Understanding PM$_{2.5}$ concentration and removal efficiency variation in urban forest park — Observation at human breathing height

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To increase our knowledge of PM$_{2.5}$ concentrations near the surface in a forest park in Beijing, an observational study measured the concentration and composition of PM$_{2.5}$ in Beijing Olympic Forest Park from 2015 to 2016. This study analyzed the meteorological factors and removal efficiency at 1.5 m above the ground (human breathing height) over the course of the day in the forest. The results showed that the average concentrations of PM$_{2.5}$ near the surface peaked at 07:00–09:30 and reached their lowest at 12:00–15:00. In addition, the results showed that the annual concentration of PM$_{2.5}$ in the forest was highest during winter, followed by spring and fall, and was lowest during summer. The main chemical components of PM$_{2.5}$ near the surface in the forest were SO$_4^{2−}$ and NO$_3^{−}$, which accounted for 68.72% of all water-soluble ions that we observed. The concentration of PM$_{2.5}$ in the forest had a significant positive correlation with relative humidity and a significant negative correlation with temperature. The removal efficiency near the surface showed no significant variation through the day or year. In the forest, the highest removal efficiency occurred between 07:00 and 09:30 in summer, while the lowest occurred between 09:30 and 12:00 in winter.
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Abstract
To increase our knowledge of PM$_{2.5}$ concentrations near the surface in a forest park in Beijing, an observational study measured the concentration and composition of PM$_{2.5}$ in Beijing Olympic Forest Park from 2015 to 2016. This study analyzed the meteorological factors and removal efficiency at 1.5 m above the ground (human breathing height) over the course of the day in the forest. The results showed that the average concentrations of PM$_{2.5}$ near the surface peaked at 07:00–09:30 and reached their lowest at 12:00–15:00. In addition, the results showed that the annual concentration of PM$_{2.5}$ in the forest was highest during winter, followed by spring and fall, and was lowest during summer. The main chemical components of PM$_{2.5}$ near the surface in the forest were SO$_4^{2-}$ and NO$_3^-$, which accounted for 68.72% of all water-soluble ions that we observed. The concentration of PM$_{2.5}$ in the forest had a significant positive correlation with relative humidity and a significant negative correlation with temperature. The removal efficiency near the surface showed no significant variation through the day or year. In the forest, the highest removal efficiency occurred between 07:00 and 09:30 in summer, while the lowest occurred between 09:30 and 12:00 in winter.
Key words: Near the surface, Forest, PM$_{2.5}$, Removal efficiency, Meteorological factors

Introduction

Air pollution has become an increasingly serious concern in China in recent years, as economic development and urbanization, automobile exhaust, and coal and industrial emissions have increased year after year (Li et al. 2016). Fine particulate matter (PM$_{2.5}$), along with other major atmospheric particulate pollution, has become the most pressing air pollution concern in the country (Ma et al. 2013). PM$_{2.5}$ refers to the particulate matter with atmospheric dynamic diameters less than 2.5 μm. Compared to other particles, the diameter of a PM$_{2.5}$ pollutant is smaller, its surficial area is larger, and its transmission range is farther. Moreover, it contains more toxic substances and remains in the atmosphere, making it more difficult to remove (O’Connor et al. 2008). As a result, PM$_{2.5}$ does great harm to human health and the environment (Viana et al. 2008). Finding ways to reduce fine particulate pollution has become a hot-button difficult issue for governments and residents of affected areas.

