International Journal of Sciences

Research Article Volume 3 - April 2014 (4)

Deposition of Particulate Matter of Different Size Fractions on Leaf Surfaces and in Epicuticular Waxes of Urban Forest Species in Summer and Fall in Beijing, China

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Abstract: This study compared eight species of urban forest trees and one grass species that are commonly cultivated in Olympic park of Beijing city to capture fine, coarse and larger particles from the air during fall and summer. Separate gravimetric analyses were performed to quantify particulate matter (PM) deposited on surfaces and trapped in epicuticular waxes. Significant differences were found between the tree species tested. In Fall, PM content of all 3 particle sizes on the leaf surface and in epicuticular wax is definitely higher than in summer. The distribution of different particle size fractions differed between and within species and also between leaf surfaces and in epicuticular waxes. Needleleaves showed absorption of PM (all 3 sizes of dust) higher than broadleaves, shrubs and grass clusters, except for S. japonica with small hairy leaves. PM deposition on leaf surfaces and waxed layers depends on many elements: leaf shape, hairyand rough surfaces, deposition time, rain, wind and urban forest system model.

Keywords: urban forest, particulate matter, coarse particles, fine particles, epicuticular wax

1. Introduction

The migration of people into urban centers and the parallel rise of industry within these centers has brought more people into contact with air pollution than ever before (Andreae, 1995). Air pollution in high concentrations can cause immediate physical symptoms such as rapid pulse and restricted breathing, but at every level of concentration and even in trace amounts, it is considered deleterious to health (Levy et al., 2000).

Trees can capture significant quantities of health-damaging particles from the atmosphere with the potential to improve local air quality (Beckett et al., 2000). Trees play an important role in filtering ambient air by adsorbing particulate matter onto leaf surfaces. The large total leaf area of trees, are considered the most effective type of vegetation for this purpose (McDonald et al. 2007). Planting trees and shrubs as air filters is a way to improve air quality (Popek et al, 2012). Trees planted at road sites are able to improve the air by capturing particles on leaves. Some particles that are captured can later be washed off from the leaves by rain and deposited in soil and some particles be uptaken into epicuticular wax (Dzierżanowski, 2011; A. Sæbø, 2012; Popek et al., 2012). Surface morphology appears to be a dominating factor in particle deposition on to the leaf surface, with ridged, hairy leaves exhibiting greatest deposition velocities. Plant species growing low to the ground are also presumably more exposed to soil splash on their leaves than trees with upright growth (A. Sæbø et al, 2012). Dzierżanowski et al (2011) observed the largest amount of PM on low growing shrubs (*Spiraea*) compared to trees. Leaves from broad-leaved species, which have rough surfaces, are more effective in capturing PM than those with smooth surfaces. Needles of coniferous trees, which produce a thicker epicuticular wax layer, are more effective in PM accumulation than broad-leaved species (Beckett et al. 1998; 2000). Leaf hair and wax content were traits with a positive correlation to PM accumulation (Sæbø et al, 2012). Biomagnetic monitoring of PM10 deposition on initially 'clean' (glasshouse-grown) tree leaves shows that particles gradually accumulate on the surfaces of deciduous tree leaves until a dynamic equilibrium between particle deposition and particle loss is reached. For birch and lime trees, the time required for equilibrium to be reached is of the order of 6 days (Mitchell et al., 2010). Different time periods also affect the levels of PM accumulated on the leaf surfaces. Dzierżanowski et al (2011) studied the PM accumulated on the leaf surfaces over 03 years demonstrating variability between years in the accumulation of PM on the leaf surfaces of the same species, but the differences between species were usually maintained.

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The aim of the study was to analysis and compare accumulation of surface PM and in epicuticular-wax PM (three different size fractions) on leaves of selected urban tree species recommended for planting at two seasons in urban areas in Beijing, China. Examination of eight tree and shrub species as well as one grass species growing under the same conditions allowed comparisons between species. Experiments comparing the capacity of the specific urban forest to capture PM from air, as well as the ability to coordinate diverse urban forest system effectiveness in preventing convergence and controlling air pollution were investigated.

