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.

33

34 **Key words:** Near the surface, Forest, PM$_{2.5}$, Removal efficiency, Meteorological factors

35

Introduction

37 Air pollution has become an increasingly serious concern in China in recent years, as economic
38 development and urbanization, automobile exhaust, and coal and industrial emissions have
39 increased year after year (Li et al. 2016). Fine particulate matter (PM$_{2.5}$), along with other major
40 atmospheric particulate pollution, has become the most pressing air pollution concern in the
41 country (Ma et al. 2013). PM$_{2.5}$ refers to the particulate matter with atmospheric dynamic diameters
42 less than 2.5 μm. Compared to other particles, the diameter of a PM$_{2.5}$ pollutant is smaller, its
43 surficial area is larger, and its transmission range is farther. Moreover, it contains more toxic
44 substances and remains in the atmosphere, making and it more difficult to remove (O'Connor et
45 al. 2008). As a result, PM$_{2.5}$ does great harm to human health and the environment (Viana et al.
46 2008). Finding ways to reduce fine particulate pollution has become a hot-button difficult issue
47 for governments and residents of affected areas.
48 Forests represent important ecosystems, and forest canopies can capture particles in their complex
49 branch structures and the stomata on their leaves. Therefore, forests have a strong role in adsorbing
50 particulate matter and removing it from the atmosphere (Freer-Smith et al. 2004, Nowak et al.
51 2006). Studying the concentration and composition of particulate matters in forests can provide a
52 basis for innovation and research into technology aimed at reducing atmospheric particulate
53 matter. The sequestration of atmospheric PM$_{2.5}$ by forests mainly occurs in the canopy (Liu et al.
54 2015), so researchers have focused most of their efforts on measuring and modeling the
55 concentration and composition of PM$_{2.5}$ far above the surface in the forest. Previous studies have
56 shown that the diurnal variation of PM$_{2.5}$ concentration at different heights in the forest includes
57 two peaks and two troughs (Wang et al. 2014, Wang et al. 2005, Zhao et al. 2009). Furthermore,
58 the relationships between meteorological factors and the concentration of PM$_{2.5}$ have also been
59 studied. Researchers have examined the relationship between large-scale climate and PM$_{2.5}$ by
60 using ArcGIS (Chen et al. 2016, Huang et al. 2015, Yuan et al. 2017), but few people have studied
61 the effects of microclimate on PM$_{2.5}$ concentration, especially in forests. The composition of PM$_{2.5}$
62 in certain areas in the atmosphere has also been studied: one study that looked at the constituents
63 of particulate matter in a forest focused on particles above the canopy and indicated that water-
64 soluble inorganic ions, including SO_4^{2-}, NO_3^-, and NH_4^+, were the main ingredients of PM$_{2.5}$. The
65 sum of their mass concentrations accounted for more than 50% of the total water-soluble inorganic
66 ions of PM$_{2.5}$, and the concentrations of these ions increased with height (Li et al. 2014).

67   In general, previous studies of fine particles have focused on the concentration and constituents of

68   the atmosphere at the height of the canopy, or in urban areas. Little interest has been shown in the

69   particles near the ground surface in forests, especially their constituent changes. An average person

70   breathes at a height of 1.5 m above the ground (Kenagy et al. 2016), where inhaled particulate

71   matter can have negative effects on respiratory and cardiovascular health, and can even damage

72   DNA (Hong et al. 2002). Studying changes in the concentration and constituents at this height will

73   provide theoretical support for future studies into the effects of $PM_{2.5}$ on human breathing and

74   health. Therefore, it's important to study the concentration and constituents of $PM_{2.5}$ near the

75   ground in forests in order to evaluate their removal efficiency.

76   In this paper, we selected the artificial forest in the southern part of Beijing Olympic Forest Park

77   as the experiment site. The concentration and constituents of $PM_{2.5}$ were collected at a height of

78   1.5 m during different seasons. The changes in the concentrations of $PM_{2.5}$ and its constituents

79   were analyzed and compared to nearby bare land in order to quantify the effects the forest had on

80   these pollutants.

81

Materials & Methods

83   1 Materials and methods

84   1.1 Experimental site

85   Beijing is the economic, cultural, and political center of China and is famous for its struggles with

86   air pollution. Beijing Olympic Forest Park is located in the North Olympic Park, Chaoyang

87   District, Beijing. It covers an area of 680 ha and is the largest city park in Beijing. Its geographic

88   coordinates are 40° 01′ 03.73″ N and 116° 23′ 09.81″ E. It has a rich variety of plants in a

89   mixed forest, including 530,000 trees and shrubs of more than 180 species that respond differently

90   to the four seasons (Li et al. 2006).

91   A sampling area was selected in a planted forest in the southern part of the park (**Fig. 1**). The

92   sampling area was bounded in the north by the Five-ring Road and in the south by Yang Mountain.

93   The forest was 60 m long from north-to-south and 50 m wide from east-to-west, with a stretch of

94   pavement through the middle. The forest was mainly composed of Chinese white poplar (*Populus*

95   *tomentosa*), mixed with a small amount of weeping willow (*Salix spp.*), Chinese ash (*Fraxinus*

96   *chinensis*), and Chinese pine (*Pinus tabulaeformis*). Shrubs grew on the edge of the forest,

97   including Chinese rose (*Rosa chinensis*), forsythia (*Forsythia suspensa*), and flowering peach

98   (*Amygdalus persica*).

99   We selected one vertical gradient sampling location and installed equipment at 1.5 m above the

100   ground. The composition of the underlying surface is mainly grass. There was no significant local

101   source of air pollutants near the monitoring station. A second site was chosen as a control, which

102   monitored the concentration over the bare land surrounding the forest. The climates were similar

103   for the two sites.

104

105   1.2 Sampling procedure

106   A Tianhong suspended particulate pollutant sampler and a small weather station were installed at

107   each sampling point to collect data on particulate concentration and constituents, and meteorology

108   (**Fig. 2**). The flow rate of the sampler was set at 100 L/min, and the $PM_{2.5}$ concentration was

109   collected every 5 minutes. We used a quartz filter membrane and burned it for four h in a muffle

110   furnace in order to avoid contamination and reduce error. The meteorological data collected by the

111   weather station included temperature, relative humidity, and wind speed.

112   Sampling was conducted from September 2014 to September 2015. Samples were collected during

113   the first 4 days of each month, measured from 07:00 to 18:00 at each sampling point. It provided

114   the same sample collecting interval and we divided the sampling period into four time periods

115   which represent the morning rush hours, morning hours, afternoon hours and the evening rush

116   hours. The weather was mainly clear during the collection period.

117

118   1.3 Analytical methods

119   1.3.1 Analysis of concentration variation

120   The $PM_{2.5}$ concentrations during each season were averaged by time of day to observe the diurnal

121   variation during each season.

