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Quantifying Particulate Matter Accumulated on Leaves by 17 Species of Urban Trees in Beijing, China

Yansen Xu^{1,2}, Wen Xu², Li Mo^{1,3}, Mathew R. Heal⁴, Xiaowu Xu¹, Xinxiao Yu^{1*}

¹Beijing Laboratory of Urban and Rural Ecological Environment, Beijing Forestry University, No.35 Tsinghua East Road, Beijing, China.

²State key laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, No. 18 Shuangqing Road, Beijing, China.

³China-ASEAN Environmental Cooperation Center, No. 5 Houyingfang Hutong, Beijing, China

⁴School of Chemistry, University of Edinburgh, David Brewster Road, Edinburgh, UK

Abstract

Airborne particulate matter (PM) has become a serious environmental problem and harms human health worldwide. Trees can effectively remove particles from the atmosphere and improve the air quality. In this study, a washing and weigh method was used to quantify accumulation of water-soluble ions and insoluble PM on the leaf surfaces and within the wax of the leaves for 17 urban plant species (including 4 shrubs and 13 trees). The deposited PM was determined in three size-fractions: fine (0.2–2.5 μm), coarse (2.5–10 μm), and large ($> 10 \mu\text{m}$). Significant differences in the accumulation of PM were detected among various species. The leaves of *Platycladus orientalis* and *Pinus armandi* were the most effective in capturing PM. Across the species, 65% and 35% of PM on average deposited on the leaf surface and in the wax, respectively. The greatest PM accumulation by mass on leaves was in the largest PM size fraction, while accumulation of coarse and fine particles size fractions was smaller. Water-soluble ions accumulated on leaf surfaces contributed 28% to the total PM mass on average. This study demonstrated that leaves of woody plants accumulate PM differently, and the most effective plant species should be selected in urban areas for attenuating ambient PM.

Key words Particulate matter; Urban trees; Leaf deposition; Wax; Water-soluble ions.

* Corresponding author.

E-mail address: yuxinxiao111@126.com

Introduction

Airborne particulate matter (PM), consisting of particles with aerodynamic diameters in the range of 0.001-100 μm , is a major atmospheric pollutant (Pope III and Dockery 2006; WHO 2006). Anthropogenic sources contributing to PM include vehicle exhausts, road dust, domestic and large-scale coal burning, and cement and other industrial processes (Bosco et al. 2005; Dzierzanowski et al. 2011). Due to rapid urbanization and industrialization, the Beijing-Tianjin-Hebei region is undergoing serious PM pollution. For example, the annual average $\text{PM}_{2.5}$ (PM with diameter $<2.5 \mu\text{m}$) concentration in Beijing was $86 \mu\text{g m}^{-3}$ in 2014 (Chen et al. 2015), which was about 2.5 times higher than the WHO Air Quality Guideline value of $35 \mu\text{g m}^{-3}$ (WHO 2006). Positive associations have been found between $\text{PM}_{2.5}$ and health impacts (e.g. lower respiratory infections, trachea bronchus, lung cancers and cerebrovascular disease) (Lelieveld et al. 2015; Liu et al. 2016). It has been estimated that $\text{PM}_{2.5}$ pollution in urban areas of China led to 763,595 premature deaths in 2013 (Song et al. 2016). Beijing was worst affected with estimates of 5.2, 9.0, 2.3, and 1.6 thousand premature mortalities from ischemic heart disease (IHD), cerebrovascular disease, chronic obstructive pulmonary disease (COPD) and lung cancer (LC), respectively (Liu et al. 2016).

Numerous studies have identified that urban greening filters accumulate atmospheric particles more effectively than other land surfaces (Chen et al. 2016a; Janhäll 2015; Tallis et al. 2011;

Thithanhthao et al. 2015). Enhanced the deposition flux to the surface is the benefit for reducing pollutant concentrations near the ground and thus exposure of people in urban areas. This is one of the recognized ecosystem services of urban vegetation (Salmond et al. 2016). Compared with other urban surfaces, vegetation enhances deposition of particles because of the finely divided structure of many leaves, especially conifers. They have a larger collecting surface per unit ground area, and reduce the laminar boundary layer that limits the particles uptake. Using the i-tree model, Nowak et al. (2013) modeled PM_{2.5} removal by trees in ten American cities and estimated that annual masses of particles removal ranged from 4.7 t in Syracuse to 64.5 t in Atlanta. Schaubroeck et al. (2014) used the canopy interception and PM removal multilayered model (CIPAM) to estimate PM accumulated on a forestry canopy. For a case study in 2010 they estimated that a Scots pine stand in Belgium accumulated about 31 kg PM_{2.5} ha⁻¹ yr⁻¹. The plain afforestation project in Beijing has been estimated to decrease annual PM_{2.5} concentrations by 0.57 µg m⁻³, or 2% of the target set by the “Beijing Clean Air Action Plan (2013-2017)” (Chen et al. 2014).

At a leaf scale, particles deposited on leaf surface and ultrafine PM (particles with diameter < 100 nm) may enter the leaf stomata. Previous studies have examined the effectiveness of urban trees around the world for accumulation of PM_{2.5} and PM₁₀ (Chen et al. 2016b; Sgrigna et al. 2015) and demonstrated that PM accumulated on leaves differed significantly among plant

70 species (Beckett et al. 2000; Przybysz et al. 2014). Conifer species have greater potential in
71 capturing PM than broad-leaved species and evergreen conifers accumulate PM throughout the
72 year (Sæbø et al. 2012). However, broad-leaved species with large amounts of pubescence and
73 rougher surfaces also accumulate greater masses of particles (Mo et al. 2015). Particles mainly
74 deposit on the adaxial leaf surfaces, and accumulated masses about six times higher than on
75 abaxial leaf surfaces (Wang et al. 2006). The importance of leaf microstructure characteristics on
76 the effectiveness of capturing PM was evidenced by using scanning electron microscopy (SEM)
77 and energy dispersive X-ray (EDX) analysis (Yan et al. 2016).

78 Given limited greening space in urban Beijing, the most effective plant species in removing
79 PM should be selected for urban greening. Although many studies have focused on quantifying
80 the amount of PM deposited on trees (Yin et al. 2011; Chen et al. 2015; Wang et al. 2015;
81 Leonard et al. 2016), there is still a knowledge gap in terms of accumulation of PM in
82 epicuticular waxes between different species. Xu et al. (2017) used an artificial rainfall
83 simulation system to investigate the influence of rainfall duration and intensity on PM removal
84 from four broad-leaved species, and they detected that final wash off rates in the rainfall events
85 was only 51-70% of initial deposition. In other words, most PM captured by leaves is stored
86 temporarily, since deposited particles on leaf surfaces may be subsequently resuspended from the
87 leaves to the air by wind and rain (Schaubroeck et al. 2014). However, PM accumulation in the

wax fraction is very important because these particles are trapped permanently (Song et al. 2015). Most studies collect leaves only once at the beginning or in the middle of the season (Binze et al. 2014; Cheng et al. 2016; Mo et al. 2015). However, the characteristics of leaf structure are different during the growing season, which may impact their ability to accumulate PM. The leaf-washing methodology is the most common experimental approach. A large proportion of PM is water-soluble ions, which comprised approximately 40% of PM_{2.5} in Beijing (Han et al. 2016). However, the rinse and weigh method may underestimate the mass of particles on leaves. Therefore, water solutions ions need to be quantified in order to accurately assess the effectiveness of plant species in capturing PM. Analyzing water-soluble ions in deposited PM on leaf surface allows to identify pollution source of PM. The aim of this study was to investigate the effectiveness of 17 plant species in accumulating PM during the growth season in Beijing for the year 2014. Two key features of this study were investigation of: 1) particles deposited onto the leaf surface and into the wax as a function of three particles size fractions; and (2) the accumulation of water-soluble ions by the leaf surface.

