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Original Research

Different Concentrations of TSP, PM_{10}, $PM_{2.5}$, and PM_1 of Several Urban Forest Types in Different Seasons

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Abstract

In this study, six types of urban green land in Beijing Olympic Park, including grassland, shrub, conifer, broadleaf tree, mixed trees, and a control, were selected to study the relationship between urban green land and particulate matter (PM). For all particles – coniferous tree forest type, broadleaf tree forest type, and broadleaf and coniferous mixed trees type – the common point was that they have big leaf areas that can absorb a large number of particles. So the concentrations in the three forest types were very low. Leaf area is a big factor for absorbing and reducing concentrations of four types of particles.

The concentrations of PMs with the four particle sizes were lower in summer than in other seasons. For TSP and PM_{10}, the concentrations were significantly higher in September and November than in other months. The differences between summer, autumn, and winter were insignificant. For $PM_{2.5}$ and PM_1, the concentrations in autumn were higher than in other seasons. In summer, $PM_{2.5}$ and PM_1 concentrations were significantly lower than in other seasons, especially in August and October.

The daily variation of particulate matter formed a "double-apex" curve, with PM concentrations higher at dawn and dusk and lower at noon. In comparison with dusk, concentration was normally lower at dawn. At night and dawn, there were usually very high levels of PM, perhaps because of the higher humidity in the air.

Keywords: concentration of PMs, six types of urban green land, Beijing, season

Introduction

Particulate matter (PM), a common air contaminant, is a mixture of solid and liquid substances of organic and inorganic characters suspended in air. Particles vary in terms of origin, chemical composition, and size. The size is described as aerodynamic diameter and ranges from 0.001 to 100 µm [1]. Particles are often defined as coarse (2.5-10 µm), fine (0.1-2.5 µm), and ultra-fine (≤0.1 µm) [2-5].

Beijing is a large city with a population of 20 million people and 5 million vehicles [6]. Pollution in Beijing is a serious problem, so it is very important to research how to reduce the $PM_{2.5}$ concentration. For example, in October 2014 there were four serious air pollution situations in one month, each lasting for about 11 days at an average concentration of 220 µg/m³ [7, 8]. $PM_{2.5}$ and other particles

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have a more antagonistic effect on the human body and they are very dangerous [9].

Vegetation naturally cleanses the atmosphere by absorbing gases and some PM through leaves [10-12]. Plants have a very large surface area, and their leaves function as an efficient pollutant-trapping device. Some plants have been classified according to their degree of sensitivity and tolerance toward various air pollutants. Sensitive plant species are suggested to act as bio-indicators [13-15]. Levels of air pollution tolerance vary from species to species, depending on the capacity of plants to withstand the effect of pollutants without showing external damage [16-18]. Some studies have investigated the effectiveness of trees in accumulating airborne particles on foliage [16-20] and have recommended efficient urban tree species to optimize the design of urban plantings to capture air pollutants [17-19]. Authors cited in [2, 4, 5, 21] provided inputs on the selection of species for urban areas to reduce exposure of the urban population to air pollution and identified species of trees and shrubs with low and high PM accumulation. Broad-leaved species with rough leaf surfaces are more efficient at capturing PM than those with smooth leaf surfaces. In addition, needles of coniferous trees, which produce a thicker epicuticular wax layer, are more effective for PM accumulation than broad-leaved species, and evergreen conifers can accumulate pollutants throughout the year.

To find the relationship between the different forest types and the particles, a new progrem was started in 2013. This study aims to determine particle concentrations in the different types of forests, changes in particle concentrations in the different seasons of different types of forests, and the positive roles of different types of forests regarding different particles (for example TSP, PM_{10}, $PM_{2.5}$, and $PM_{1.0}$).

Experiment

Sampling Sites

Beijing, the capital of China, lies in a warm temperate zone and has a typical continental monsoon climate with four distinct seasons. From November to April the prevailing airflow from the northwest is dry and cold, whereas at other times the local winds are moderate and mostly from the south and southeast.

The study site, Beijing Olympic Forest Park, is 680 ha in area, of which 480 ha (71%) is a green area located north of urban Beijing (37º49′29″S 144º58′52″E), where the city meets natural forests.

Research Materials

As Fig. 1 shows, there are five urban forest types: shrub and small tree forest (deciduous trees), coniferous tree forest (evergreen trees), broadleaf tree forest (deciduous trees), broadleaf and coniferous mixed trees, and grassland. These urban forest types are commonly grown in urban forest parks in Beijing and were selected for this study, and an area of the forest was selected for comparative analysis (Control). The distances between the urban forest types and the control site were 5-10 m.