Forests represent important ecosystems, and forest canopies can capture particles in their complex branch structures and the stomata on their leaves. Therefore, forests have a strong role in adsorbing particulate matter and removing it from the atmosphere (Freer-Smith et al. 2004, Nowak et al. 2006). Studying the concentration and composition of particulate matters in forests can provide a basis for innovation and research into technology aimed at reducing atmospheric particulate matter. The sequestration of atmospheric PM$_{2.5}$ by forests mainly occurs in the canopy (Liu et al. 2015), so researchers have focused most of their efforts on measuring and modeling the concentration and composition of PM$_{2.5}$ far above the surface in the forest. Previous studies have shown that the diurnal variation of PM$_{2.5}$ concentration at different heights in the forest includes two peaks and two troughs (Wang et al. 2014, Wang et al. 2005, Zhao et al. 2009). Furthermore, the relationships between meteorological factors and the concentration of PM$_{2.5}$ have also been studied. Researchers have examined the relationship between large-scale climate and PM$_{2.5}$ by using ArcGIS (Chen et al. 2016, Huang et al. 2015, Yuan et al. 2017), but few people have studied the effects of microclimate on PM$_{2.5}$ concentration, especially in forests. The composition of PM$_{2.5}$ in certain areas in the atmosphere has also been studied: one study that looked at the constituents of particulate matter in a forest focused on particles above the canopy and indicated that water-soluble inorganic ions, including SO$_4^{2-}$, NO$_3^-$, and NH$_4^+$, were the main ingredients of PM$_{2.5}$. The sum of their mass concentrations accounted for more than 50% of the total water-soluble inorganic ions of PM$_{2.5}$, and the concentrations of these ions increased with height (Li et al. 2014).
In general, previous studies of fine particles have focused on the concentration and constituents of the atmosphere at the height of the canopy, or in urban areas. Little interest has been shown in the particles near the ground surface in forests, especially their constituent changes. An average person breathes at a height of 1.5 m above the ground (Kenagy et al. 2016), where inhaled particulate matter can have negative effects on respiratory and cardiovascular health, and can even damage DNA (Hong et al. 2002). Studying changes in the concentration and constituents at this height will provide theoretical support for future studies into the effects of PM$_{2.5}$ on human breathing and health. Therefore, it’s important to study the concentration and constituents of PM$_{2.5}$ near the ground in forests in order to evaluate their removal efficiency.

In this paper, we selected the artificial forest in the southern part of Beijing Olympic Forest Park as the experiment site. The concentration and constituents of PM$_{2.5}$ were collected at a height of 1.5 m during different seasons. The changes in the concentrations of PM$_{2.5}$ and its constituents were analyzed and compared to nearby bare land in order to quantify the effects the forest had on these pollutants.

**Materials & Methods**

1 Materials and methods

1.1 Experimental site

Beijing is the economic, cultural, and political center of China and is famous for its struggles with air pollution. Beijing Olympic Forest Park is located in the North Olympic Park, Chaoyang District, Beijing. It covers an area of 680 ha and is the largest city park in Beijing. Its geographic coordinates are 40°01′ 03.73″ N and 116°23′ 09.81″ E. It has a rich variety of plants in a mixed forest, including 530,000 trees and shrubs of more than 180 species that respond differently to the four seasons (Li et al. 2006).

A sampling area was selected in a planted forest in the southern part of the park (Fig. 1). The sampling area was bounded in the north by the Five-ring Road and in the south by Yang Mountain. The forest was 60 m long from north-to-south and 50 m wide from east-to-west, with a stretch of pavement through the middle. The forest was mainly composed of Chinese white poplar (*Populus tomentosa*), mixed with a small amount of weeping willow (*Salix spp.*), Chinese ash (*Fraxinus chinensis*), and Chinese pine (*Pinus tabulaeformis*). Shrubs grew on the edge of the forest, including Chinese rose (*Rosa chinensis*), forsythia (*Forsythia suspensa*), and flowering peach (*Amygdalus persica*).

We selected one vertical gradient sampling location and installed equipment at 1.5 m above the ground. The composition of the underlying surface is mainly grass. There was no significant local
source of air pollutants near the monitoring station. A second site was chosen as a control, which
monitored the concentration over the bare land surrounding the forest. The climates were similar
for the two sites.

1.2 Sampling procedure

A Tianhong suspended particulate pollutant sampler and a small weather station were installed at
each sampling point to collect data on particulate concentration and constituents, and meteorology
(Fig. 2). The flow rate of the sampler was set at 100 L/min, and the PM$_{2.5}$ concentration was
collected every 5 minutes. We used a quartz filter membrane and burned it for four hours in a muffle
furnace in order to avoid contamination and reduce error. The meteorological data collected by the
weather station included temperature, relative humidity, and wind speed.