Material and methods

Study Area

All of the plant materials were collected from the campus of Beijing Forestry University (BFU) (40°0'29.64"N, 116°20'46.04"E), Beijing City, China. The BFU campus is located in Haidian

District outside the Fourth Ring Road, which is the transition from urban to suburban areas. There are no polluting industries or power plants within 5 km space range. All plant species were located within 600 m each other, in the center of the BFU campus and 50 m away from surrounding streets. It is a reasonable assumption that all species were exposed to the same background PM concentrations. The average background PM₁₀ and PM_{2.5} concentrations were 139 and 84 $\mu\text{g m}^{-3}$ from April to September 2014, respectively, in Olympic Sport Center which was the nearest air quality monitoring station (about 4.4 km apart) set by the Ministry of Environmental Protection of China (<http://113.108.142.147:20035/emcpublish/>).

Plant material and sample collection

Vegetation samples were collected from 17 plant species (listed in Table 1). All are common plants in northern China and widely used in urban areas. For each species three similar individuals were used as replicates. Leaves were collected on 16 April, 20 May, 30 June, 27 July, 11 September and 14 October 2014. Criteria for the weather on a sampling day were sunny, wind speed less than 5 m s^{-1} , and 9-10 days since precipitation amount of the last rain event >5 mm. Leaves were assumed to be washed clean by rainfall, so the average mass of daily deposited PM was measured for the same exposure days. The study of Liu et al. (2013) investigated the dust-retaining capacity of the four urban species in Guangzhou, and their results showed that the amounts of PM deposited on leaf surface may approach saturation around 24 days. In the present study, the average mass of daily deposited PM was measured for the same exposure days without

saturation, and leaves were assumed to be fully washed by rainfall. Intact leaves were in good growth conditions, namely, with little or no disease and/or pests. They were sampled from four directions in the canopy with the same height for each species. Between 200 and 300 cm² of leaf area (about 5 - 30 leaves) were cut off with scissors and stored in plastic bags. Great care was taken to ensure that particles did not dislodge from the leaves. The samples were then transported to the laboratory and stored at 4°C freezer prior to analysis. Although the detailed collection method of leaves samples has described in our previous studies (Chen et al. 2016b; Mo et al. 2015), it is repeated here for the reader's convenience.

Quantitative analysis

PM was washed and quantified from the leaf surfaces and in leaf waxes using the methods described by Dzierzanowski et al. (2011). The methods for rinsing water-soluble ions from the leaves were as described by Freer-Smith et al. (2005). Leaves were first washed with 250 mL of deionized water. The rinse water was passed through a 100 µm metal sieve to remove particles >100 µm and then filtered sequentially through 10 µm, 2.5 µm and 0.2 µm filters (EMD Millipore Corp., Billerica, Massachusetts, USA) to separate the PM into the following three particles size fractions: fine (0.2–2.5 µm), coarse (2.5–10 µm), and large (> 10 µm). The aqueous sample after filtering was stored in the freezer (–18°C) prior to determination of the water-soluble ions (see below). Before filtering, a deionizer gate (AP-BC2451, AP&T, Shanghai, China) was be use to avoid an electrostatic charge on the filters. Before and after analysis, filters were dried in

an oven for 30 minutes at 50°C and stabilized in an 80 cm × 80 cm × 80 cm polytetrafluoroethylene (PTFE) balance box at 25°C and 40% relative humidity for 24 hours, which was controlled by a balance and a humidity controller (WHD48-11, ACREL Co., Ltd., Jiangsu, China). Filters were weighed using a BT125D balance (Sartorius, precision: 10 µg). PM accumulated in waxes was also measured similarly except that the deionized water was replaced with chloroform in order to dissolve the wax on the leaves. Also since nitrocellulose filters are damaged by chloroform, PTFE filters were used in the filtering for in-wax PM.

Each washed broad-leaved sample was scanned using a scanner (HP Scanjet 4850, China Hewlett-Packard Co., Ltd., Beijing, China), then the area was measured by Image J (1.50i, National Institutes of Health, Bethesda, US). For needle leaves, leaf area was measured by measuring the water displacement leaf volume and converting to leaf area using the following equation:

$$S = 2L(1 + \frac{\pi}{n})\sqrt{\frac{nV}{\pi L}}$$

where S represents leaf area; L is the average length of the leaves; V is the needle volume, and n is the number of needle leaves.

To analyze the concentrations of water-soluble inorganic ions, the volumes of post-filtering aqueous extracts were measured (V_{water}) and stored at -18 °C until analysis within four weeks. Three anions (Cl^- , SO_4^{2-} , NO_3^-) and five cations (NH_4^+ , Ca^{2+} , Na^+ , Mg^{2+} , K^+), were determined using a Dionex model ICS-120 ion chromatograph equipped with a conductivity detector (ASRS-ULTRA) following the method of Lun et al. (2003) and Tang et al. (2016). The mass of these ions obtained in each filtrate was calculated by multiplying V_{water} by the ion concentration, and was expressed in per unit area per leaf.

Statistical analysis

One-way analysis of variance (ANOVA) was used to test for significant differences in PM accumulation between species. Post-Hoc analysis (Duncan's test) was performed when multiple comparisons among species were necessary. Spearman's correlation analysis was used to assess the linear correlations between surface PM, in-wax PM and water-soluble ions. All statistical analyses were carried out using SPSS 17.0 (SPSS 17.0 for Windows, SPSS Inc., IL, USA).

Results and discussion

PM accumulation on leaves

Fig. 1 shows the mass of accumulated surface and in-wax PM on the 17 plant species. The PM accumulation on leaves varied significantly between plant species. Several studies have also identified that different height of trees may affect the capacity for accumulating PM

183 (Dzierżanowski et al. 2011; Sæbø et al. 2012; Mo et al. 2015). In this study, we divided the
184 species into shrubs and trees (Table 1). The average PM accumulation for four shrubs was $49 \mu\text{g cm}^{-2}$.
185 *E. japonicus* showed the highest PM accumulation ($56 \mu\text{g cm}^{-2}$) of the four shrubs.
186 Although the difference was not significant. Xie et al. (2014) and Wang et al. (2006) reported that
187 *E. japonicas* captured larger amounts of PM than other shrubs such as *Buxus sinica*, *Syringa*
188 *oblata* and *Lagerstroemia indica*. The leaf surface structure of *E. japonicus* is unique to those
189 shrubs. Tomentose pubescence distributes on the abaxial leaf surface, which can efficiently
190 capture and accumulate PM (Mo et al. 2015).

