$).

Hence $PM_{2.5}$ concentrations over four seasons shows Haidian Wanliu to be greater than Beijing Botanical Garden's forest interior monitoring station, which in turn is greater than Haidian Beijing Botanical garden. The worst air quality was in winter and best in summer. Such seasonal change shows that characteristics of atmospheric pollution in China are dominated by soot and secondary dust, also related to climate, which are weather conditions and seasonal change of local factors. In winter the limited rainfall, dry vegetation, and strong northwest wind tend to cause sandstorms. In addition, inversion layers are frequent, preventing dissipation of pollutants in winter – especially during morning and evening. Furthermore, a large amount of coal is burnt in winter for heat, resulting in higher pollutant emissions [31]. Thermal inversion weather is common in winter, so the atmosphere is relatively stable and not conducive to the diffusion and dilution of pollutants in the air. There are frequent sandstorms in spring, which lead to an increase of dust in the air [32], further affecting air quality. However, precipitation increases in summer and autumn, as well as humidity, vegetation coverage, and solar radiation – all of which enhance heat convection at ground level and reduce the chance of thermal inversion.

Particle Absorption and Species Variation

Many nations use reforestation to control air pollution [33] because trees effectively remove fine particulate matter in the air [34-35]. Forests prevent, detain, and absorb dust and remove pollutants, thereby improving air quality [36-37]. Leaves are the agent in $PM_{2.5}$ absorption by trees, enabled by their different structural adsorption characteristics. Hwang et al. [4] conducted a study that shows that different tree species with different morphological characteristics (such as leaf surface characteristics, canopy structure, leaf density, and leaf angle) have different dust retention potential. Because the leaf is the main agent of ambient particle entrapment by plants [37], Chai et al. [38] tested leaves and found that roughness and density of villi as adhesion points affect particle detention. Neinhuis [39] proved by research that particle detention ability of easily-wet leaves is strong, while those with special surface structures and hydrophobic wax are not readily wetted and also have poor particle detention ability. Tomasevic et al. [40; using SEM-EDAX] studied particles on leaves of horse chestnut *(Aesculus hippocastanum)* and Turkish hazel (*Corylus colurna)*. His results show that particles exist in the form of single particles or aggregates, and particle size ranges above 50 μm, but 50-60% fall within 2 μm. The particle detention ability of leaves possessing groove structures and densely ciliated regions is strong, while those with nodular or warty protuberances is poor [33].

Due to vast morphological differences in the proportions of stem to leaf, leaf type, and leaf weight, a study of species to determine particle detention potential is of great scientific and practical significance. The study on $PM_{2.5}$ adsorption quantity of conifer and broadleaf is less, but for the results of the present study the $PM_{2.5}$ adsorption quantity of a conifer is larger than broadleaf [4]. Compared to shrubs and forbs, trees capture suspended particles more effectively. The findings of Li and Liu [41] indicate that dust detention capacity per unit of leaf area varies widely among species. For example, the dust detention abilities of *Platanus, Ligustrum lucidum,* and *Buxus megistophylla* are strong, while for *Fraxinus chinensis* it is low, whose results are consistent with Zhao et al. [42]. These results also indicate that, under different environmental conditions the dust detention ability of plants remains consistent. Wang et al. [43] pointed out that the influence of villi, surface hydrophilia, surface free energy, and its components on dust detention ability are maximal. In terms of the influence of leaf characteristics, the maximum dust detention amount of tested plants varied greatly: between 0.8 $g \cdot cm^{-2}$ and 38.6 $g \cdot cm^{-2}$. Of those tested, the top four were *Platanus spp., Sophora japonica*, *Amygdalus, syn. Prunus triloba*, and *Chukrasia tabularis*, while the lowest performers were *Syzygium aromaticum* and *Cercis chinensis*. Leaf surface morphology affects the dust detention ability of garden plants directly, and the more intensive the micro-topography, the more readily atmospheric particulates are trapped, while the more smooth the leaf surface of a species, the weaker the detention of dust [44]. Further research is needed on leaf structure and particle interactions to confirm the effect of structure on adsorption.

Conclusions

From the mean $PM_{2.5}$ concentration in March 2013 to February 2014, $PM_{2.5}$ concentrations of three monitoring stations were Haidian Wanliu > Beijing botanical garden forest interior monitoring station > Haidian Beijing botanical garden. Daily $PM_{2.5}$ concentration flux was higher by day than at night, showing double peaks with valleys regardless of location.

From the different months, maximum values of three monitoring stations were all in February 2014, with the minimums of Haidian Wanliu and Haidian Beijing botanical garden both in August 2013, and Beijing Botanical Garden's forest interior monitoring station in February 2013. There were also differences among other months, but the variation here was small. In July and August the average $PM_{2.5}$ concentrations in Beijing Botanical Garden's forest interior monitoring station were both higher than at Haidian Wanliu and Haidian Beijing Botanical Garden. Concentration within the forest was greater than in the open area of the botanical garden, but still lower than non-vegetated areas.

$PM_{2.5}$ concentrations in the forest area were far lower than in non-vegetated areas, the cause being foliar adsorption of particles, which perform a role in air purification. Using our invented aerosol generator to analyze $PM_{2.5}$ absorption capacity of different tree species, we found that the largest $PM_{2.5}$ absorption capacity per unit leaf area belongs to *Cedrus deodara* and the minimum belongs to *Sophora japonica*. Conifers yielded higher values than broadleaf species, and June appears as a more effective month than May, further confirming actual removal of fine particles in the air by trees. This reflects the forest ecosystem function of purifying the atmosphere and absorbing $PM_{2.5}$ particles. The air quality of forest areas was better than non-vegetated areas, and the open forest was better than the forest interior.

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