Sampling was conducted from September 2014 to September 2015. Samples were collected during
the first 4 days of each month, measured from 07:00 to 18:00 at each sampling point. It provided
the same sample collecting interval and we divided the sampling period into four time periods
which represent the morning rush hours, morning hours, afternoon hours and the evening rush
hours. The weather was mainly clear during the collection period.

1.3 Analytical methods

1.3.1 Analysis of concentration variation

The PM$_{2.5}$ concentrations during each season were averaged by time of day to observe the diurnal
variation during each season.

1.3.2 Analysis of constituents and variation

Water-soluble ion analysis of the particulate matter was performed by soaking quarters of
standard-sized portions of the sample filter membranes in 50 ml of deionized water and performing
WAYEE IC6200 ion chromatography to determine the concentrations of selected anions and
cations. The main constituents of PM$_{2.5}$ were determined from these data.

1.3.3 Quantification of removal efficiency

In order to evaluate the importance of deposition of PM$_{2.5}$ in a forest environment, the removal
efficiency needed to be calculated. The removal efficiency differs based on a number of
deposition-related variables, and it was calculated using the Eq. (1) (Escobedo & Nowak 2009, Liu
et al. 2016, Nowak et al. 2006):

\[
E = I/(I + D)
\]

(1)
Where $I$ is the removed deposition of PM$_{2.5}$ on the surface and $\bar{D}$ is the daily average deposition flux. The variables $I$ and $\bar{D}$ were calculated by Eq. (2) and Eq. (3) with values from the forest and bare land (Escobedo & Nowak 2009, Nowak et al. 2006):

$$I = (1 - R) \times V_d \times C \times t$$

(2)

$$\bar{D} = C \times T$$

(3)

Where $R$ is the resuspension rate of PM$_{2.5}$, $V_d$ is the deposition velocity, $C$ is the particle concentration, $\bar{C}$ is the daily average concentration, and $T/t$ is the evaluated time. In this process, $R$ of the forest and bare land can be derived using the regression method, which can be expressed by Eq. (4) (Liu et al. 2016):

$$y = -0.01x^2 + 0.17x \quad (R^2 = 0.91, P < 0.001)$$

(4)

Deposition velocity depends on the surface and environment since it is related to wind speed. When the wind speed was $\geq 10$ m/s, the $V_d$ of PM$_{2.5}$ was set as 2.11 cm/s; when the wind speed was $< 2$ m/s, the $V_d$ of PM$_{2.5}$ was always 1.52 cm/s (Nowak et al. 2013). When the wind speed was between 2 m/s and 10 m/s, the $V_d$ in the forest was calculated by Eq. (5) (Nowak et al. 2013):

$$y = -0.02x^2 - 0.08x + 0.14 \quad (R^2 = 0.92, \quad P < 0.001)$$

(5)

The comparable equation for the $V_d$ of PM$_{2.5}$ on bare land was calculated by Eq. (6) (Liu et al. 2016):

$$y = -0.01x^2 + 0.05x^2 + 0.41x - 0.05 \quad (R^2 = 0.98, \quad P = 0.002)$$

(6)

**Results**

2.1 Concentration variation of PM$_{2.5}$ in the forest

2.1.1 Diurnal variation

The mean mass concentration across the entire sampling period was divided into four time periods: 07:00–09:30, 09:30–12:00, 12:00–15:00, and 15:00–18:00, which represent the morning rush hours, morning hours, afternoon hours and the evening rush hours. As shown in Fig. 3, the diurnal variations of PM$_{2.5}$ concentrations in the forest were largely consistent and showed a U-shaped pattern. Summer was the exception, during which a general downward trend was observed. PM$_{2.5}$ showed the highest average concentrations between 07:00 and 09:30. During this period, the average concentration of PM$_{2.5}$ was approximately 12.98 $\mu$g/m$^3$ in spring, 6.58 $\mu$g/m$^3$ in summer, 11.85 $\mu$g/m$^3$ in the fall and 190.22 $\mu$g/m$^3$ in the winter. Moreover, all seasons showed the highest instantaneous concentrations at 07:00, except for winter, when the instantaneous concentration
reached 303.32 μg/m³ at 18:00, which was the highest value during the sampling period. In the 09:30–12:00 and 12:00–15:00 periods, the average concentrations showed a relatively smooth variation, and bottomed out between 12:00 and 15:00 (except for summer), reaching 9.92 μg/m³ during spring, 6.06 μg/m³ during the fall, and 111.09 μg/m³ during the winter. During summer, the lowest PM$_{2.5}$ average concentration in the forest, 1.52 μg/m³, occurred between 15:00 and 18:00.