191 PM accumulation on *P. orientalis* and *P. armandi* were significantly higher than for other
192 trees. Accumulations on *F. pennsylvanica*, *P. tomentosa*, *A. altissima* and *S. japonica* were
193 significantly lower than for other trees (Fig. 1). The average PM accumulation on *P. orientalis*
194 and *P. armandi* ($156 \mu\text{g cm}^{-2}$) was 4.5 times greater than the average accumulation on the latter
195 four species ($28.4 \mu\text{g cm}^{-2}$). The PM accumulation on *R. typhina* ($76 \mu\text{g cm}^{-2}$) was second only to
196 *P. orientalis* and *P. armandi*. Trees can be divided into conifer or broad-leaved species. *P.*
197 *tabulaeformis*, *P. orientalis* and *P. armandi* are three common evergreen conifer species, which
198 accumulated more PM on leaves than other species except *R. typhina*. The PM accumulation
199 difference between the adaxial and abaxial broad-leaved surfaces is due to wind turbulence.
200 Wang et al (2006) investigated 11 broad-leaved species such as *P. tomentosa*, *S. Japonica* and

201 *Ailanthus altissima* using a scanning electron microscope (SEM) in Beijing urban area. They
202 found that on average only 17% of PM accumulated on the abaxial surface. However, the needles
203 of conifer species can accumulate PM over the entire leaf surface (Ottel et al. 2010). The leaves
204 of conifer species also have unique microstructure, such as mucus oils, a thicker epicuticular wax
205 layer and a grooved ridge protuberance, which can help leaves to accumulate large particles
206 (Sabin et al. 2006). Previous studies showed that the leaves of *Platycladus* were more rough than
207 *Pinus* (Wang et al. 2007). This structure retained more particles on leaves of *P. orientalis*. The
208 average PM accumulation of broad-leaved trees was less than broad-leaved shrubs. The meta-
209 analysis results showed that PM leaf deposition on shrubs was significantly higher than that of
210 trees (Cai et al. 2017).

211 Across all species, PM was found both on leaf surface and in waxes. Fig. 1 shows that particles
212 distribution between surface and waxes is similar for all shrub species, with PM mass in waxes
213 about 4 times lower than on surface. The average surface and in-wax PM deposition on the shrub
214 leaves were 39 and 10 $\mu\text{g cm}^{-2}$. This corresponds to 21% of PM deposition in waxes, on average.
215 There were significant differences between tree species in the accumulation of PM on leaf
216 surfaces and in waxes. The lowest and highest surface PM deposition were found in *P. tomentosa*
217 (12.5 $\mu\text{g cm}^{-2}$) and *P. armandi* (56.9 $\mu\text{g cm}^{-2}$). The in-wax PM accumulation of *P. orientalis*
218 (101.9 $\mu\text{g cm}^{-2}$) and *P. armandi* (96.6 $\mu\text{g cm}^{-2}$) was significantly higher than other tree species. A

219 positive relationship between different PM fractions accumulation and the quantity of leaf waxes
220 was detected (Sæbø et al. 2012). Popek et al (2013) analyzed all tested species and also detected a
221 positive correlation between the amount of waxes and coarse PM. But the model had a low
222 partial fit ($r=0.54$). By analyzing for each species separately, a significant correlation was found
223 in leaves of *Tilia cordata* (Dzieranowski et al. 2011) and *Corylus colurna* (Popek et al. 2013). In
224 some cases, only weak, no relationship or negative correlation between mass of in-wax PM and
225 mass of wax were reported across some plant species (Jouraeva et al. 2002; Dzieranowski et al.
226 2011). The relationship showed different results among species. Song (2015) found that the
227 waxes in conifer species was a factor of about 2.5 times higher than broadleaves. *P. orientalis*
228 and *P. armandi*, of which the waxes can accumulate large fraction of the PM. The composition
229 and structure of the waxes may significantly affect the capacity of leaves in accumulating PM
230 (Kaupp et al. 2000; Jouraeva et al. 200; Bukhardt et al. 2010). On the other hand, *P.*
231 *tabulaeformis*, *P. orientalis* and *P. armandi* which accumulated greater in-wax PM than other
232 plant species are evergreen conifer species. The leaf growth cycle of these evergreen conifer
233 species of more than 12 months is considerably longer than for deciduous species. Song et al
234 (2015) investigated the mass of PM deposited on five evergreen species in Beijing. The PM
235 accumulated on the leaf surface were range from 72.31 to 231.84 $\mu\text{g cm}^{-2}$. Cai et al. (2017)
236 reviewed 150 studies and used a meta-analysis and also found that the weekly PM leaf deposition

237 of conifer species was significantly higher than broad leaves, by approximately 31.9%. These
238 results showed that evergreen conifer species had better performance in accumulating PM both
239 on the leaf surface and in the surface wax, which was accounted for by the structural
240 characteristics and habits of conifer species.

241 In our study we found significant positive correlation between in-wax PM accumulation and
242 surface PM accumulation ($R^2 = 0.43$, $p = 0.002$). Based on collection and analysis of existing raw
243 data of 56 plant species in 3 different urban areas (Popek et al. 2013; A. Przybysz et al. 2014; Mo
244 et al. 2015; and Song et al. 2015), a positive correlation relationship between total amount of
245 surface PM and in-wax PM accumulated on foliage was also detected ($R^2=0.64$, $P<0.0001$, In-
246 wax PM= $0.24 \times$ Surface PM+2.35). The leaf surface PM deposition amounts was 3.57 times
247 higher than that of in-wax. Actually, PM in the wax layer can account for a significant amount, about
248 22% in the present study. The epicuticular wax layer and releasing PM were dissolved by
249 chloroform, which has environmental health concern. In the previous studies, PM accumulated on
250 leaf surface was assessed (Freer-Smith et al. 2005; Chen et al. 2015). Lack of the examination of
251 PM encapsulated in the wax layer may lead to an underestimation of the present results. However,
252 a significant correlation was found between surface and in-wax PM, which can improve our
253 knowledge on this issue. Because leaves with greater amounts of surface PM may also

accumulate high mass of PM in wax layer, and these species should be attractive options for urban greening.