Measurement and Quality Control of $PM_{2.5}$

DustMate (Turnkey; Dustmate, Germany) is a handheld direct-reading fume and dust detection instrument with a fast response that is designed to locate sources of workplace airborne dust and fumes, even at very low concentrations. It is highly effective for checking air quality

Fig. 1. Six sampling sites in the Beijing Olympic Forest Park; the red point is the control site.

within buildings. Its one-second time resolution also allows it to be used as a roadside indicator to identify high-polluting vehicles as they pass. The instrument continuously indicates concentrations of thoracic, inhalable, and respirable particles down to 0.1 μg/m³. In its environmental mode, it indicates TSP, PM_{10}, $PM_{2.5}$, and PM_1 concentrations.

TSP, PM_{10}, $PM_{2.5}$, and PM_1 from air samples were collected from five urban forest types and a control (Fig. 2). Sampling locations were located in the center of each forest type at a height of 1.5 m above the ground (human respiration height) with two replications per forest type. Sampling times were chosen as follows: each month of 2013 (from May to December) and repeated sampling every two days without rain. The sampling time was early in the morning from 07:00 to 19:00 the next day. The tested species were randomized within the test fields, which were relatively small in area. Thus, variation in the environment within the locations should not significantly influence the results.

Statistical Analysis

Data were subjected to one-way and multi-way analysis of variance using StatGraphics Centurial XVI software (StatPoint Technologies, Inc., USA). Significance of differences between mean values was tested using Tukey's honest significance difference (HSD) test at $\alpha = 0.05$. Values on dot charts represent individuals with a trend line and correlation coefficient. The latter two were calculated using Microsoft Excel (Microsoft Corp., USA).

Results and Discussion

Meteorological Conditions and Annual PM Concentrations (TSP, PM_{10}, $PM_{2.5}$, and PM_1) in Different Urban Forest Types

Sample monitoring began in May 2013. Results of PM concentrations in the air were compared from May to

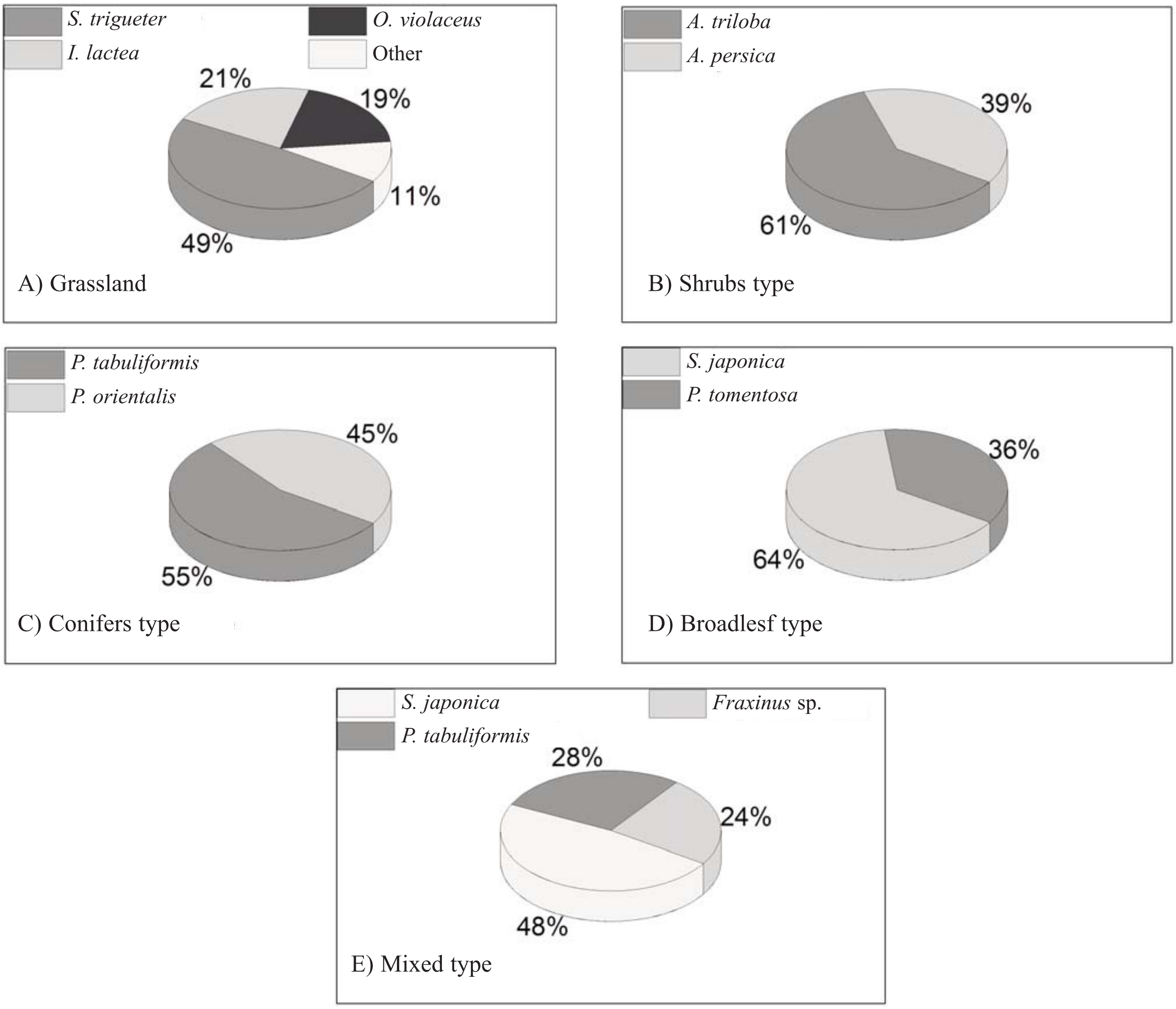

Fig. 2. Plant structures in different forest types.