2.1.2 Variations between seasons

As shown in Fig. 4, the variation in PM$_{2.5}$ average concentrations in different time periods in the forest was similar in each season. The daily average concentration of PM$_{2.5}$ reached its highest point during winter, which was 149.31 μg/m³, vastly exceeding those of the other seasons. In the spring and fall, the daily average concentrations of PM$_{2.5}$ were low, at 11.31 μg/m³ and 8.40 μg/m³, respectively. In summer, the daily average concentration of PM$_{2.5}$ reached its minimum value of 3.17 μg/m³.

2.2 Constituents of PM$_{2.5}$ in the forest

2.2.1 Constituents and proportion of ions in PM$_{2.5}$

Average concentrations of ten ions were detected in this study: SO$_4^{2-}$ (97.49 μg/m³), NO$_3^-$ (20.50 μg/m³), Cl$^-$ (16.15 μg/m³), Na$^+$ (11.80 μg/m³), Ca$^{2+}$ (8.73 μg/m³), K$^+$ (6.87 μg/m³), NH$_4^+$ (7.08 μg/m³), HCOO$^-$ (3.46 μg/m³), Mg$^{2+}$ (1.62 μg/m³), and F$^-$ (0.44 μg/m³). As shown in Fig. 5, SO$_4^{2-}$ was most abundant, representing 55.93% of the ions, by mass, followed by NO$_3^-$, Cl$^-$, Na$^+$, Ca$^{2+}$, K$^+$, NH$_4^+$, HCOO$^-$, and Mg$^{2+}$. F$^-$ was the least abundant at 0.24%.

2.2.2 Seasonal variations in negative and positive ions

As shown in Fig. 6, the proportion of SO$_4^{2-}$ in fine particular matter showed a U-shaped variation across seasons. NO$_3^-$ experienced an obvious spike during summer. Na$^+$ showed a downward overall trend and had a sharp decrease between spring and summer. Ca$^{2+}$ and K$^+$ had the same trend and both peaked during the fall. Cl$^-$ and NH$_4^+$ showed an upward trend, while the remaining ions did not show significant changes in relative abundance.

2.3 Influence of meteorological factors on PM$_{2.5}$ in the forest

Meteorological factors, including temperature, relative humidity, and wind speed, were recorded during each time period by a small weather station. As the PM$_{2.5}$ concentration was significantly higher during winter than during other seasons, we chose the data from winter to be representative for most meteorological variables. The exception was wind speed, which was negligible during the winter, but was relatively high during the spring. Thus, we used the data from the spring to analyze the relationship between wind speed and concentration (Fig. 7). Temperature, relative...
humidity, and wind speed were all correlated with the concentration of PM$_{2.5}$ (Table 1). The concentration of PM$_{2.5}$ had a significant positive correlation ($p < 0.01$) with relative humidity and a significant negative correlation with temperature. The correlations between the concentration of PM$_{2.5}$ in the forest and relative humidity and temperature were particularly strong.

2.4 Removal efficiency of PM$_{2.5}$ in the forest

The removal efficiency of PM$_{2.5}$ during different time periods was calculated according to the removal efficiency model. Fig. 8 shows the PM$_{2.5}$ removal efficiencies of the forest and bare land during each daily time period. The removal efficiency of PM$_{2.5}$ in the forest was relatively consistent throughout the day for each season. The variation in the removal efficiency for the four seasons between 07:00 and 09:30 had a same relative trend as that between 09:30 and 12:00. Summer had the highest removal efficiency between 07:00 and 09:30 and winter had the lowest between 09:30 and 11:00, which were 71.3% and 34.5%, respectively. For bare land, the removal efficiencies were significant during spring, but the other seasons varied considerably, even registering negative removal efficiencies during some time periods and seasons.