The average mass of surface PM accumulation in trees ($34 \mu\text{g cm}^{-2}$) was lower than that in shrubs ($39 \mu\text{g cm}^{-2}$). But trees have the higher average of in-wax PM accumulation ($28 \mu\text{g cm}^{-2}$) relative to shrubs ($10 \mu\text{g cm}^{-2}$) but not statistical significant. Contributions of in-wax depositions to leaf total (surface plus in-wax) depositions were $> 50\%$ for *P. tomentosa* (54%), *P. orientalis* (65%) and *P. armandi* (63%). In the remaining 10 tree species, the contributions of in-wax to total insoluble PM were on average 32%. In Norway and Poland, *Fagus silvatica* and *Stephanandra incisa* also accumulated about 25% and 28% of PM in the waxes and on the surface, respectively. *Betula pendula* accumulated 82.6% of PM in the wax fraction (Sæbø et al. 2012), which is significantly higher than the value of coniferous species obtained in this study. Popek et al. (2013) reported that more PM was deposited on the leaf surface. In their study, the waxes in 5 of 39 woody species accumulated greater than 50% of insoluble PM (range 53%-63%), consistent with our findings.

This study (Fig. 6 and 7) showed that PM leaf accumulation varied greatly among months, which was different between leaf surface and waxes. Leaf surface PM retention amounts in trees and shrubs were significantly higher in April and May, respectively, compared with those in other months. The lowest amounts were measured in September. Masses of PM accumulated on

272 surfaces of trees and shrubs showed inconsistent relations among different months. Atmospheric
273 PM concentration, meteorological condition and leaf characteristics varied among months, which
274 may influence PM leaf deposition. Basis on analysis of our dataset, monthly ambient average
275 concentrations of PM₁₀ and PM_{2.5} did not correlate with deposited amounts of total surface
276 particle. However, with increasing atmospheric PM concentrations, particles accumulated on leaf
277 surface raised slightly. By quantitatively analyzing in four districts of the city in Italy, leaf
278 surface PM deposition didn't correlate with local atmospheric PM₁₀ concentration (G. Sgrigna et
279 al. 2015). On the other hand, a meta-analysis result showed that PM accumulation is generally
280 highest in winter compared to other seasons and thought this variable is affected by atmospheric
281 PM concentration (Cai et al. 2017). In this study, monthly data was converted to seasons and
282 showed highest total PM deposited was in spring for trees and shrubs. Leaf PM depositions were
283 all most equally between summer and autumn. But background PM concentrations in summer
284 were lower than spring and autumn. On the other hand, monthly change of PM accumulation in
285 waxes is increased firstly and then decreased during growing season, which in trees and shrubs
286 were highest in July and September, respectively. Vegetable characteristics and ambient PM
287 concentrations show the interaction in leaf PM deposition. In winter, most studies focused on
288 evergreen species such as coniferous plants, which show high capacity to capture particles. So,
289 the conclusion that PM leaf deposition is highest in winter is one-sided. Across all growing

months, trees show higher PM accumulation in wax than shrubs. The PM accumulation on leaves varied significantly among months. Leaves only once at the begin or the middle of the seasons to assess the capacity of PM capturing may underestimate or overestimate it.

Overall, results suggested that leaf surface accumulated more PM than waxes. Although for most species there was lower mass of PM deposited in epicuticular waxes. However, PM accumulation in the wax fraction is very important because these particles are trapped permanently (Song et al. 2015).

Different Size-fraction Particles

Different size fractions of airborne PM have different chemical composition and posed adverse effects on human health (Luo et al. 2011; Li et al. 2017). For example, particulate matters were responsible for respiratory, cardiovascular and others (Cai et al. 2017), especially fine particles (Englert et al. 2004). To assess the capacity of plant leaves to capture different size fractions, the present study separated quantification of PM into: fine (0.2–2.5 μm), coarse (2.5–10 μm), and large ($> 10 \mu\text{m}$). The masses in each of these size fractions accumulated on leaf surface and in waxes are presented in Fig. 2 and 3, respectively.

PM of different size fractions accumulated on leaf surface and in waxes differed among the species. Non-significant differences were observed among the different size-fraction surface PM accumulations on shrubs (Fig. 2). The averages of the three size fractions for surface PM

308 accumulations on shrubs were $31.5 \mu\text{g cm}^{-2}$ (81%), $4.7 \mu\text{g cm}^{-2}$ (12%) and $2.5 \mu\text{g cm}^{-2}$ (7%) for
309 large, coarse and fine PM, respectively.

310 Across all trees, *P. orientalis* ($44.4 \mu\text{g cm}^{-2}$) and *P. armandi* ($43.7 \mu\text{g cm}^{-2}$) showed the greatest
311 large particles fraction accumulation on the leaf surface. Large particles fraction accumulation on
312 *P. tomentosa* ($9.8 \mu\text{g cm}^{-2}$), *A. altissima* ($15.4 \mu\text{g cm}^{-2}$) and *S. japonica* ($12.7 \mu\text{g cm}^{-2}$) leaves
313 were significantly lower than the greatest accumulators. The average surface accumulation of
314 large particles fraction was $25.0 \mu\text{g cm}^{-2}$, which accounted for 75% of the total insoluble PM.

315 The average coarse fraction PM accumulated on leaf surfaces ($5.1 \mu\text{g cm}^{-2}$) comprised 15% of
316 the total insoluble PM. The greatest accumulation of coarse PM was found on *P. armandi* leaves
317 ($8.9 \mu\text{g cm}^{-2}$), which was weakly significant difference from accumulation by other trees. The
318 species with the lowest surface accumulation of the coarse fraction was on *P. tomentosa* ($1.8 \mu\text{g}$
319 cm^{-2}).

320 The greatest accumulation of fine fraction PM on the leaf surface was on *R. typhina* ($9.30 \mu\text{g}$
321 cm^{-2}), which was significantly greater than for other trees. *P. occidentalis* ($2.0 \mu\text{g cm}^{-2}$), *F.*
322 *pennsylvanica* ($1.2 \mu\text{g cm}^{-2}$), *P. tomentosa* ($1.0 \mu\text{g cm}^{-2}$), *G. biloba* ($2.1 \mu\text{g cm}^{-2}$) and *S. japonica*
323 ($1.6 \mu\text{g cm}^{-2}$) had considerably lower accumulation of fine fraction PM. The average fine PM
324 fraction surface accumulation was $3.5 \mu\text{g cm}^{-2}$, or 10% of the total insoluble PM deposition.

325 These present results showed that shrubs accumulated more mass of large size fraction PM on
326 leaf surface than most of the trees, except that *P. orientalis* and *P. amandi* which showed slightly
327 higher accumulation than that of shrubs. However, trees were more efficient than shrubs in
328 accumulating coarse and fine PM on the leaf surface.