This experiment is part of overall research on the impact of urban forest for capturing, regulating and controlling the pollution of particulate matter in the air in order to discover urban forest systems which have the ability to regulate and control air pollution effectively.

2. Materials and Methods

2.1 Materials and Sample Collection

Two conifers: Arborvitae: ***P. orientalis*** (*Platycladus orientalis* (Linn.) Franco): Coniferous tree with dense leaves, leaf structure small, short, rough surface. Leaves 1-2 cm long. Chinese red pine: ***P. tabuliformis*** (*Pinus tabuliformis*): Coniferous tree with dense leaves, small leaf structure, long, smooth surface. 6-15 cm long leaves.

Four broadleaf tree species: Small leaf White wax: ***F. sogdiana*** (*Fraxinus sogdiana* Bunge) and Large leaf White wax: ***F. rhynchophylla*** (*Fraxinus rhynchophylla*): Deciduous trees, long leafy lozenges, smooth, sparsely hairy, leaf size 8-10 cm (large leaf White wax); 4-6 cm (small leaf White wax). Tomentosa: ***P. tomentosa*** (*Populus tomentosa* Carr): Deciduous trees, heart-shaped leaves, leaf surface wide, smooth, leaves 8-15 cm in size. *Sophora japonica* Linn: ***S. japonica*** (*Sophora japonica* Linn): Deciduous trees, lozenge-shaped leaves, leaf surface small, dense hairs, leaves 2-3 cm in size.

Two small tree and shrub species: Flowering peach: ***P. persica*** (*Prunus persica* Batsch. var. *duplex* Rehd): Deciduous trees, long lozenge leaves, smooth surface, leaf size 8-15 cm. Flowering plum: ***A. triloba*** (*Amygdalus triloba*): Deciduous trees, lozenge leaves, surface roughness, fine hairs, leaf size 4-8 cm.

One grass species: *Iris ensata:* ***Iris ensata*** (*Iris ensata* Thunb*)*: Perennial grasses, narrow leaves, striped ribbed surface, smooth, 40-80 cm long, 1.2-2.0 cm wide.

The plants studied were grown at the urban forest park in Beijing (The Beijing Olympic Forest Park), China. The design merges traditional Chinese landscape arts with ecological techniques to form an urban green lung and a site for public recreation. Samples were collected in August (summer) when the leaves grow to maturity, and early November (autumn), at the end of the vegetative season, a few days before autumn defoliation, 2013. All trees were fully foliated and in relatively good health, and varied in five urban forests chosen for this study. For each species, leaves were harvested from three plants (replicates) in two growing seasons (at the same place). In order to obtain sufficient material to determine the fine fraction of PM and still avoid filter blockage by particles during filtration, the leaf area per sample ranged between 200 and 300 cm^2. This leaf area was found to be suitable for washing off particles in the rinse liquids used (water, chloroform). For each species four batches of 8–12 leaves (quantity depending on leaf area) were collected from from the lower crown with a pole pruner approximately 1.5 – 2m, except for grass species at 0,5-0.7m.

2.2 Quantitative Analysis of PM on leaf surface and in waxes

After the collection of leaves from the plants in the field, the samples were carefully handled with plastic gloves, enclosed in plastic bags and immediately returned to the laboratory. The samples were stored in paper bags at room temperature in a clean storage facility until analysis of PM. PM of three size fractions were determined on leaf surfaces and in waxy layers using the method described by Dzierźanowski et al. (2011). Filters were weighed before and after filtration (XS105DU balance, Mettler-Toledo International Inc., Switzerland).