Discussion

3.1 Concentration and removal efficiency of PM$_{2.5}$ in different seasons and periods in the forest

Our monitoring results showed that the highest concentrations of PM$_{2.5}$ near surface in the forest were observed in the morning. At this time, the forest still had a high relative humidity and the traffic was heavy. By noon, and continuing into the afternoon, the concentrations decreased. Around dusk, the traffic was heavy again as commuters returned home, and the exhaust emissions increased, bringing particulate matter concentrations up, as well. Summer’s high relative humidity was the dominant factor controlling the concentration during that season, instead of traffic. In summer, water vapor descended to the ground and condensed at dusk, which led to a decrease in the relative humidity. As PM$_{2.5}$ in the air settled along with the water vapor and became dust, the atmospheric concentration decreased (Qiu et al. 2015).

We analyzed the concentration differences of PM$_{2.5}$ near the surface during different seasons. We showed that over a year, the concentration of PM$_{2.5}$ near the surface in the forest was highest during winter, and lowest during summer. In addition, the concentration of PM$_{2.5}$ near the surface during winter was significantly higher than in other seasons. The poor air quality measured during winter was not caused entirely by an increase in the severity of anthropogenic pollution during this season. Another important factor was the relative function of the forest. A forest canopy can capture particulate matter with its branches, leaves, and pores, thereby reducing the concentration of particulate matter in the atmosphere (Freer-Smith et al. 2004, Nowak et al. 2006). In the winter,
deciduous leaves, which are prevalent in our forested study location, had withered and fallen, and the air humidity was low. As a result, the adsorption of PM$_{2.5}$ by the forest was low. In contrast, the canopy was thick during summer and the air humidity was high, so the removal effects of the forest were prominent. The concentration of PM$_{2.5}$ in the forest was the lowest and, the air quality was at its best, during summer. This result reflects the capacity of forests to regulate and intercept PM$_{2.5}$ during the year. This conclusion is consistent with many studies. For example, (Yang et al. 2002b) studied the variation in PM$_{2.5}$ concentration and its correlation with PM$_{10}$ and total suspended particulates in Beijing in 2002, and they found that the concentration of PM$_{2.5}$ had clear seasonal variations, with the highest concentrations during the winter and the lowest concentrations in the summer. Many other studies (Balestrini et al. 2007, Escobedo &Nowak 2009, Escobedo et al. 2008, Prajapati &Tripathi 2008) have shown similar trends.

Table 2 shows the PM$_{2.5}$ removal efficiencies during different seasons and time periods near the surface in the forest. These removal efficiencies are based on the deposition flux ($F$) and the average concentration; however, deposition is influenced by the deposition velocity ($V_d$), which is related to the wind speed. The uncertainty in the data possibly stems from the fact that the parameterization did not consider the processes of upward flux or rain, nor did it account for measurement uncertainties. A study has found that the blocking effects in the forest were much better under lower air quality grades (Cong et al. 2018), which means PM$_{2.5}$ might stay in the canopy under higher PM concentration. Thus, the removal efficiency in Fig.8 was not significantly different from other seasons. But what we showed in Table.2 could indicate that the removal efficiency was lower than other seasons in morning hours and afternoon hours during winter. Although Fig. 8 shows no significant changes throughout the day, some conclusions can still be drawn. Summers in the forest experienced the highest removal efficiency between 07:00 and 09:30 when the traffic was heavy and the concentration of PM$_{2.5}$ was relatively high. The thick summer canopy had better adsorption rates than at other times during the day or in other seasons. Winter had the lowest removal efficiency between 09:30 and 12:00. At this time, the morning rush hour had passed but the concentration of PM$_{2.5}$ remained high. The poor adsorption rates, reduced by the lack of foliage and low humidity, contributed to the low removal efficiency. For the bare land, the removal efficiencies near the surface were influenced by the wind and the herb layer. Herb layers can help reduce dust pollution caused by wind erosion, which carries particulate matter back into the air (Liu et al. 2015). In spring, there was a very high wind speed near the surface, so the particles were effectively scrubbed or moved away over time. In other seasons, when wind speeds were low and the herb layer was sparse at our sampling site, the particles tended to be resuspended, which led to negative removal efficiency values.
3.2 Constituents and ions changes of PM$_{2.5}$ in the forest