Table 1. Mean values (n =1,624) and associated standard errors in parentheses for TSP, PM_{10}, $PM_{2.5}$, and PM_1 concentrations May to December 2013 for the four particle size classes (μg/m³).

	TSP	PM_{10}	$PM_{2.5}$	PM_1
Mean	286.42	169.31	65.03	21.40
Standard error (SD)	120.21	97.80	45.51	15.58

December. The results of February, March, and April were averaged for spring; May, June, and July were averaged for summer; August, September, and October were averaged for autumn; and the last two months were averaged for winter. Fig. 3 shows the meteorological conditions in different months.

Table 1 shows the mean concentrations of particles for the four size classes of particles measured by the Dustmate monitor at each urban forest site. The results showed that the means of almost all the concentrations exceeded the National Ambient Air Quality Standards (NAAQS) 24 h mean value of 150 μg/m³ for PM_{10} and 15 μg/m³ for $PM_{2.5}$, and China's ambient air quality standards (GB 3095, 2012) secondary standard mean value of 200 μg/m³ for TSP, 70 μg/m³ for PM_{10}, and 35 μg/m³ with $PM_{2.5}$. The intensity of major air pollutants remained the same in 2013 as in the previous year. The $PM_{2.5}$ reading in 2013 was 89.5 μg/m³ on average. By comparison, the national standard is 35 μg/m³. The explanation may be that the experiment was implemented at the park where there were many trees, and air quality was much better than the average for the entire city.

The analysis of variance revealed significant effects of months of urban forest types and particle sizes on their concentrations in the air (Fig. 4). Large particulate concentrations (TSP and PM_{10}) were lower for the fixed tree type than others, but coarse and fine particulate concentrations ($PM_{2.5}$ and PM_1) are low in conifer and fixed tree types.

Daily Variation in Air PM Concentrations in Different Seasons

For sampling during eight months in 2013, Dustmate monitors were used to measure the concentrations of PM over a range of size categories at each of five urban forest types and the control. Power supply and the poor reliability of Dustmate recorders in high humidity restricted measurements between 00:00 and 19:00. However, the diurnal variation of particle concentrations followed a similar pattern at most urban sites studied.

For example, the data for 1993-1995 presented by Muir et al. [22, 23] showed that average concentrations between 23:00 and 06:00 in six UK cities were approximately 20% lower than those for the other 17 h of the day. From these data, 24-h profiles of particle concentrations were calculated for the seven-day period for Withdean Park and Sussex University field sites [22, 23]. Wu et al. [24] reported that the daily variation of PM in Tsinghua University (Beijing) is a "double-apex" curve, with PM concentrations higher at dawn and dusk and lower at noon. Concentrations are normally higher at dawn than at dusk [24].

These observations showed that variation in PM concentration during the daytime widely differs among seasons and strongly depends on the daily fluctuation of humidity. However, the general rule is always that it is high at dawn and dusk. The time period when PM in the air is the lowest of the day was from approximately 11:00-15:00 – considered the ideal time for people to perform outside activities in order to avoid being affected by PM pollution in the air.

Daily PM variation was seen to be greatly affected by humidity. Moisture content fluctuation in the air led to fluctuating PM concentrations (Fig. 5). During days of high and unstable humidity in the forest, the PM concentration was also high and unstable. The concentrations of PM in the air at night and dawn were higher than those in the afternoon, which clearly showed the influence of humidity on aerosol PM concentrations. In the forest, respiratory action will lead to high humidity, which can let PM be adsorbed by the leaves.