329 There were no significant differences between the three particles size fraction accumulations in
330 the wax of shrub leaves. On average, the PM accumulation in wax on the shrub leaves was $6.8 \mu\text{g cm}^{-2}$
331 cm^{-2} (65%) for the large particles size fraction, $2.3 \mu\text{g cm}^{-2}$ (21%) for the coarse size fraction and
332 $1.5 \mu\text{g cm}^{-2}$ (14%) for the fine particles size fractions. For the trees, *P. orientalis* ($84.1 \mu\text{g cm}^{-2}$)
333 and *P. armandi* ($85.3 \mu\text{g cm}^{-2}$) showed significantly greater accumulation of the large particles
334 size fraction in wax. The average accumulation of the large particles size fraction in wax on trees
335 was $22.0 \mu\text{g cm}^{-2}$, which was 77% of the total accumulated PM. The highest coarse particles
336 accumulation in wax was for *P. orientalis* ($10.9 \mu\text{g cm}^{-2}$). The coarse particles in-wax deposition
337 on *P. armandi* ($6.5 \mu\text{g cm}^{-2}$) and *S. matsudana* ($6.6 \mu\text{g cm}^{-2}$) were marginally higher than for the
338 remaining trees. *F. pennsylvanica* ($1.1 \mu\text{g cm}^{-2}$) and *A. altissima* ($0.9 \mu\text{g cm}^{-2}$) had low deposition
339 of fine particles in waxes. The average coarse and fine particles size fraction accumulations in
340 wax were $3.8 \mu\text{g cm}^{-2}$ and $2.5 \mu\text{g cm}^{-2}$, which corresponded to 13% and 9% of the total in-wax
341 particles deposition. Particle size fraction is very similar for surface and in wax PM accumulated
342 by trees, but differs for shrubs showing amount of large PM on surface about 5 more than in wax,

343 which led to less fine and coarse PM fractions on surface. Dzierzanowski et al (2011) detected
344 a small shrub accumulated the largest amounts of PM as compared to trees, and more large PM
345 also deposited on surface than wax. As we explained above, shrubs growing low to the ground
346 were presumably more exposed to soil splash and traffic dust on the leaves than trees with an
347 upright growth habit, which were mostly large particles. However, these large PM deposited on
348 surface cannot be fixed by epicuticular wax in shrubs, which was significantly different with
349 trees.

350 Overall, PM depositions by mass for the three size fraction was in the order: large > coarse >
351 fine. The average proportions of large, coarse and fine PM were 73%, 16% and 11%. Previous
352 studies reported slightly different proportions of these three size fractions (Popek et al. 2013;
353 Song et al. 2015; Zhang et al. 2014), which may be due to the local ambient PM composition.
354 The proportions of the three size fractions were slightly different between species. This might be
355 explained by the leaf and structural characteristics of species (Song et al. 2015). However, as we
356 introduced that the average background PM₁₀ and PM_{2.5} concentrations in this area were 139 and
357 84 $\mu\text{g m}^{-3}$, respectively. The concentration of fine PM was higher than that of coarse particles,
358 which was different with fine and coarse PM deposited in leaf surface and waxes. Freer-smith et
359 al. (2005) found that sedimentation under gravity principally leads to large PM deposited on leaf
360 surfaces. Impaction and interception affects the deposition of coarse and fine PM on leaf surfaces.

Therefore, particles sedimentation is the main process by which PM deposits to foliage. The mass of fine PM deposited by impaction and interception was $5.5 \mu\text{g cm}^{-2}$ on average, which contributed only 11% of the total. However, the number of fine particles on leaves was large. Previous studies proposed that the number of particles in the fine fraction contributed over 90% of total insoluble PM (Li et al. 2015; Zhao et al. 2014). Therefore, plant also showed high efficiently accumulation of fine PM in urban areas. The amount of coarse and fine PM contributed 18% and 12% of total in-wax PM respectively. This ratio was higher than for deposition to leaf surfaces. Shrub leaf surfaces accumulated greater mass of the three size fractions PM than most of trees. Shrub and tree leaves grow at different heights, which may have an effect on PM accumulations on leaf surface because there is more dust near the ground (Dzierżanowski et al. 2011; A. Sæbø et al. 2012; Mo et al. 2015). The significant correlation between the mass of PM size fraction was detected (R^2 for large, coarse and fine PM are 0.99 ($p < 0.0001$), 0.78 ($p < 0.0001$) and 0.52 ($p = 0.001$), respectively). So, species that accumulated more total particles also have the high capability to capture greater amounts of fine particles, which is the most dangerous for human health. The most efficient species of fine PM accumulation should be used for urban greening, such as *R. typhina*, *P. orientalis*, *P. armandi*, and *M. denudate*. Tree-dimensional configuration of the most efficient shrub and tree species can reduce PM pollution

on different spatial scales. We also suggest that conifer species should be priority in urban greening, which show high capability in capturing PM during winter.

Water-soluble ions on leaf surfaces

The foliage analyzed for water-soluble ions was that sampled on July 27, 2014. Fig. 4 shows the results for ions and total insoluble suspended particulate (TSP). The ratio in Fig. 4 represents the percentage of water-soluble ions and the total of soluble and insoluble PM. Across all species, the mass of ions on leaf surfaces ranged from $3.7 \mu\text{g cm}^{-2}$ (in *M. denudata*) to $31.6 \mu\text{g cm}^{-2}$ (in *P. armandi*). There were significant differences between plant species, *U. pumila*, *S. matsudana*, *P. orientalis* and *P. armandi* accumulating more ions on leaf surfaces ($p < 0.05$). For other species, accumulations for all ions were low to $10 \mu\text{g cm}^{-2}$. The mean value for ions deposition was $12.9 \mu\text{g cm}^{-2}$. Significant positive correlations were observed between the amounts of ions and TSP across species ($R^2=0.48$, $p=0.001$). The highest and lowest percentages of water-soluble ions to total PM on leaves were 50% and 7% respectively, with an average of 28%. The proportions of water-soluble ions in total PM varied greatly among different plant species, especially for trees. Variations of proportion between species were also detected in the study of Freer-Smith et al. (2005). The data show that the contributions of ions to total PM was in the order $\text{NO}_3^- > \text{Ca}^{2+} > \text{SO}_4^{2-} > \text{Mg}^{2+} > \text{Cl}^- > \text{Na}^+ > \text{K}^+ > \text{NH}_4^+$. The proportion of NH_4^+ in the ions was lowest across all species, which is surprising considering the ambient levels of NH_4^+ in Beijing. However, the findings are consistent with Freer-Smith et al. (2005) who also showed that NO_3^- was the main

ion component and that the proportion of NH_4^+ was low. Cheng et al. (2016) reported average concentrations of SO_4^{2-} , Cl^- and NO_3^- on plant leaves of $0.9098 \mu\text{g cm}^{-2}$, $0.7298 \mu\text{g cm}^{-2}$ and $0.0878 \mu\text{g cm}^{-2}$, respectively, which are slightly different from this study. The difference may be accounted for by the composition of inorganic compounds in the air. Shen et al. (2011) showed ions comprised 33% PM_{10} at the Dongbeiwang experiment site, near to this study site, which was relatively high compared with this study. The contribution of NH_4^+ to ions was 16%. Liu et al. (2015) used ^{15}N tracer techniques to show that water-soluble ions (NH_4^+ and NO_3^-) in $\text{PM}_{2.5}$ can be absorbed effectively by *P. euramericana* seedlings. Given that plant leaves absorb ultrafine PM through their stomata (Bell and Treshow 2002), we postulate that NH_4^+ is translocated into stomata which leads to the low contribution of NH_4^+ to ions on the leaf surface. The concentration of NO_3^- was in the range of previous studies. In summary this study has shown that water-soluble ions on leaf surfaces are also an important component of total PM deposited onto plant leaves. As many past studies did not analyze the soluble PM components this means that the interception capacity of plant species for PM has previously been undervalued. According to studies on water soluble ions in atmosphere particles, without considering the mass of soluble ions was slightly undervalued the effects of plants on PM deposition and may be a deviation in the estimation of the PM accumulated by the whole trees (Song et al. 2015). In this study, the percentages of water-soluble ions to total PM on coniferous leaves ranged from 24% to 29%.