122   1.3.2 Analysis of constituents and variation

123   Water-soluble ion analysis of the particulate matter was performed by soaking quarters of

124   standard-sized portions of the sample filter membranes in 50 ml of deionized water and performing

125   WAYEE IC6200 ion chromatography to determine the concentrations of selected anions and

126   cations. The main constituents of $PM_{2.5}$ were determined from these data.

127   1.3.3 Quantification of removal efficiency

128   In order to evaluate the importance of deposition of $PM_{2.5}$ in a forest environment, the removal

129   efficiency needed to be calculated. The removal efficiency differs based on a number of

130   deposition-related variables, and it was calculated using the Eq. (1) (Escobedo &Nowak 2009, Liu

131   et al. 2016, Nowak et al. 2006):

132    $$E = I/(I + D)^{\square} \tag{1}$$

133   Where I is the removed deposition of $PM_{2.5}$ on the surface and $\bar{D}$ is the daily average deposition

134   flux. The variables I and $\bar{D}$ were calculated by Eq. (2) and Eq. (3) with values from the forest and

135   bare land (Escobedo &Nowak 2009, Nowak et al. 2006):

136    $$I = (1 - R) \times V_d \times C \times t \qquad (2)$$

137    $$\bar{D} = \bar{C} \times T \qquad (3)$$

138   Where R is the resuspension rate of $PM_{2.5}$, V_d is the deposition velocity, C is the particle

139   concentration, $\bar{C}$ is the daily average concentration, and T/t is the evaluated time. In this process,

140   R of the forest and bare land can be derived using the regression method, which can be expressed

141   by Eq. (4) (Liu et al. 2016):

142    $$y = -\, 0.01x^2 + 0.17x \; (R^2 = 0.91, P < 0.001) \qquad (4)$$

143   Deposition velocity depends on the surface and environment since it is related to wind speed.

144   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

145   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

146   between 2 m/s and 10 m/s, the V_d in the forest was calculated by Eq. (5) (Nowak et al. 2013):

147    $$y = -\, 0.02x^2 - 0.08x + 0.14 \; (R^2 = 0.\,92, \; P < 0.\,001) \qquad (5)$$

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

149   2016):

150    $$y = -\, 0.01x^3 \; + \; 0.\,05x^2 + 0.41x - 0.05 \; (R^2 \; = \; 0.\,98, \; P \; = \; 0.\,002) \qquad (6)$$

151

Results

153   2.1 Concentration variation of $PM_{2.5}$ in the forest

154   2.1.1 Diurnal variation

155   The mean mass concentration across the entire sampling period was divided into four time periods:

156   07:00–09:30, 09:30–12:00, 12:00–15:00, and 15:00–18:00, which represent the morning rush

157   hours, morning hours, afternoon hours and the evening rush hours. As shown in **Fig. 3**, the diurnal

158   variations of $PM_{2.5}$ concentrations in the forest were largely consistent and showed a U-shaped

159   pattern. Summer was the exception, during which a general downward trend was observed. $PM_{2.5}$

160   showed the highest average concentrations between 07:00 and 09:30. During this period, the

161   average concentration of $PM_{2.5}$ was approximately 12.98 µg/m^3 in spring, 6.58 µg/m^3 in summer,

162   11.85 µg/m^3 in the fall and 190.22 µg/m^3 in the winter. Moreover, all seasons showed the highest

163   instantaneous concentrations at 07:00, except for winter, when the instantaneous concentration

164   reached 303.32 μg/m^3 at 18:00, which was the highest value during the sampling period. In the
165   09:30–12:00 and 12:00–15:00 periods, the average concentrations showed a relatively smooth
166   variation, and bottomed out between 12:00 and 15:00 (except for summer), reaching 9.92 μg/m^3
167   during spring, 6.06 μg/m^3 during the fall, and 111.09 μg/m^3 during the winter. During summr, the
168   lowest PM$_{2.5}$ average concentration in the forest, 1.52 μg/m^3, occurred between 15:00 and 18:00.
169
170   2.1.2 Variations between seasons
171   As shown in **Fig. 4**, the variation in PM$_{2.5}$ average concentrations in different time periods in the
172   forest was similar in each season. The daily average concentration of PM$_{2.5}$ reached its highest
173   point during winter, which was 149.31 μg/m^3, vastly exceeding those of the other seasons. In the
174   spring and fall, the daily average concentrations of PM$_{2.5}$ were low, at 11.31 μg/m^3 and 8.40 μg/m^3,
175   respectively. In summer, the daily average concentration of PM$_{2.5}$ reached its minimum value of
176   3.17 μg/m^3.
177
178   2.2 Constituents of PM$_{2.5}$ in the forest
179   2.2.1 Constituents and proportion of ions in PM2.5
180   Average concentrations of ten ions were detected in this study: SO$_4{}^{2-}$ (97.49 μg/m^3), NO$_3{}^-$ (20.50
181   μg/m^3), Cl$^-$ (16.15 μg/m^3), Na$^+$ (11.80 μg/m^3), Ca^{2+} (8.73 μg/m^3), K$^+$ (6.87 μg/m^3), NH$_4{}^+$ (7.08
182   μg/m^3), HCOO$^-$ (3.46 μg/m^3), Mg^{2+} (1.62 μg/m^3), and F$^-$ (0.44 μg/m^3). As shown in **Fig. 5**, SO$_4{}^{2-}$
183   was most abundant, representing 55.93% of the ions, by mass, followed by NO$_3{}^-$, Cl$^-$, Na$^+$, Ca^{2+},
184   K$^+$, NH$_4{}^+$, HCOO$^-$, and Mg^{2+}. F$^-$ was the least abundant at 0.24%.
185
186   2.2.2 Seasonal variations in negative and positive ions
187   As shown in **Fig. 6**, the proportion of SO$_4{}^{2-}$ in fine particular matter showed a U-shaped variation
188   across seasons. NO$_3{}^-$ experienced an obvious spike during summer. Na$^+$ showed a downward
189   overall trend and had a sharp decrease between spring and summer. Ca^{2+} and K$^+$ had the same
190   trend and both peaked during the fall. Cl$^-$ and NH$_4{}^+$ showed an upward trend, while the remaining
191   ions did not show significant changes in relative abundance.
192
193   2.3 Influence of meteorological factors on PM$_{2.5}$ in the forest
194   Meteorological factors, including temperature, relative humidity, and wind speed, were recorded
195   during each time period by a small weather station. As the PM$_{2.5}$ concentration was significantly
196   higher during winter than during other seasons, we chose the data from winter to be representative
197   for most meteorological variables. The exception was wind speed, which was negligible during
198   the winter, but was relatively high during the spring. Thus, we used the data from the spring to
199   analyze the relationship between wind speed and concentration (**Fig. 7**). Temperature, relative

200   humidity, and wind speed were all correlated with the concentration of $PM_{2.5}$ (**Table 1**). The

201   concentration of $PM_{2.5}$ had a significant positive correlation ($p < 0.01$) with relative humidity and

202   a significant negative correlation with temperature. The correlations between the concentration of

203     $PM_{2.5}$ in the forest and relative humidity and temperature were particularly strong.