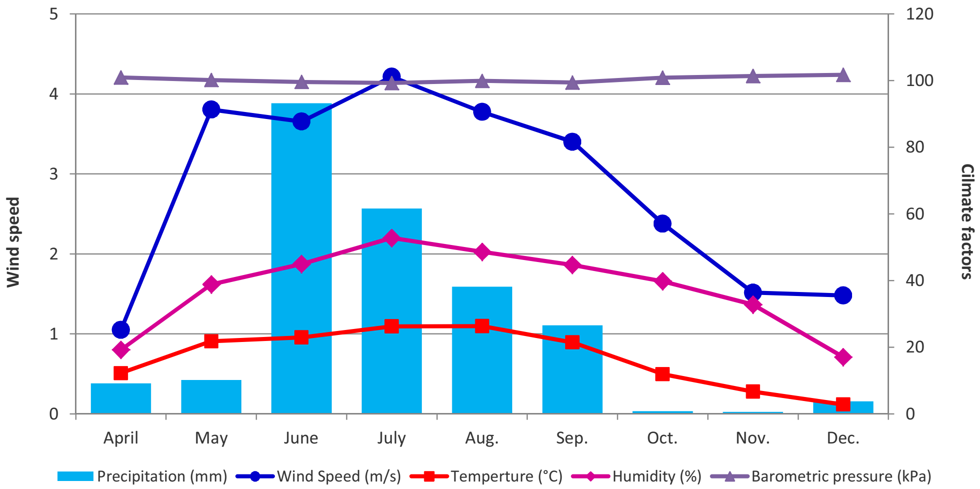

Fig. 3. Meteorological conditions in different months.

The daily variation of PM is caused by emissions from human activities and climatic factors [24]. During the morning, from 05:00 to 09:00, human activities such as cooking and vehicle traffic generate emissions of large dust particles. After sunrise, the sun warms the ground and enhances air circulation. Around noon, in the period from 11:00 to 14:00, the air is unstable, reaching the highest peak and creating favorable conditions for dust particles in the movement and dispersal of air. In the afternoon, at rush hour (after 17:00), traffic movement increases, increasing the concentration of dust particles. At night (after 21:00), humidity increases and the air is relatively stable, which is not conducive to dust particles for their movement and dispersal in the air. Deposition of dust particles in the air increases. This one explains why the concentration of $PM_{2.5}$ was high at night and early morning.

Seasonal Variation in Air PM Concentration in Different Urban Forest Types

Fig. 6 shows the different seasonal concentrations in different urban forest types. For TSP $PM_{2.5}$ and $PM_{1.0}$, the concentrations were lowest in the broadleaf and coniferous-mixed vegetation type in summer. The main reason was in summer, mixed forests have very complex structure. This structure is a dimensional construct, and in this condition the small forest climate and air concentration of four types of particles will be changed. And the change was bigger than in the other five vegetation types. So the concentration was lowest.

In winter, the concentrations of four types of particles were very large, perhaps because of large amounts of emissions and leafless trees. The concentrations in the coniferous type was at a much lower level than other vegetation types.

For $PM_{2.5}$ and $PM_{1.0}$, in summer the concentration variances were the most obvious among the six vegetation types. The biggest variance was between fixed vegetation type and grassland type at about 50%. Wu et al. reported that TSP and PM_{10} concentrations of deciduous tree-herb, evergreen tree-herb, and greenbelt-herb were different than control and herb, arbor-shrub-herb [24].

Seasonal variation in air PM concentration may be affected by many factors. First, in the summer plants/trees enter the stage of strong growth and metabolism, plus highest forest density and grass coverage, and thereby reach their most effective dust absorption ability. Second, the average and maximum wind speeds during the experimental period was high. Wind has a relatively significant effect on the distribution of particles in the air. Third, summer rainfall is relatively high. Rain increases wet deposition; after coming in contact with rain, most dust particles condense and are deposited onto the ground. Meanwhile, raindrops on their way to the ground collide with and capture particles, leading to a reduction in PM concentration.