Based on analysis of their data (Song et al. 2015), undervalued mass of water ions on conifer species was about $38.59 \mu\text{g cm}^{-2}$ on average. This may have more serious impact on the whole plant assessment. The elemental composition of the ions helps the identification the source of the particles, which provides further important new information. In previous studies, the water-soluble ions in PM in Beijing were classified into 4 sources (Sun et al. 2004; Wang et al. 2005): NO_3^- , SO_4^{2-} and NH_4^+ were assigned to type 1, which comes from secondary inorganic aerosol; Ca^{2+} and Mg^{2+} were to type 2, which comes from road and construction dusts; Na^+ and Cl^- is assigned to type 3, which mainly come from waste incineration; and K^+ is assigned to type 4, which mainly comes from biomass combustion. Figure 5 shows the average concentrations of ions in each type. The greatest contribution to was from type 1 secondary aerosol; NO_2 and SO_2 from coal combustion and vehicle exhausts are converted to NO_3^- and SO_4^{2-} by gas-to-particles reactions, which are mainly of anthropogenic origin. The contribution of Ca^{2+} and Mg^{2+} to total PM were the next greatest and was significantly higher than contribution from type 3 and 4. Type 3 and 4 were low in our study site, which indicated the burning of waste and biomass. The important feature of the data reported is that traffic was the main source of pollution for the background air at this study site.

Conclusion

Seventeen urban plant species showed significantly different capacity in accumulating PM. The average accumulation of PM on leaves was $58.9 \mu\text{g cm}^{-2}$, of which 65% was deposited on the leaf surface and 35% in the leaf wax. The greatest PM accumulations on leaves occurred in *P. orientalis* and *P. armandi*, both of which are evergreen conifer species. *F. pennsylvanica*, *P. tomentosa*, *A. altissima* and *S. japonica* was less effective for PM deposition. *P. tomentosa*, *P. orientalis* and *P. armandi* were the only three of seventeen species, which accumulated greater than 50% of total insoluble PM in waxes. PM larger than $10 \mu\text{m}$ comprised 73% of PM deposited on leaves, with the coarse and fine particles size fractions comprising 16% and 11% of the deposited PM, respectively. Water-soluble ions comprised 28% of total PM on leaves on average. Lack of knowledge about ions captured by leaves obviously leads to underestimation of the ability of plant species to intercept PM. This study has shown that trees and shrubs should be considered as an effective approach to remove aerial PM in urban areas.

Acknowledgments

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References

455

456 Beckett KP, Freer-Smith PH, Taylor G (2000) Particulate pollution capture by urban trees: effect
 457 of species and windspeed. *Glob. Change Biol* 6: 995-1003

458 Bell JNB, Treshow M (2002) *Air Pollution and Plant Life*. second ed. John Wiley, Chichester

459 Bosco ML, Varrica D, Dongarrà G (2005) Case study: Inorganic pollutants associated with
 460 particulate matter from an area near a petrochemical plant. *Environ. Res* 99: 18-30

461 Cai MF, Xin ZB, Yu XX (2017) Spatio-temporal variations in PM leaf deposition: A meta-
 462 analysis. *Environ. Pollut* 231: 207-218

463 Chen B, Li SN, Yang XB, Lu SW, Wang B, Niu X (2016a) Characteristics of atmospheric PM_{2.5}
 464 in stands and non-forest cover sites across urban-rural areas in Beijing, China. *Urban*
 465 *Ecosystems* 19: 867-883

466 Chen L, Liu C, Zou R, Yang M, Zhang Z (2016b) Experimental examination of effectiveness of
 467 vegetation as bio-filter of particulate matters in the urban environment. *Environ. Pollut* 208:
 468 198-208

469 Chen L, Liu CL, Pan T, Chen CC, Li Z, Wang HH, Pei X, Sun L (2014) Assessment of the effect
 470 of PM_{2.5} reduction by plain afforestation project in Beijing based on dry deposition model.
 471 *Chin. J. Appl. Ecol* 33: 2897-2904

472 Chen W, Tang H, Zhao H (2015) Diurnal, weekly and monthly spatial variations of air pollutants
 473 and air quality of Beijing. *Atmos. Environ* 119: 21-34

474 Cheng Y, Wang Y, Wang Y, Zhang H, Liang D (2016) Particulate matter adsorption and the main
 475 influencing factors of five typical plants in Beijing. *Environ. Chem* 35: 1690-1697

476 Dzierzanowski K, Popek R, Gawronska H, Saebo A, Gawronski SW (2011) Deposition of
 477 particulate matter of different size fractions on leaf surfaces and in waxes of urban forest
 478 species. *Int. J. Phytoremediat* 13: 1037-1046

479 Enqlert N (2004) Fine particles and human health--a review of epidemiological studies. *Toxicol.*
 480 *Lett* 149: 235-242

481 Freer-Smith PH, Beckett KP, Taylor G (2005) Deposition velocities to *Sorbus aria*, *Acer*
 482 *campestre*, *Populus deltoides* × *trichocarpa* ‘Beaupré’, *Pinus nigra* and × *Cupressocyparis*
 483 *leylandii* for coarse, fine and ultra-fine particles in the urban environment. *Environ. Pollut* 133:
 484 157-167

485 Gao G, Xu YS, Mo L, Yu XX (2016) The Ability of Plant Leaves on Depositing Size-fractionated
 486 Particles. *Ecol. Environ. Sci* 25: 260-265

487 Han X, Guo QJ, Liu CQ, Strauss H, Yang JX, Hu J, Wei RF, Tian LY, Kong J (2016) Effect of
 488 the pollution control measures on PM_{2.5} during the 2015 China Victory Day Parade:
 489 Implication from water-soluble ions and sulfur isotope. *Environ. Pollut* 218: 230-241

490 Janhäll S (2015) Review on urban vegetation and particle air pollution – Deposition and
 491 dispersion. *Atmos. Environ* 105: 130-137

492 Jun L, Han YQ, Tang X, Zhu J, Zhu T (2016) Estimating adult mortality attributable to PM2.5
 493 exposure in China with assimilated PM2.5 concentrations based on a ground monitoring
 494 network. *Sci. Total Environ* 568: 1253-1262