204

205   2.4 Removal efficiency of $PM_{2.5}$ in the forest

206   The removal efficiency of $PM_{2.5}$ during different time periods was calculated according to the

207   removal efficiency model. **Fig. 8** shows the $PM_{2.5}$ removal efficiencies of the forest and bare land

208   during each daily time period. The removal efficiency of $PM_{2.5}$ in the forest was relatively

209   consistent throughout the day for each season. The variation in the removal efficiency for the four

210   seasons between 07:00 and 09:30 had a same relative trend as that between 09:30 and 12:00.

211   Summer had the highest removal efficiency between 07:00 and 09:30 and winter had the lowest

212   between 09:30 and 11:00, which were 71.3% and 34.5%, respectively. For bare land, the removal

213   efficiencies were significant during spring, but the other seasons varied considerably, even

214   registering negative removal efficiencies during some time periods and seasons.

215

Discussion

217   3.1 Concentration and removal efficiency of $PM_{2.5}$ in different seasons and periods in the forest

218   Our monitoring results showed that the highest concentrations of $PM_{2.5}$ near surface in the forest

219   were observed in the morning. At this time, the forest still had a high relative humidity and the

220   traffic was heavy. By noon, and continuing into the afternoon, the concentrations decreased.

221   Around dusk, the traffic was heavy again as commuters returned home, and the exhaust emissions

222   increased, bringing particular matter concentrations up, as well. Summer's high relative humidity

223   was the dominant factor controlling the concentration during that season, instead of traffic. In

224   summer, water vapor descended to the ground and condensed at dusk, which led to a decrease in

225   the relative humidity. As $PM_{2.5}$ in the air settled along with the water vapor and became dust, the

226   atmospheric concentration decreased (Qiu et al. 2015).

227   We analyzed the concentration differences of $PM_{2.5}$ near the surface during different seasons. We

228   showed that over a year, the concentration of $PM_{2.5}$ near the surface in the forest was highest during

229   winter, and lowest during summer. In addition, the concentration of $PM_{2.5}$ near the surface during

230   winter was significantly higher than in other seasons. The poor air quality measured during winter

231   was not caused entirely by an increase in the severity of anthropogenic pollution during this season.

232   Another important factor was the relative function of the forest. A forest canopy can capture

233   particulate matter with its branches, leaves, and pores, thereby reducing the concentration of

234   particulate matter in the atmosphere (Freer-Smith et al. 2004, Nowak et al. 2006). In the winter,

235   deciduous leaves, which are prevalent in our forested study location, had withered and fallen, and

236   the air humidity was low. As a result, the adsorption of $PM_{2.5}$ by the forest was low. In contrast,

237   the canopy was thick during summer and the air humidity was high, so the removal effects of the

238   forest were prominent. The concentration of $PM_{2.5}$ in the forest was the lowest and, the air quality

239   was at its best, during summer. This result reflects the capacity of forests to regulate and intercept

240     $PM_{2.5}$ during the year. This conclusion is consistent with many studies. For example, (Yang et al.

241   2002b) studied the variation in $PM_{2.5}$ concentration and its correlation with PM_{10} and total

242   suspended particulates in Beijing in 2002, and they found that the concentration of $PM_{2.5}$ had clear

243   seasonal variations, with the highest concentrations during the winter and the lowest

244   concentrations in the summer. Many other studies (Balestrini et al. 2007, Escobedo &Nowak 2009,

245   Escobedo et al. 2008, Prajapati &Tripathi 2008) have shown similar trends.

246   **Table 2** shows the $PM_{2.5}$ removal efficiencies during different seasons and time periods near the

247   surface in the forest. These removal efficiencies are based on the deposition flux (F) and the

248   average concentration; however, deposition is influenced by the deposition velocity (V_d), which is

249   related to the wind speed. The uncertainty in the data possibly stems from the fact that the

250   parameterization did not consider the processes of upward flux or rain, nor did it account for

251   measurement uncertainties. A study has found that the blocking effects in the forest were much

252   better under lower air quality grades (Cong et al. 2018), which means $PM_{2.5}$ might stay in the

253   canopy under higher PM concentration. Thus, the removal efficiency in Fig.8 was not significantly

254   different from other seasons. But what we showed in Table.2 could indicate that the removal

255   efficiency was lower than other seasons in morning hours and afternoon hours during winter.

256   Although **Fig. 8** shows no significant changes throughout the day, some conclusions can still be

257   drawn. Summers in the forest experienced the highest removal efficiency between 07:00 and 09:30

258   when the traffic was heavy and the concentration of $PM_{2.5}$ was relatively high. The thick summer

259   canopy had better adsorption rates than at other times during the day or in other seasons. Winter

260   had the lowest removal efficiency between 09:30 and 12:00. At this time, the morning rush hour

261   had passed but the concentration of $PM_{2.5}$ remained high. The poor adsorption rates, reduced by

262   the lack of foliage and low humidity, contributed to the low removal efficiency. For the bare land,

263   the removal efficiencies near the surface were influenced by the wind and the herb layer. Herb

264   layers can help reduce dust pollution caused by wind erosion, which carries particulate matter back

265   into the air (Liu et al. 2015). In spring, there was a very high wind speed near the surface, so the

266   particles were effectively scrubbed or moved away over time. In other seasons, when wind speeds

267   were low and the herb layer was sparse at our sampling site, the particles tended to be resuspended,

268   which led to negative removal efficiency values.

269

270   3.2 Constituents and ions changes of $PM_{2.5}$ in the forest

271   The chemical composition of $PM_{2.5}$ has been received considerable attention. The composition and

272   sources of $PM_{2.5}$ have been studied extensively, and SO_4^{2-}, NO_3^-, and NH_4^+ have been

273   demonstrated as the major ions in $PM_{2.5}$ in Beijing (Xu et al. 2007). In our study, ten ions were

274   observed near surface. Anion and cation concentrations were largely consistent with a study that

275   examined lower-atmospheric aerosols in winter in a northern suburb of Beijing (Yang et al. 2002a).

276   Most water-soluble ions had similar propotions to those measured in previous studies (**Fig. 9**). In

277   our study, the concentration of Na^+ near the surface was strikingly high during the spring (**Fig. 6**).