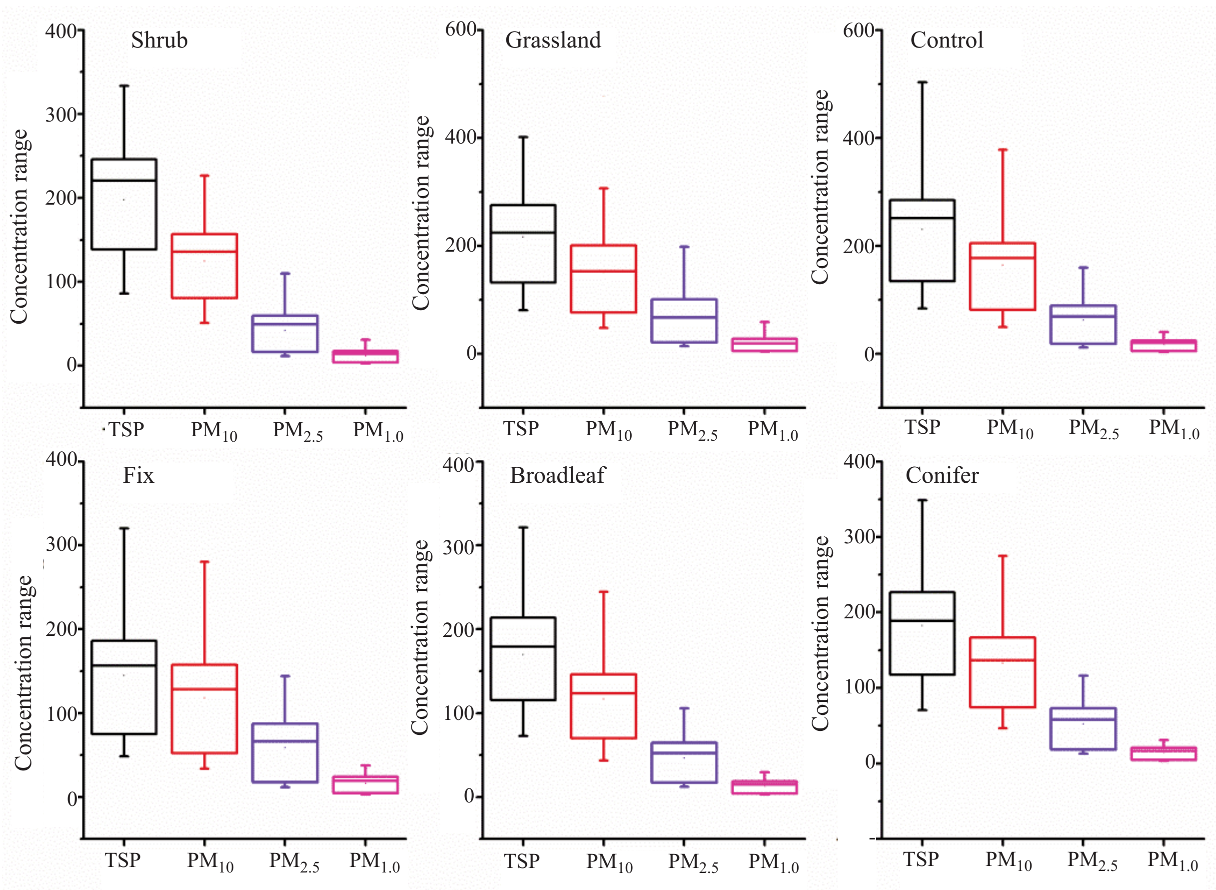

Fig. 4. Mean values (n=1,624) and associated standard errors in parentheses for particle concentrations at six sites between 07:00 to 00:00 for four particle-size classes (μg/m³).