The chemical composition of PM$_{2.5}$ has been received considerable attention. The composition and sources of PM$_{2.5}$ have been studied extensively, and SO$_4^{2-}$, NO$_3^-$, and NH$_4^+$ have been demonstrated as the major ions in PM$_{2.5}$ in Beijing (Xu et al. 2007). In our study, ten ions were observed near surface. Anion and cation concentrations were largely consistent with a study that examined lower-atmospheric aerosols in winter in a northern suburb of Beijing (Yang et al. 2002a). Most water-soluble ions had similar proportions to those measured in previous studies (Fig. 9). In our study, the concentration of Na$^+$ near the surface was strikingly high during the spring (Fig. 6). In coastal cities, Na$^+$ in the atmosphere is mostly derived from the ocean (Xiao et al. 2013). In addition to differences between of sampling sites and measurement errors, dust may also cause high concentrations of Na$^+$ in PM$_{2.5}$ (Gao et al. 2011), which may help explain our results. The mass ratio of [NO$_3^-$]:[SO$_4^{2-}$] is used as an indicator of the contribution of mobile and stationary sources of nitrogen and sulfur in the atmosphere (Arimoto et al. 1996). If the ratio is greater than one, then mobile sources should be considered the main pollution sources for the sampling area, and vice versa. In our study, the ratio of [NO$_3^-$]:[SO$_4^{2-}$] during the sampling period was 0.21, which implies that the main pollution sources for the near-surface atmosphere in the forest were stationary. The ratio measured in this study was lower than ratios from Xiamen (0.51) (Gao et al. 1996), Changsha (0.31) (Li et al. 2007), Guangzhou (0.79) (Tan et al. 2009), Beijing (0.83–0.87) (Zhang et al. 2013), Beijing (0.67) (Wang et al. 2005), Beijing (1.00), and Nanjing (>1) (Fang et al. 2016). In those studies, sampling sites were mostly set on the roofs of buildings, while ours was near the surface in a forest, where vehicle exhaust was presumably blocked. Thus, the mass ratio of [NO$_3^-$]:[SO$_4^{2-}$] in our study was lower than others’. However, the influence of vehicle exhaust still can’t be ignored given the rapid increase in the number of motor vehicles in Chinese cities.

3.3 Influence of meteorological factors on PM$_{2.5}$ near surface in the forest

A study about the influence of meteorological factors on PM$_{10}$ and PM$_{2.5}$ in Beijing found that the concentrations of particulate matter were most affected by humidity and temperature, followed by wind speed (Luo et al. 2013), which is consistent with the results of our study. However, other studies had yielded different results. (Bi et al. 2013) performed a correlation analysis of meteorological factors and PM$_{2.5}$ in Kunming, and they found that the order of influence of meteorological factors was relative humidity > wind speed > atmospheric pressure > temperature. Three differences may account for these research finding discrepancies: first, the sampling sites were different, with our sampling site near the surface in a forest, where wind speed was naturally lower; second, we analyzed different meteorological factors with different equipment; third, the
statistical analysis may have been different. The PM$_{2.5}$ concentration was also affected by various factors such as the atmospheric conditions and the source (Wu et al. 2018). Thus, the different results may be caused by the background environments of the different study sites. Our results were similar to the study of Deng in Beijing (Deng et al. 2019). Their study had a rather large time span which covered four different seasons in green land and they showed the relationship between meteorological factors and PM concentration in urban green land. It also indicated that the PM concentration was significantly positively correlated with the relative humidity ($P < 0.01$), and was significantly negatively correlated with temperature ($P < 0.05$). The PM$_{2.5}$ concentration had the positive correlation to relative humidity during winter, and it was confirmed not only an occasional phenomenon in Beijing but also in other regions of China such as Yangtze River Delta region (Cheng et al. 2015). With the increase of relative humidity and PM$_{2.5}$, water-soluble components became more abundant (Cheng et al. 2015).