278   In coastal cities, Na^+ in the atmosphere is mostly derived from the ocean (Xiao et al. 2013). In

279   addition to differences between of sampling sites and measurement errors, dust may also cause

280   high concentrations of Na^+ in $PM_{2.5}$ (Gao et al. 2011), which may help explain our results.

281   The mass ratio of $[NO_3^-]:[SO_4^{2-}]$ is used as an indicator of the contribution of mobile and

282   stationary sources of nitrogen and sulfur in the atmosphere (Arimoto et al. 1996). If the ratio is

283   greater than one, then mobile sources should be considered the main pollution sources for the

284   sampling area, and vice versa. In our study, the ratio of $[NO_3^-]:[SO_4^{2-}]$ during the sampling period

285   was 0.21, which implies that the main pollution sources for the near-surface atmosphere in the

286   forest were stationary. The ratio measured in this study was lower than ratios from Xiamen (0.51)

287   (Gao et al. 1996), Changsha (0.31) (Li et al. 2007), Guangzhou (0.79) (Tan et al. 2009), Beijing

288   (0.83–0.87) (Zhang et al. 2013), Beijing (0.67) (Wang et al. 2005), Beijing (1.00), and Nanjing

289   (>1) (Fang et al. 2016). In those studies, sampling sites were mostly set on the roofs of buildings,

290   while ours was near the surface in a forest, where vehicle exhaust was presumably blocked. Thus,

291   the mass ratio of $[NO_3^-]:[SO_4^{2-}]$ in our study was lower than others'. However, the influence of

292   vehicle exhaust still can't be ignored given the rapid increase in the number of motor vehicles in

293   Chinese cities.

294

295   3.3 Influence of meteorological factors on $PM_{2.5}$ near surface in the forest

296   A study about the influence of meteorological factors on PM_{10} and $PM_{2.5}$ in Beijing found that the

297   concentrations of paticulate matter were most affected by humidity and temperature, followed by

298   wind speed (Luo et al. 2013), which is consistent with the results of our study. However, other

299   studies had yielded different results. (Bi et al. 2013) performed a correlation analysis of

300   meteorological factors and $PM_{2.5}$ in Kunming, and they found that the order of influence of

301   meteorological factors was relative humidity > wind speed > atmospheric pressure > temperature.

302   Three differences may account for these research finding discrepencies: first, the sampling sites

303   were different, with our sampling site near the surface in a forest, where wind speed was naturally

304   lower; second, we analyzed different meteorological factors with different equipment; third, the

305 statistical analysis may have been different. The $PM_{2.5}$ concentration was also affected by various

306 factors such as the atmospheric conditions and the source (Wu et al. 2018). Thus, the different

307 results may be caused by the background environments of the different study sites. Our results

308 were similar to the study of Deng in Beijing (Deng et al. 2019). Their study had a rather large time

309 span which covered four different seasons in green land and they showed the relationship between

310 meteorological factors and PM concentration in urban green land. It also indicated that the PM

311 concentration was significantly positively correlated with the relative humidity ($P < 0.01$), and was

312 significantly negatively correlated with temperature ($P < 0.05$). The $PM_{2.5}$ concentration had the

313 positive correlation to relative humidity during winter, and it was confirmed not only an occasional

314 phenomenon in Beijing but also in other regions of China such as Yangtze River Delta

315 region(Cheng et al. 2015). With the increase of relative humidity and $PM_{2.5}$, water-soluble

316 components became more abundant(Cheng et al. 2015).

317

Conclusions

319 In the daytime, $PM_{2.5}$ concentrations near the surface in the forest of Beijing Olympic Forest Park

320 showed the highest average concentrations between 07:00 and 09:30. The lowest average

321 concentrations occurred between 12:00 and 15:00, except during the summer, which reached its

322 average daily low values between 15:00 and 18:00. Over a year of measurements, the

323 concentrations were the highest in the winter and the lowest in the summer, and the concentration

324 during the winter was significantly higher than in other seasons. The constituents of $PM_{2.5}$ near the

325 surface in the forest were dominated by SO_4^{2-}(55.93%) and NO_3^-(12.79%). The concentrations of

326 $PM_{2.5}$ near the surface had a significant positive correlation with relative humidity and a significant

327 negative correlation with temperature, but no significant negative correlation with wind speed. The

328 removal efficiency showed no significant changes over the course of the day. For the forest, the

329 highest removal efficiency occurred between 07:00 and 09:30 in the summer while the lowest

330 occurred between 09:30 and 12:00 in the winter. Different adsorption capacities of the deciduous

331 canopy in different seasons contributed to the result. The removal efficiency of bare land was

332 significantly lower than that of the forest; in some time periods and seasons, the removal efficiency

333 was even negative.

334

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339

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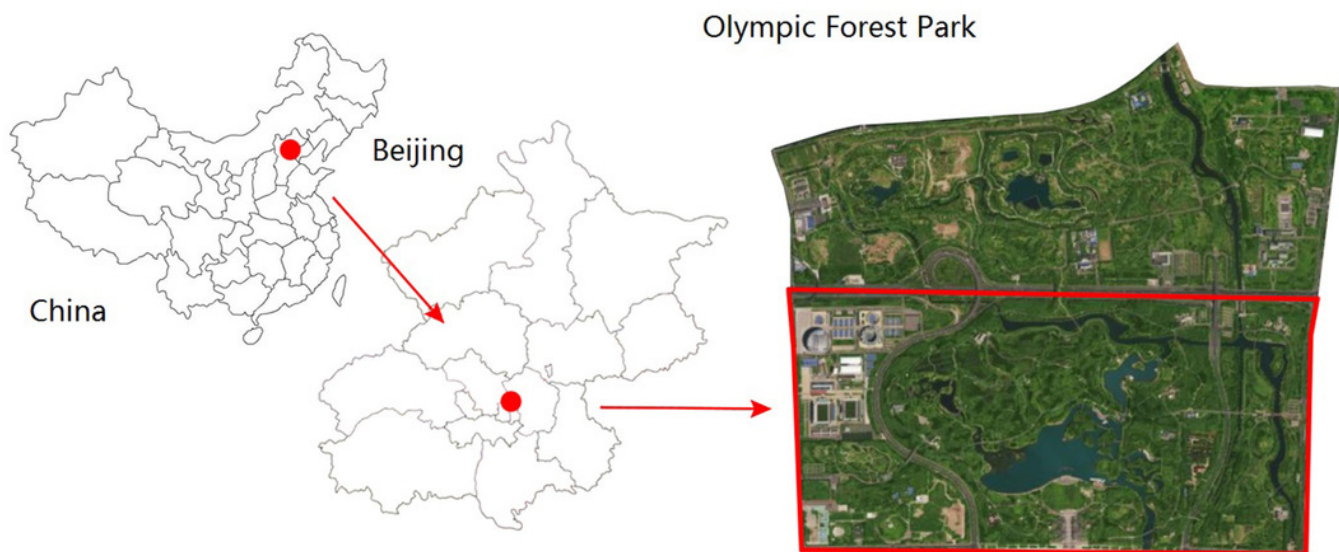
Fig. 1 Map of the study area and sampling site locations.