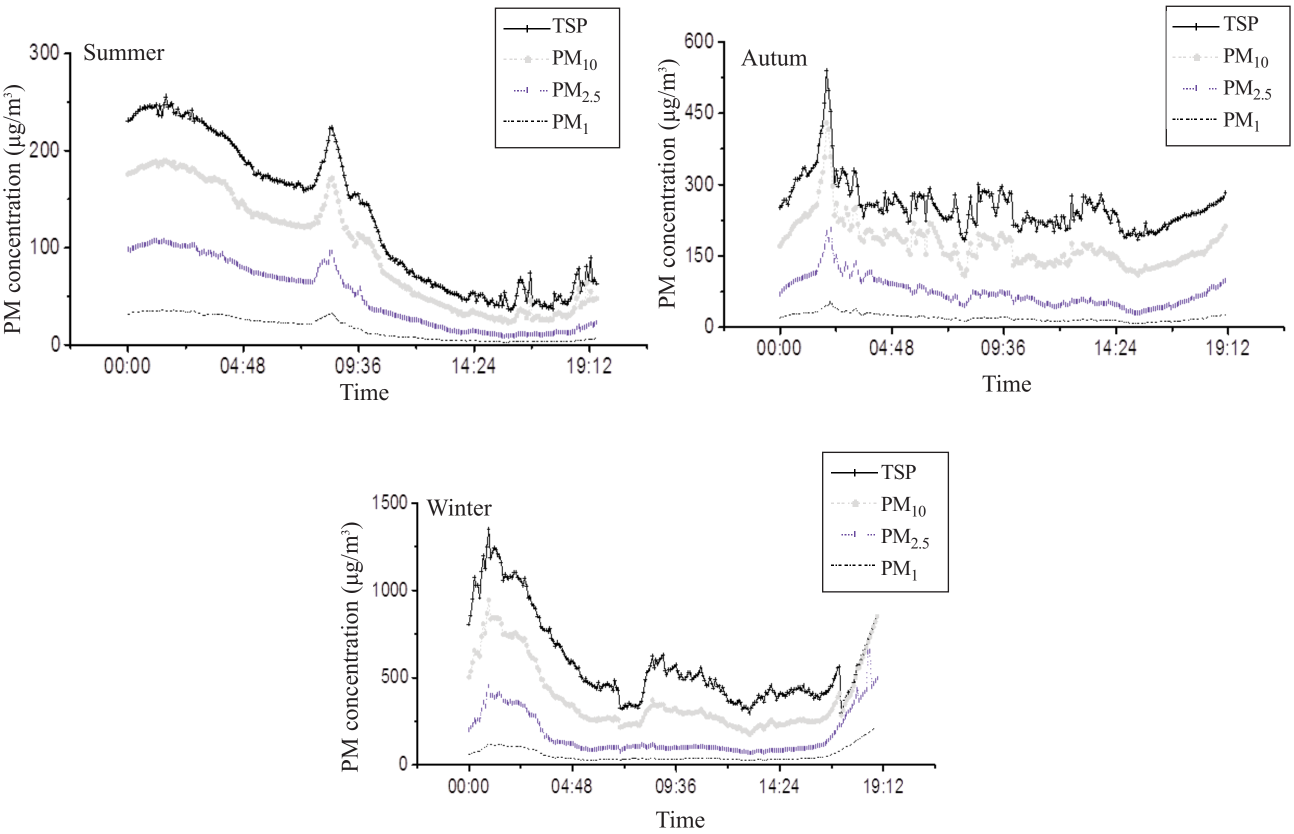

Fig. 5. Daily variation of PM concentrations in different seasons.

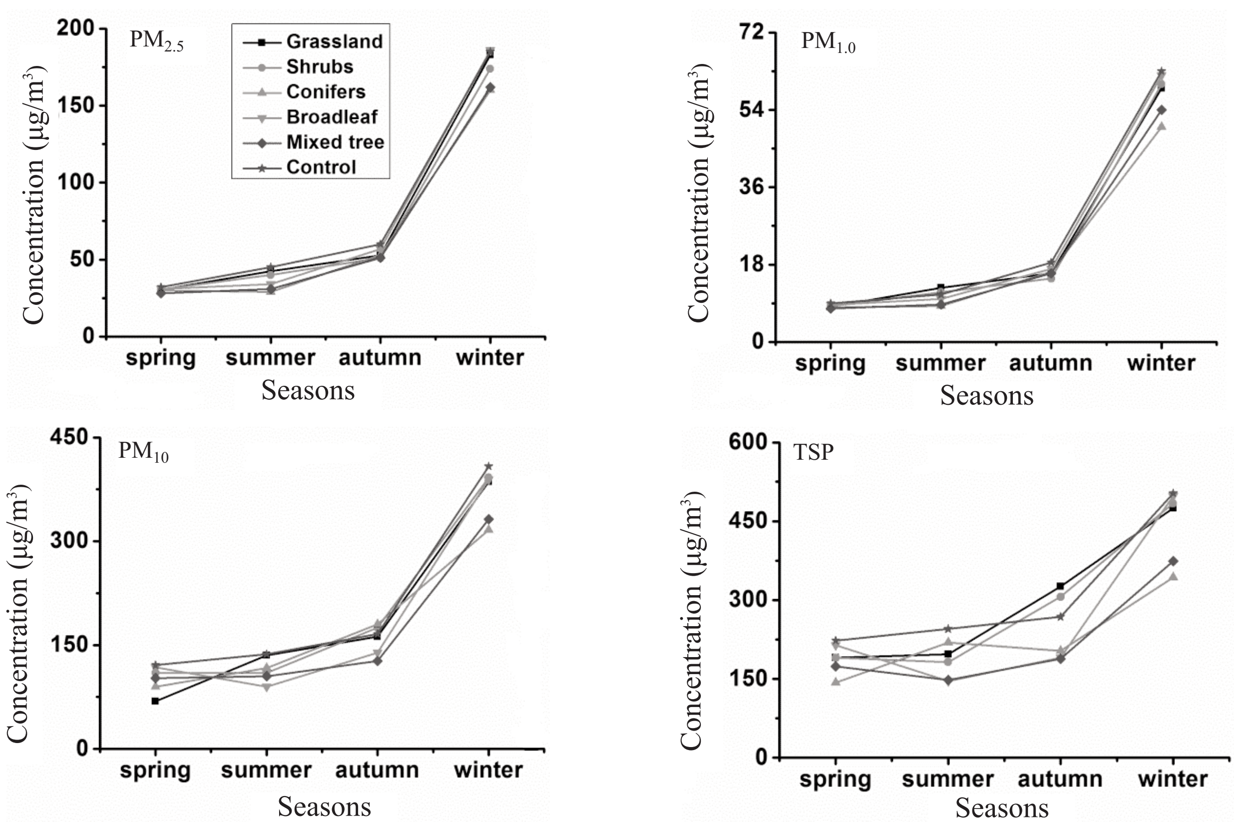

Fig. 6. Different seasonal concentrations in different urban forest types.

The frequently clear sky in Beijing during autumn is conducive to the movement and dispersal of dust particles in the air. As a result, PM concentrations were lower in autumn than during winter. PM concentrations in November and December were high, which may be caused by climate factors as late autumn moves to early winter.

Winter in Beijing is relatively long, with a relatively large number of foggy days, which are not conducive to the dispersal of dust particles in the air, leading to increased particles. In winter, deciduous trees experience complete leaf loss and begin dormancy, while evergreen trees take advantage. PM concentration for the evergreens (conifers) was higher than for deciduous trees.