495 Jouraeva VA, Johnson DL, Hassett JP, Nowak DJ (2002) Differences in accumulation of PAHs
 496 and metals on the leaves of *Tilia×euchlora* and *Pyrus calleryana*. *Environ. Pollut* 120: 331-338

497 Lelieveld J, Evans JS, Fnais M, Giannadaki D, Pozzer A (2015) The contribution of outdoor air
 498 pollution sources to premature mortality on a global scale. *Nature* 525: 367-371

499 Leonard R J, Mcarthur C, Hochuli D F (2016) Particulate matter deposition on roadside plants
 500 and the importance of leaf trait combinations. *Urban For. Urban Gree* 20: 249-253

501 Li D, Xu YX, Wang BT (2015) The Deposition of Particulate Matters on Climbing Plant. *Ecol.*
 502 *Environ. Sci* 24: 1486-1492

503 Li HX, Ji HB, Shi CJ, Yang G, Yan Z, Xu XY, Ding HJ, Tang L, Xing YX (2017) Distribution of
 504 heavy metals and metalloids in bulk and particle size fractions of soils from coal-mine
 505 brownfield and implications on human health. *Chemosphere* 172: 505-515

506 Liu J, Han Y, Tang X, Zhu J, Zhu T (2016) Estimating adult mortality attributable to PM2.5
 507 exposure in China with assimilated PM2.5 concentrations based on a ground monitoring
 508 network. *Sci. Total Environ* 568: 1253-1262

509 Liu Q, Shi J, An HL, Cao XH, Liu C, Ying WL, Xia XL, Guo HH (2015) Absorption and

510 Distribution of PM_{2.5} NH₄⁺ and NO₃⁻ in *Populus euramericana* Neva.. Acta Ecol. Sin 35: 6541-
 511 6548
 512 Lun X, Zhang X, Mu Y, Nang A, Jiang G (2003) Size fractionated speciation of sulfate and nitrate
 513 in airborne particulates in Beijing. China. Atmos. Environ 37: 2581-2588
 514 Luo XS, Yu S, Li XD (2011) Distribution, availability, and sources of trace metals in different
 515 particle size fractions of urban soils in Hong Kong: Implications for assessing the risk to
 516 human health. Environ. Pollut 159: 1317-1326
 517 Mo L, Ma ZY, Xu YS, Sun FB, Lun XX, Liu XH, Chen J, Yu XX (2015) Assessing the Capacity
 518 of Plant Species to Accumulate Particulate Matter in Beijing, China. Plos One 10: e0140664
 519 Nowak DJ, Hirabayashi S, Bodine A, Hoehn R (2013) Modeled PM_{2.5} removal by trees in ten
 520 U.S. cities and associated health effects. Environ. Pollut 178: 395-402
 521 Ottelé M, van Bohemen HD, Fraaij ALA (2010) Quantifying the deposition of particulate matter
 522 on climber vegetation on living walls. Ecol. Eng 36: 154-162
 523 Pope III CA, Dockery DW (2006) Health effects of fine particulate air pollution: lines that
 524 connect. J. Air Waste Manage 56: 709-742
 525 Popek R, Gawronska H, Wrochna M, Gawronski SW, Sæbø A (2013) Particulate matter on
 526 foliage of 13 woody species: deposition on surfaces and phytostabilisation in waxes--a 3-year
 527 study. Int. J. Phytoremediat 15: 245-256

528 Przybysz A, Sæbø A, Hanslin HM, Gawronski SW (2014) Accumulation of particulate matter and
 529 trace elements on vegetation as affected by pollution level, rainfall and the passage of time.
 530 Sci. Total Environ 481: 360-369

531 Sabin LD, Hee Lim J, Teresa Venezia M, Winer AM, Schiff KC, Stolzenbach KD (2006) Dry
 532 deposition and resuspension of particle-associated metals near a freeway in Los Angeles.
 533 Atmos. Environ 40: 7528–7538

534 Sæbø A, Popek R, Nawrot B, Hanslin HM, Gawronska H, Gawronski SW (2012) Plant species
 535 differences in particulate matter accumulation on leaf surfaces. Sci. Total Environ 427–428:
 536 347-354

537 Salmond JA, Tadaki M, Vardoulakis S, Arbuthnott K, Coutts A, Demuzere M, Dirks KN,
 538 Heaviside C, Lim S, Macintyre H, McInnes RN, Wheeler BW (2016) Health and climate
 539 related ecosystem services provided by street trees in the urban environment. Environ. Health
 540 15: S36

541 Schaubroeck T, Deckmyn G, Neiryneck J, Staelens J, Adriaenssens S, Dewulf J, Muys B, Verheyen
 542 K (2014) Multilayered modeling of particulate matter removal by a growing forest over time,
 543 from plant surface deposition to washoff via rainfall. Environ. Sci. Technol 48: 10785-10794

544 Sgrigna G, Sæbø A, Gawronski S, Popek R, Calfapietra C (2015) Particulate Matter deposition on
 545 Quercus ilex leaves in an industrial city of central Italy. Environ. Pollut 197: 187-194

546 Shen J, Tang A, Liu X, Kopsch J, Fangmeier A, Goulding K, Zhang F (2011) Impacts of Pollution
 547 Controls on Air Quality in Beijing during the 2008 Olympic Games. *J. Environ. Qual* 40: 37-45
 548 Song YS (2015) The study on fine particulate air pollution characteristics and the dust detention
 549 effect of greening trees in Beijing. Dissertation, Research Center for Eco-Environmental
 550 Sciences, Chinese Academy of Sciences.
 551 Song YS, Maher B, Li F, Wang X, Sun X, Zhang H (2015) Particulate matter deposited on leaf of
 552 five evergreen species in Beijing, China: Source identification and size distribution. *Atmos.*
 553 *Environ* 105: 53-60
 554 Song YS, Wang XK, Maher B, Li F, Xu C, Liu X, Sun X, Zhang Z (2016) The spatial-temporal
 555 characteristics and health impacts of ambient fine particulate matter in China. *J. Clean. Prod*
 556 112: 1312-1318
 557 Sun Y, Zhuang G, Wang Y, Han L, Guo J, Dan M, Zhang W, Wang Z, Hao Z (2004) The air-borne
 558 particulate pollution in Beijing—concentration, composition, distribution and sources. *Atmos.*
 559 *Environ* 38: 5991-6004
 560 Tallis M, Taylor G, Sinnett D, Freer-Smith P (2011) Estimating the removal of atmospheric
 561 particulate pollution by the urban tree canopy of London, under current and future
 562 environments. *Landscape Urban Plan* 103: 129-138
 563 Tang X, Zhang X, Wang Z, Ci Z (2016) Water-soluble organic carbon (WSOC) and its

564 temperature-resolved carbon fractions in atmospheric aerosols in Beijing. *Atmos. Res* 181:
 565 200-210