Figure 2

Fig. 2 Diagram of the field installation design
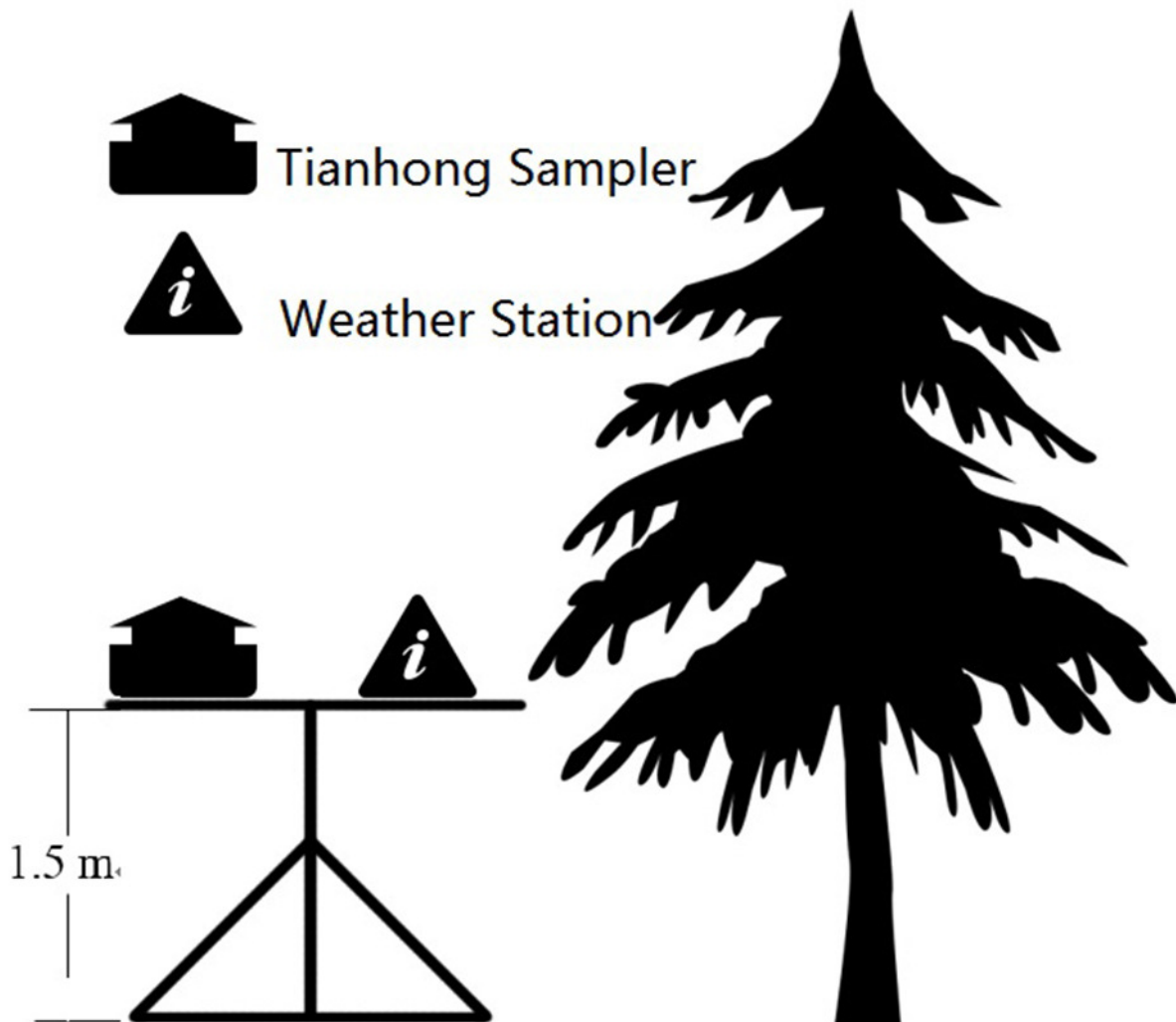

Tianhong Sampler

i Weather Station

1.5 m

Figure 3

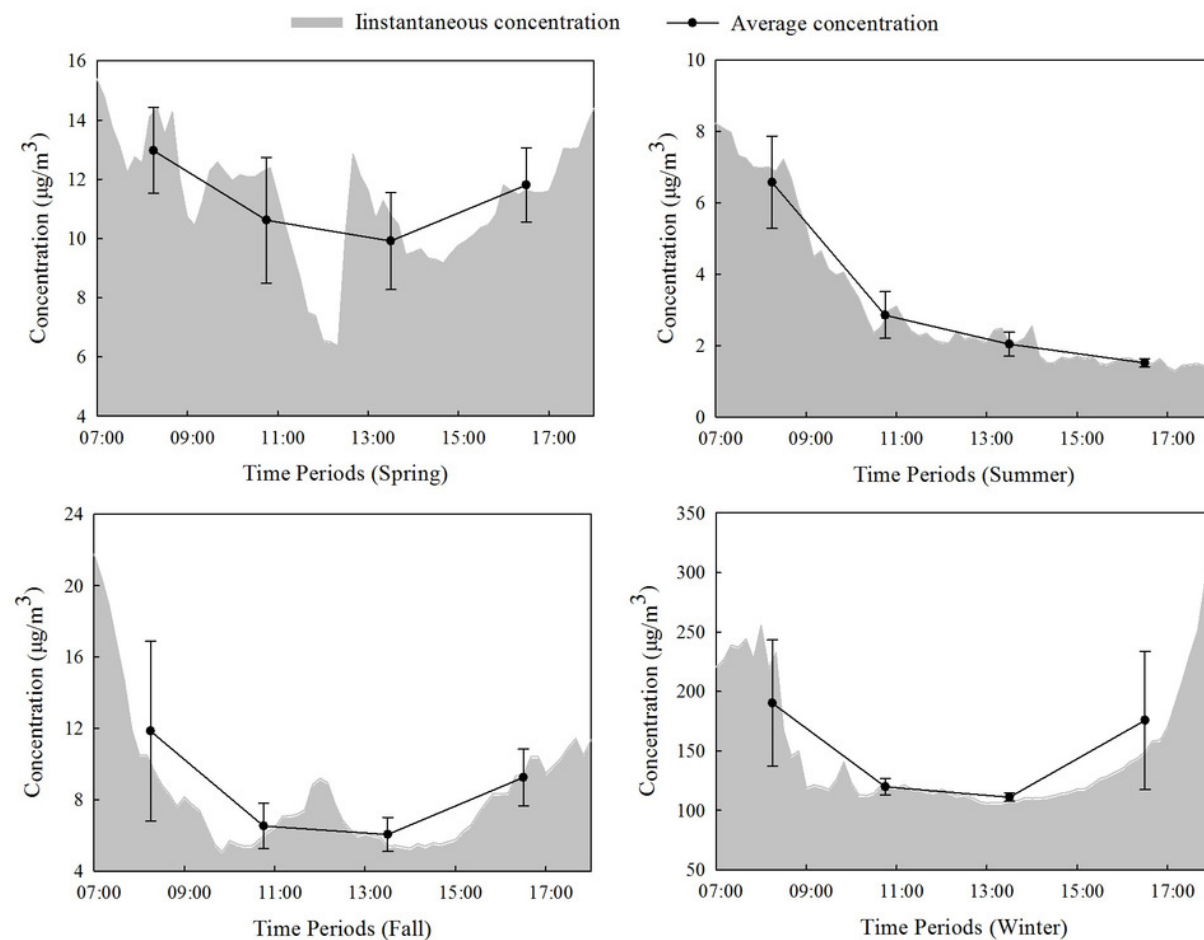Fig. 3 Daytime concentration changes in PM$_{2.5}$ in the forest.