The aerosol $PM_{2.5}$ and PM_1 concentrations in six types of urban greenland were significantly lower than the control in autumn. This result is similar to results of Zhou et al. [20] researched on the dust capture of the different types of plants, and authors found that different types of plants have a lag effect after analyzing, and the order is as follows: conifers > herb > shrubs > climbers > deciduous trees. However, other studies of Han et al. [25] on Binhe Street in Linyi city showed that dust catching was the opposite conclusion of Zhou et al. [20], as they thought the different types of green plant dust-catching order was trees > shrubs > herbs. Wang et al. [26] integrated and analyzed dust catching of the common garden plants in Jinhua City, and showed that different types of dust-catching garden plants are in the order: evergreen trees > evergreen shrubs > deciduous shrubs > deciduous trees> grassland. Yang et al. [27] demonstrated the effect of dust accumulation can be significantly different according to species, with the order shrubs > evergreen trees > deciduous trees. These results also show that the PM concentrations of forest types with trees are mostly higher those of grassland and no-tree [20, 26, 27].

Annual Variation in Air PM Concentration in the Different Urban Forest Types

The annual variation in air PM concentration in different urban forest types is presented in Fig. 7.

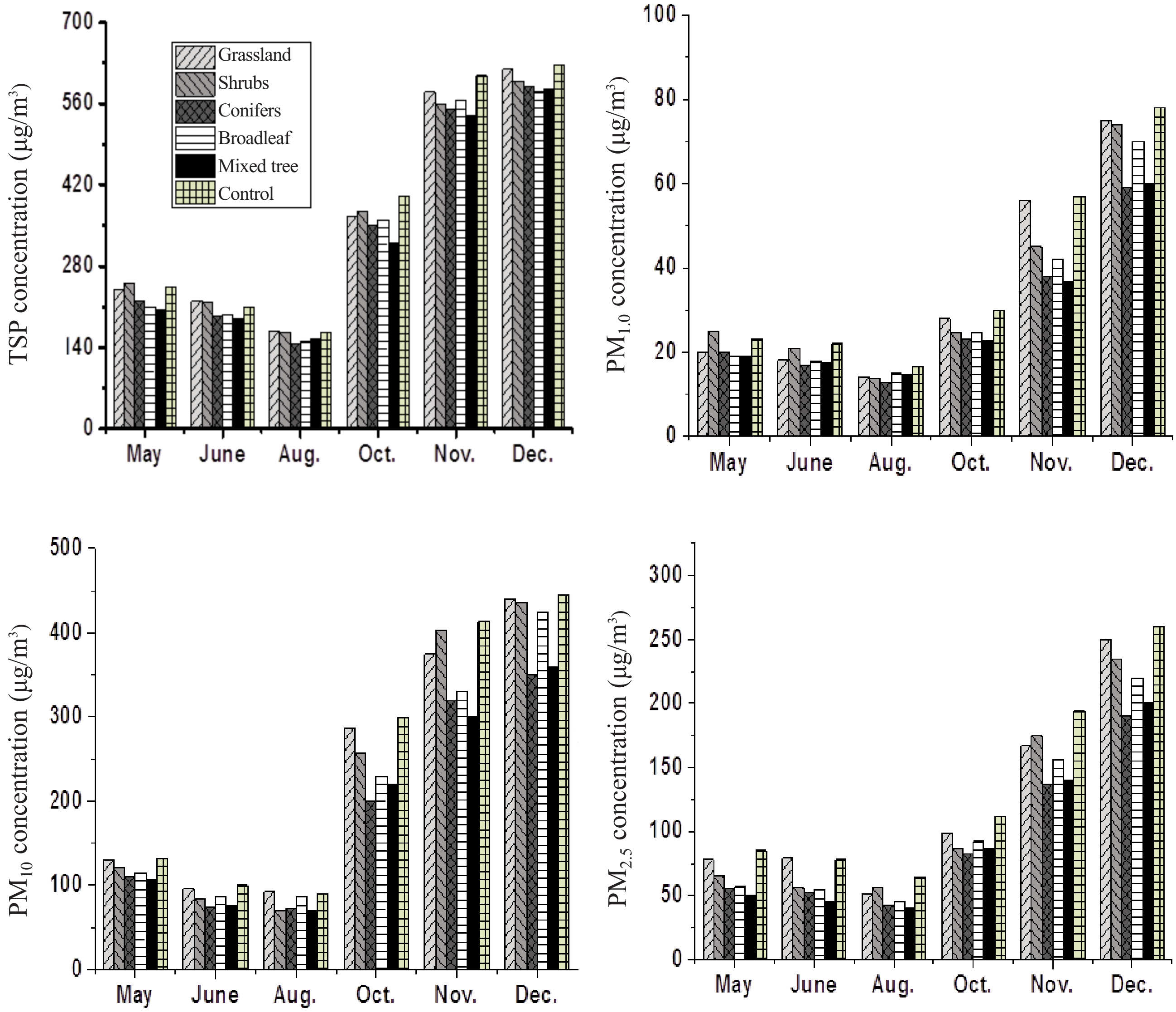

Fig. 7. Annual variation in air PM concentration in different urban forest types.