566 Thithanhthao N, Yu X, Zhang Z, Liu M, Liu X (2015) Relationship between types of urban forest
 567 and PM_{2.5} capture at three growth stages of leaves. *J. Environ. Sci* 27: 33-41

568 Wang L, Gao S, Liu L, Ha S (2006) Atmospheric particle -retaining capability of eleven garden
 569 plant species in Beijing. *Chin . J. Appl . Ecol* 17, 597-601

570 Wang L, Gong HL, Liao WB, Wang Z (2015) Accumulation of particles on the surface of leaves
 571 during leaf expansion. *Sci. Total Environ* 532: 420-434
 572 Wang L, Hasi E, Liu L, Gao S (2007)
 573 Physico-chemical characteristics of ambient particles settling upon leaf surface of six conifers
 in Beijing. *Chin. J. Appl. Ecol* 18: 487-492

574 Wang Y, Zhuang G, Tang A, Yuan H, Sun Y, Chen S, Zheng A (2005) The ion chemistry and the
 575 source of PM_{2.5} aerosol in Beijing. *Atmos. Environ* 39: 3771-3784

576 WHO (2006) WHO air quality guidelines for particulate matter, ozone, nitrogen dioxide and
 577 sulfur dioxide. Global Update 2005. Summary of Risk Assessment World Health Organization.
 578 Geneva

579 Xie BZ, Wang HX, Yang J (2014) Retention capability of PM_{2.5} and it's explanation by leaf
 580 surface micro-structure of common broad-leaved plant species in Beijing. *Acta Bot. Boreal. -*
 581 *Occident. Sin* 34: 2432-2438

582 Yan J, Lin L, Zhou W, Ma K, Pickett STA (2016) A novel approach for quantifying particulate
 583 matter distribution on leaf surface by combining SEM and object-based image analysis.
 584 Remote Sens. Environ 173: 156-161

585 Yin S, Shen Z, Zhou P, Zou X, Che S, Wang WH (2011) Quantifying air pollution attenuation
 586 within urban parks: An experimental approach in Shanghai, China. Environ. Pollut 159: 2155-
 587 2163

588 Zhang ZD, Xi BY, Cao ZG, Jia LM (2014) Exploration of a quantitative methodology to
 589 characterize the retention of PM_{2.5} and other atmospheric particulate matter by plant leaves:
 590 Taking *Populus tomentosa* leaves as an example. Chin. J. Appl. Ecol 25: 2238-2242

591 Zhao ST, Li XY, Li YM (2014) The Characteristics of deposition of airborne particulate matters
 592 with different size on certain plants. Ecol. Environ. Sci 23: 271-276
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Table 1. Species and allometric data for the trees sampled. (mean $\pm$ SD, n = 3)

Classification	Species	Height (m)	Diameter at breast height (cm)	Crown diameter (m)
Shrubs	<i>Amygdalus triloba</i> (Lindl.) Ricker	2.1 $\pm$ 0.4	7.7 $\pm$ 1.4	2.8 $\pm$ 0.2
	<i>Euonymus japonicus</i> Thunb.	1.9 $\pm$ 0.2	5.0 $\pm$ 1.1	2.4 $\pm$ 0.2
	<i>Lonicera maackii</i> (Rupr.) Maxim.	3.2 $\pm$ 0.3	10.8 $\pm$ 3.4	5.6 $\pm$ 0.4
	<i>Prunus Cerasifera</i> Ehrh	2.4 $\pm$ 0.3	23.0 $\pm$ 2.4	5.4 $\pm$ 1.2
Trees	<i>Magnolia denudata</i> Desr.	10.5 $\pm$ 0.4	23.6 $\pm$ 3	6.8 $\pm$ 1.7
	<i>Rhus typhina</i> Nutt.	3.6 $\pm$ 0.2	8.8 $\pm$ 1.3	2.3 $\pm$ 1.1
	<i>Platanus occidentalis</i> L.	14.4 $\pm$ 0.6	53.7 $\pm$ 6.2	6.6 $\pm$ 2.1
	<i>Fraxinus pennsylvanica</i> Marsh.	9.4 $\pm$ 0.6	25.0 $\pm$ 2.1	7.9 $\pm$ 2.6
	<i>Populus tomentosa</i> Carr.	13.4 $\pm$ 0.7	51.9 $\pm$ 3.6	5.3 $\pm$ 0.9
	<i>Ginkgo biloba</i> L.	14.5 $\pm$ 0.5	53.5 $\pm$ 5.6	5.8 $\pm$ 1.4
	<i>Ulmus pumila</i> L.	8.4 $\pm$ 0.3	77.1 $\pm$ 7.4	6.8 $\pm$ 2.3
	<i>Salix matsudana</i> Koidz.	12.6 $\pm$ 0.4	34.4 $\pm$ 5.8	6.9 $\pm$ 2.3
	<i>Pinus tabulaeformis</i> Carr.	10.0 $\pm$ 0.8	29.4 $\pm$ 5.3	5.6 $\pm$ 0.8
	<i>Platyclusus orientalis</i> (L.) Franco	6.1 $\pm$ 0.1	16.1 $\pm$ 2.3	1.7 $\pm$ 0.6
	<i>Pinus armandi</i> Franch.	5.4 $\pm$ 0.6	16.5 $\pm$ 1.6	3.8 $\pm$ 0.8
	<i>Ailanthus altissima</i> (Mill.) Swingle	9.8 $\pm$ 0.5	27.8 $\pm$ 3.5	4.6 $\pm$ 0.7
	<i>Sophora japonica</i> L.	10.7 $\pm$ 0.3	24.5 $\pm$ 0.3	3.4 $\pm$ 0.5

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Figure Captions

Fig. 1. Total amount of PM accumulated on leaf surfaces and in-wax. Data are mean $\pm$ SE, n = 18.

Bars marked with different letters are significantly different ($p < 0.05$).

Fig. 2. The sum of PM accumulation of three size fractions on leaf surfaces. Data are mean $\pm$ SE,

n=18. Bars marked with different letters are significantly different ($p < 0.05$).

Fig. 3. The sum of PM accumulation of three size fractions in waxes. Data are mean $\pm$ SE, n=18.

Bars marked with different letters are significantly different ($p < 0.05$).

Fig. 4. Total insoluble suspended particulate and water-soluble ions accumulated on leaf

surfaces. The ratio of ions to TSP. Data are mean $\pm$ SE, n =3.

Fig. 5. The concentrations of dissolvable inorganic ions presented as the sum mass of four types

ions. Data are mean $\pm$ SE, n=3.

Fig. 6. Monthly change of PM accumulation on leaf surface between shrubs and trees. Data are

mean $\pm$ SE, n=3. Bars marked with different letters are significantly different ($p < 0.05$).

Fig. 7. Monthly change of PM accumulation in waxes between shrubs and trees. Data are mean

$\pm$ SE, n=3. Bars marked with different letters are significantly different ($p < 0.05$).

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.

Fig. 6.

Fig. 7.