Figure 4

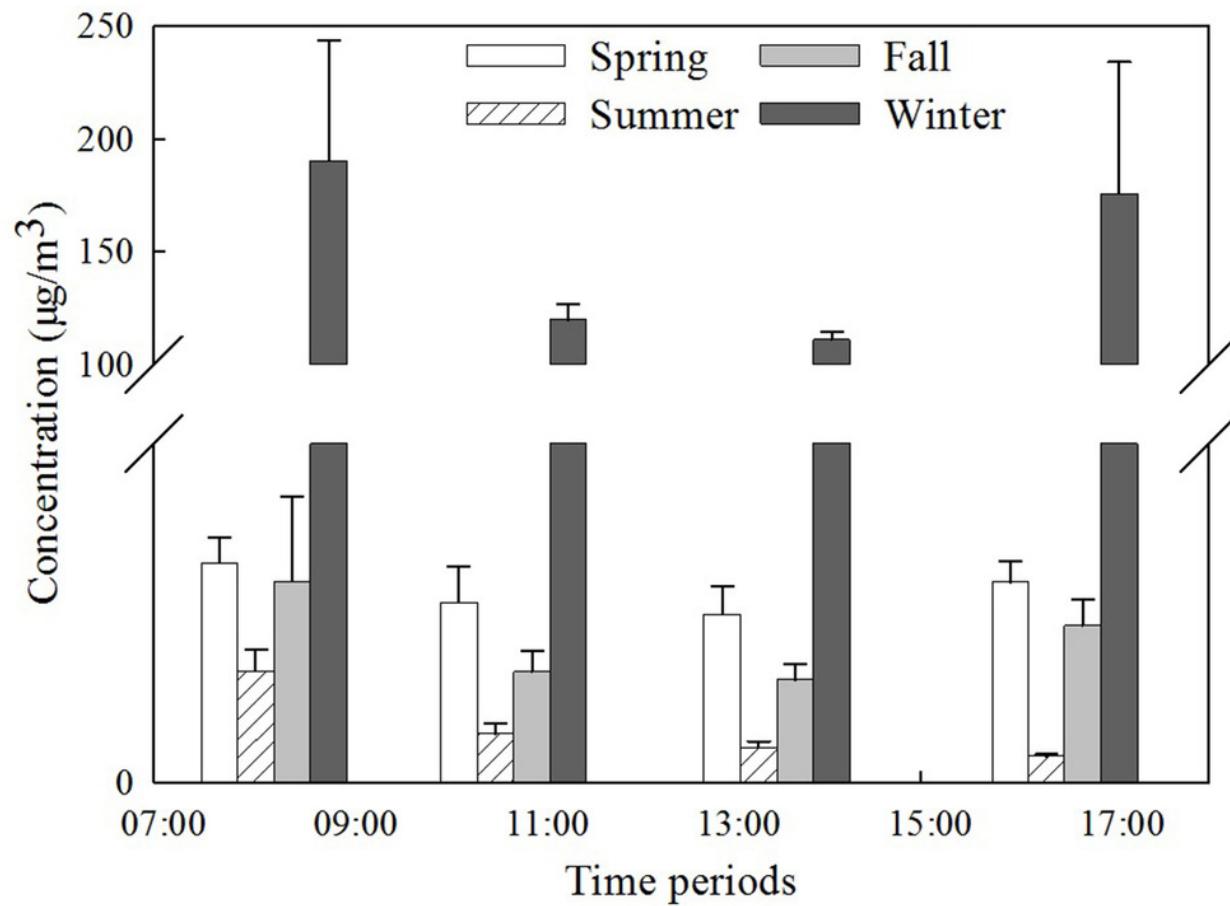Fig. 4 Average concentration of PM$_{2.5}$ during different seasons in the forest.