Conclusions

In the daytime, PM$_{2.5}$ concentrations near the surface in the forest of Beijing Olympic Forest Park showed the highest average concentrations between 07:00 and 09:30. The lowest average concentrations occurred between 12:00 and 15:00, except during the summer, which reached its average daily low values between 15:00 and 18:00. Over a year of measurements, the concentrations were the highest in the winter and the lowest in the summer, and the concentration during the winter was significantly higher than in other seasons. The constituents of PM$_{2.5}$ near the surface in the forest were dominated by SO$_4^{2-}$ (55.93%) and NO$_3^-$ (12.79%). The concentrations of PM$_{2.5}$ near the surface had a significant positive correlation with relative humidity and a significant negative correlation with temperature, but no significant negative correlation with wind speed. The removal efficiency showed no significant changes over the course of the day. For the forest, the highest removal efficiency occurred between 07:00 and 09:30 in the summer while the lowest occurred between 09:30 and 12:00 in the winter. Different adsorption capacities of the deciduous canopy in different seasons contributed to the result. The removal efficiency of bare land was significantly lower than that of the forest; in some time periods and seasons, the removal efficiency was even negative.

Acknowledgements

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Figure 1

Fig. 1 Map of the study area and sampling site locations.
Figure 2

Fig. 2 Diagram of the field installation design
Figure 3

Fig. 3 Daytime concentration changes in PM$_{2.5}$ in the forest.
Figure 4

Fig. 4 Average concentration of PM$_{2.5}$ during different seasons in the forest.
Figure 5

Fig. 5 Ion composition of PM$_{2.5}$ in the forest, by mass.
Figure 6

Fig. 6 Relative abundance of anions (left) and cations (right) in the forest, across all seasons.
Figure 7

Fig. 7 Plots showing PM$_{2.5}$ concentrations and meteorological measurements: air temperature and relative humidity during the winter and wind speeds during the spring.
Figure 8

Fig. 8 Removal efficiencies of PM$_{2.5}$ in the forest (left) and over bare land (right) during different seasons and time periods.
Figure 9

Fig. 9 Major ion components of PM$_{2.5}$, by mass, measured in recent years.
Table 1 (on next page)

Regression analysis relating meteorological factors and concentrations of PM$_{2.5}$ in the forest
Table 1 Regression analysis relating meteorological factors and concentrations of PM$_{2.5}$ in the forest

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Meteorological factors</th>
<th>R$^2$</th>
<th>p-Value</th>
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<td>Temperature</td>
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<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>Relative humidity</td>
<td>0.3326</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td></td>
<td>Wind speed</td>
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<td>0.0003</td>
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Table 2 (on next page)

PM$_{2.5}$ removal efficiencies in different seasons and time periods in the forest
### Table 2 PM$_{2.5}$ removal efficiencies in different seasons and time periods in the forest

<table>
<thead>
<tr>
<th>Seasons</th>
<th>07:00–09:30</th>
<th>09:30–12:00</th>
<th>12:00–15:00</th>
<th>15:00–18:00</th>
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<tbody>
<tr>
<td>Spring</td>
<td>48.63%</td>
<td>43.73%</td>
<td>59.68%</td>
<td>56.68%</td>
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<tr>
<td>Summer</td>
<td>71.31%</td>
<td>46.12%</td>
<td>41.00%</td>
<td>38.93%</td>
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<td>Fall</td>
<td>60.01%</td>
<td>44.64%</td>
<td>50.30%</td>
<td>61.65%</td>
</tr>
<tr>
<td>Winter</td>
<td>59.84%</td>
<td>34.53%</td>
<td>39.28%</td>
<td>63.69%</td>
</tr>
</tbody>
</table>