The PM concentrations significantly differed between months of the year in all forestry types. The concentrations of PM of the four diameters were lower in summer (May, June) and early autumn (August) than in other seasons. For TSP and PM_{10}, the concentrations in late autumn (October) and winter (November and December) were significantly higher than in other seasons.

For all particles, concentrations in control were higher than in the other five forest types. The concentration in grassland is second highest. The depositions in the control and grassland areas were very small. So the concentrations in the two areas were very high. Shrub and small tree forest type was scrub, and the leaf area was very small, so it could not absorb more particles. So the concentration of four types of particles was very high, too. But for the coniferous tree forest type, broadleaf tree forest type, and broadleaf and coniferous mixed trees types, the common point of these three forest types is that there were big leaf areas that can absorb a large number of particles. So the concentrations in the three forest types were very low. Leaf area is a big factor to absorb and reduce the concentrations of four types of particles. And plant height was also very important for absorbing and reducing the concentrations of four types of particles.

For TSP and PM_{10}, the concentrations are lowest in the broadleaf and coniferous mixed-trees types (the other five forest types). The main reason is that there is a complex canopy structure in the broadleaf and coniferous mixed-trees type. The canopy structure add the broadleaf tree canopy to the coniferous tree canopy, which is more complex than any other type. So the complex structure can reduce wind speed, and the big TSP and PM_{10} particles can be grabbed by the leaves. And the second and third lower were in the broadleaf tree forest type and coniferous tree forest type, respectively.

For $PM_{2.5}$ and $PM_{1.0}$ the concentrations are lowest also in the broadleaf and coniferous mixed-trees type, but the second and third lower were in coniferous tree forest type and the broadleaf tree forest type, respectively. This result is different with TSP and PM_{10}. The main reason is that the needle-leaved tree has a large specific surface area and the $PM_{2.5}$ and $PM_{1.0}$ size is very small, so the leaves have more collision frequency and collision probability, and more collision direction. The mixed trees type has very complex structures, the complex structures can change the forest micrometeorology and increase contact area of leaves.

In summer, $PM_{2.5}$ and PM_1 concentrations in September were significantly higher than in other months, and August had the lowest concentration. In winter, $PM_{2.5}$ and PM_1 concentrations were significantly higher than summer, but not autumn, and the difference was not significant between winter and autumn.

TSP and PM_{10} were the highest in September and December, similar to $PM_{2.5}$ and PM_1. TSP and PM_{10} were the lowest in June and August, and $PM_{2.5}$ and PM_1 are also lowest in August. These results are partly similar to those of Gehrig and Bauchmann [28], who reported that the correlation between the daily values of $PM_{2.5}$ and PM_{10} at seven sites during 1998-2001 in Switzerland were generally high. For PM_{10} as well as $PM_{2.5}$, the highest concentrations were normally observed during winter, low in August and June, and increasing in November and December. This result also is similar to that of Wu et al. [24], who investigated variation in air PM concentrations in different urban green lands, and Xu et al. [29], who investigated componential characteristics and source identification of $PM_{2.5}$ in Beijing. Their results showed that the mean concentration of $PM_{2.5}$ was lowest in summer, whereas it reached the maximum of the year in winter [24, 29]. A characteristic seasonal variation can be observed for PM_{10} and $PM_{2.5}$ with elevated concentrations during winter. The reasons for this pattern are not primarily seasonal fluctuations of the emissions but rather meteorological effects [28].

Conclusions

The PM concentrations significantly differed among the three seasons. The concentrations of PMs with the four particle sizes were lower in summer than in other seasons. For TSP and PM_{10}, the concentrations were significantly higher in September and November than in other months. The differences between summer, autumn, and winter were not significant. For $PM_{2.5}$ and PM_1, the concentrations in autumn were higher than in other seasons. In summer, $PM_{2.5}$ and PM_1 concentrations were significantly lower than in other seasons, especially in August and October.

For all particles, the concentration in control was higher than other five forest type, and the concentration in grassland is second higher compared to others. For the coniferous tree forest type, broadleaf tree forest type, and broadleaf and coniferous mixed trees type, the common point of these three forest types were that there were big leaf areas and the concentrations in the three forest types were very low. The leaf area is a big factor to absorb and reduce the concentration of four types of particles. And the height of the plant was also very important for absorbing and reducing the concentrations of four types of particles.

For $PM_{2.5}$ and $PM_{1.0}$ the concentrations also are lowest in the broadleaf and coniferous mixed trees type. The mixed trees type has very complex structures, the complex structures can change the forest micrometeorology, and increase contact area of leaves. In the future, further work will confirm which tree composition form is most useful for adsorbing the different particles.

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