Figure 5

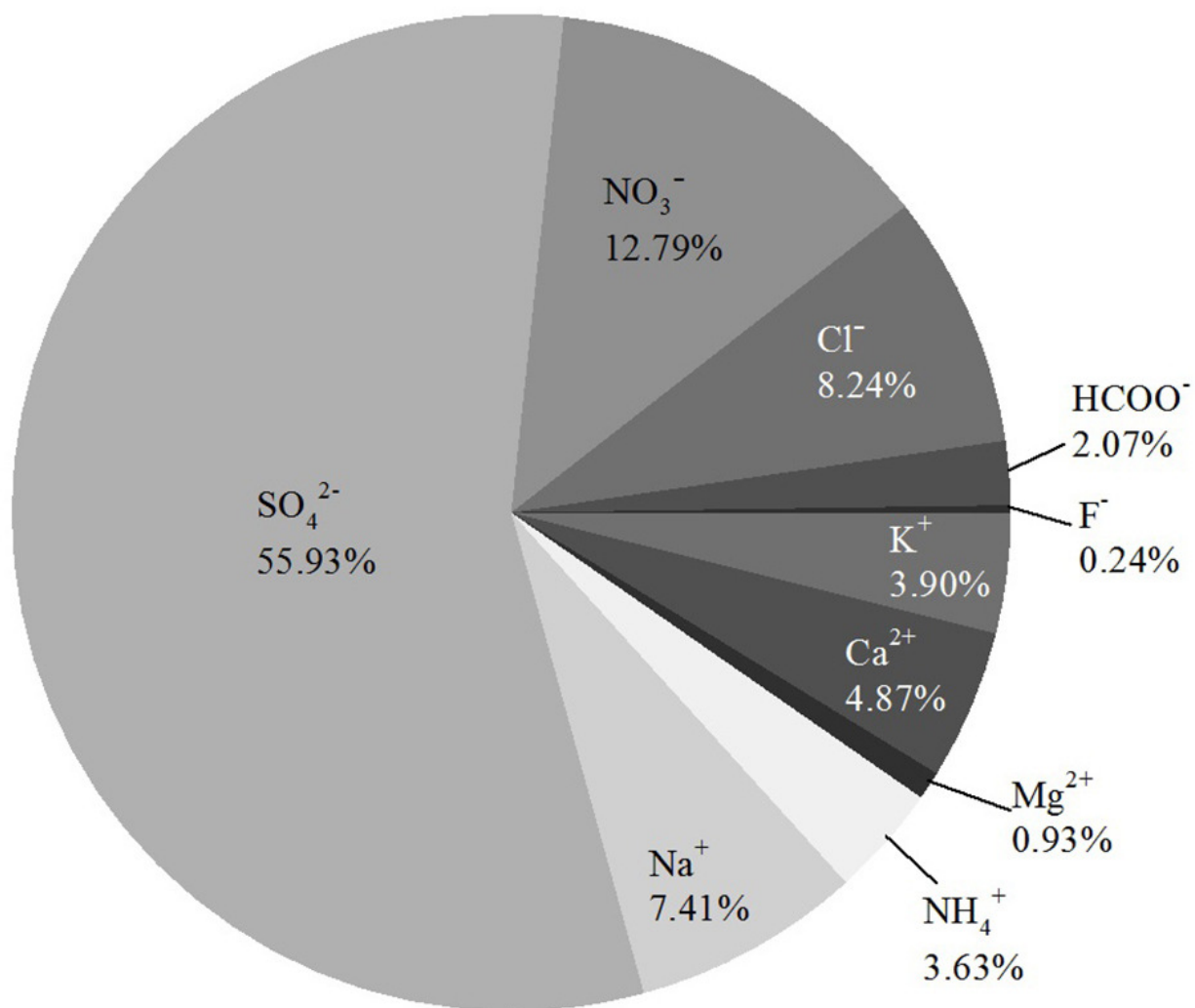Fig. 5 Ion composition of $PM_{2.5}$ in the forest, by mass.

Figure 6

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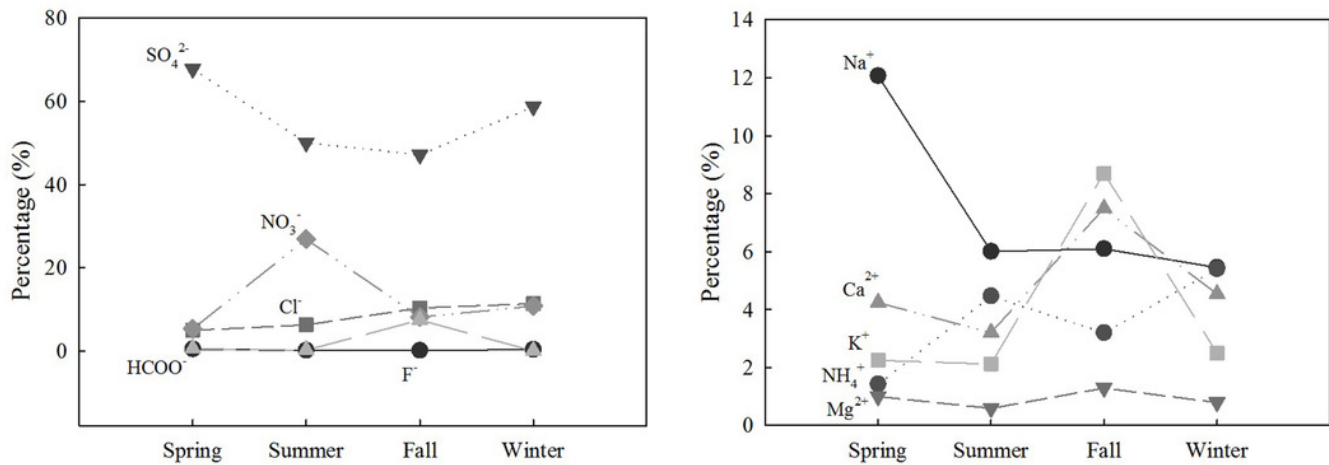
Figure 7

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.
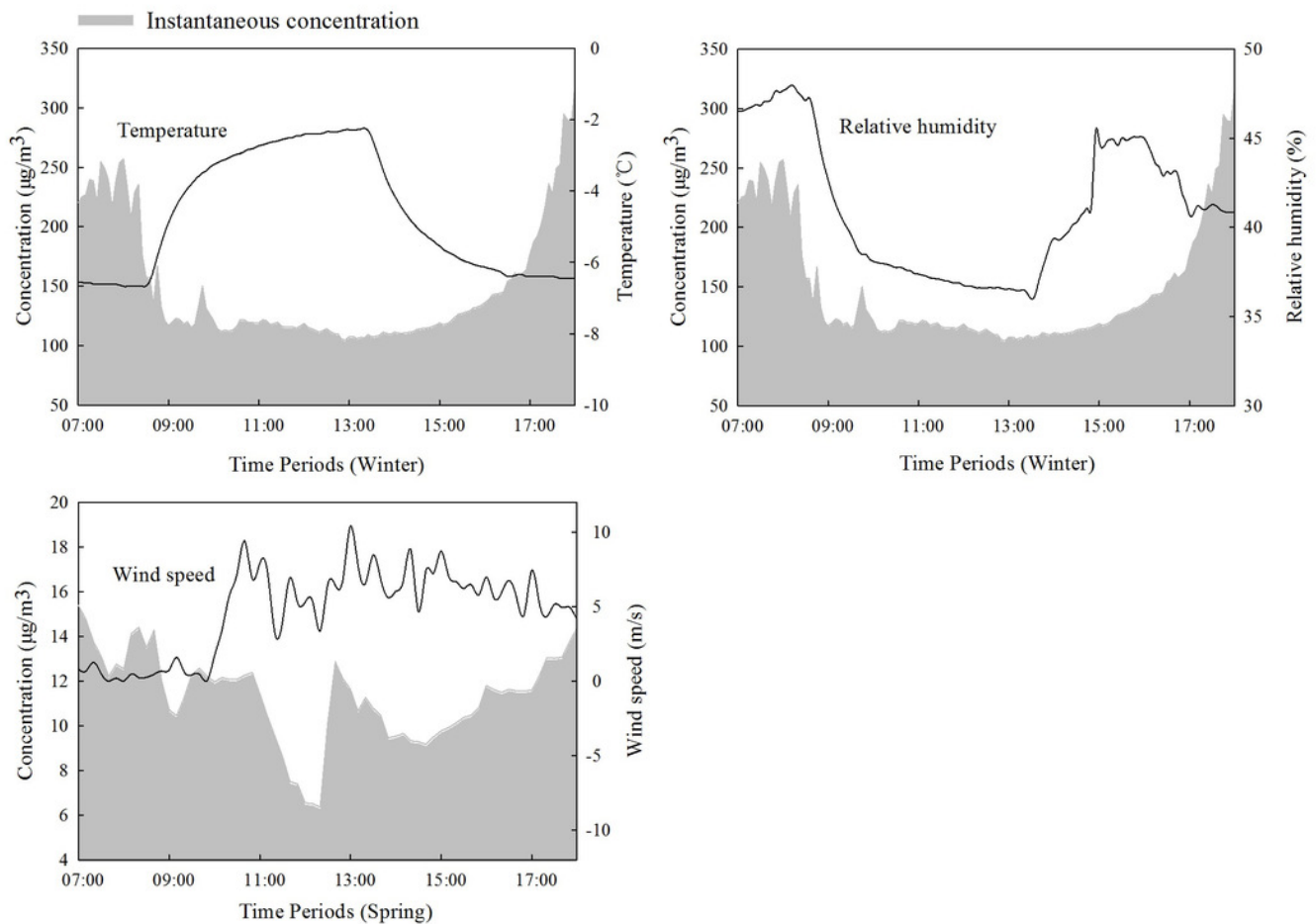
Figure 8

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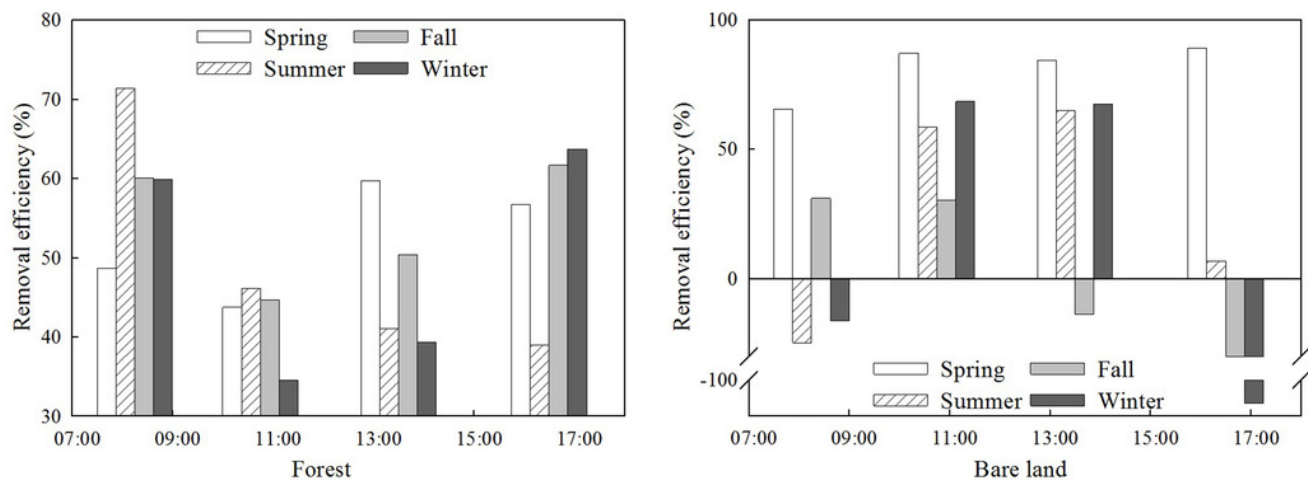
Figure 9

Fig. 9 Major ion components of PM$_{2.5}$, by mass, measured in recent years.
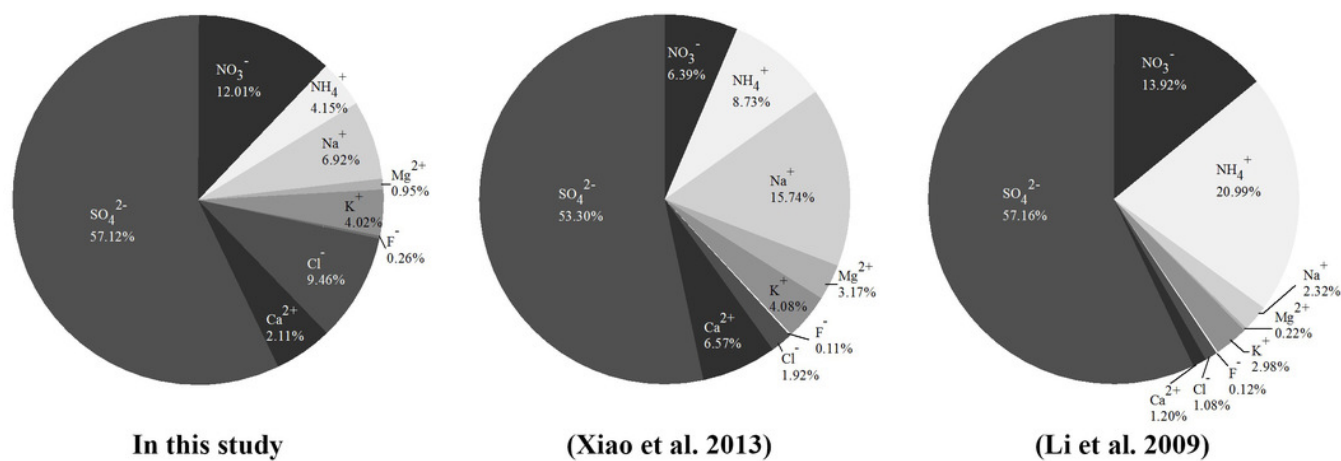

In this study   (Xiao et al. 2013)   (Li et al. 2009)

Table 1(on next page)

Regression analysis relating meteorological factors and concentrations of $PM_{2.5}$ in the forest

1

2 **Table 1** Regression analysis relating meteorological factors and concentrations of $PM_{2.5}$ in the

3 forest

Parameter	Meteorological factors		
	Temperature	Relative humidity	Wind speed
R^2	0.4942	0.3326	0.1825
p-Value	<0.0001	<0.0001	0.0003

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Table 2(on next page)

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

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

Seasons	Time Periods			
	07:00–09:30	09:30–12:00	12:00–15:00	15:00–18:00
Spring	48.63%	43.73%	59.68%	56.68%
Summer	71.31%	46.12%	41.00%	38.93%
Fall	60.01%	44.64%	50.30%	61.65%
Winter	59.84%	34.53%	39.28%	63.69%

2