The isopore™ membrane filters used for the water fractions were Type 10.0µm TCTP (retention of 10 µm) in the first filtration, Type 3.0 um TSTP (retention of 3.0 µm) in the second filtration and Type 0.4 µm HTTP (retention of 0.4 µm) in the final filtration (all filters by Millipore, Ireland). The filters used for the chloroform fractions were the mitex™ membrane filters Type 10.0µm LC (retention of 10 µm) in the first filtration, the flouropore™ membrane filters Type 3.0 um FS (retention of 3.0 µm) in the second filtration and the flouropore™ membrane filters Type 0.45 µm FH (retention of 0.4 µm) in the final filtration (all filters by Millipore, Ireland). Thus, three fractions of PM were collected on the filters: i) 10–100 µm (large particles), ii) 3.0–10 µm (coarse particles) and iii) 0.4–3.0 µm (fine particles).

Every batch (sample) of leaves was placed into a glass container and rinsed with water for 60 seconds in order to wash off particles that are potentially washed off during rainfall. Water was then filtered using a metal sieve with mesh diameter of 100 µm to eliminate bigger elements. Then, it was filtered using a PALL filtering set with a vacuum pump on pre-weighed paper filters with retention of 10 µm, then 3.0 µm and then 0.4 µm to separate into three fractions of particles: large particles, coarse particles and fine particles. Filters were then dried and post-weighed to calculate the mass of each PM fraction in the sample. The same batch of leaves was then rinsed with chloroform for 40 seconds to wash out particles trapped by waxes. The filtering procedure was the same as for water-rinsed particles. Also, the leaf area of each sample was measured using LI3000C Portable Area Meter (LI-COR Inc., Norway), so that results are shown in micrograms of PM per square centimeter of leaf area (µg/cm^2). Every batch of leaves (sample) was measured separately as a replicate for statistical analysis.

To test for relationships between leaf traits and PM accumulation, leaf samples of selected species at the Beijing Olympic park site were collected (3 samples per species) from the trees described above and leaf area per leaf, dry weight per leaf, specific leaf area (grams dry weight per cm^2 of leaf area) and leaf longevity (deciduous or evergreen) were recorded. The ratio between PM deposited on the surface and that in waxes was calculated based on the original data for each of the plants sampled.

2.3 Statistical Analysis

Data were subjected to one-way and multi-way analysis of variance using StatGraphics Centurial XVI software (StatPoint Technologies, Inc., USA). Significance of differences between mean values was tested using Tukey's honestly significant difference test (HSD) at α=0.05. Values presented on bar charts are means, while values on dot charts are individuals with trend line and correlation coefficient (r). The latter two were calculated using Microsoft Excel (Microsoft Corp., USA).

3. Results and Discussion

3.1 PM concentration deposited at different seasons

The amount of PM accumulated on foliage of the nine urban plant species tested differed depending on species, seasons (summer and autumn) and whether total PM or size fractions, both on the surface and in-wax, was analyzed.

Species differed in accumulation of all PM fractions ($P<0.0000$) in both seasons and the differences were considerable for most fractions (Fig 1 and Fig 2). However, between the two seasons there was no statistical significance ($P>0.2124$).

The deposition of PM content on leaf surfaces could vary from season to season in a year. With deciduous trees, leaves start growing in spring and develop until late autumn (or early winter), then fall. During this process, there is a depositon of PM from the air on to the leaf surface and leaves will capture some in the waxed layer. Rain and wind could wash off part of the PM on leaf surface during this process. With evergreen trees, this depositon process is year round.

The result from Fig. 2 – Charts A and B show the mass of coarse, fine and aqueous soluble ultra-fine particles washed from the foliage of nine urban plant species in August (late summer) and November (late autumn) 2013. There were significant differences observed between the nine species with *P. orientalis* and *S. japonica* having more large particles present ($P<0.035$) and also coarse particles ($P<0.041$), but not for fine particles ($P>0.083$). For large particles, there were very much larger masses of particles present in autumn than in summer. The different effects of different species were statistically significant ($P<0.000$); with a considerably higher quantity of fine particles present on the foliage at the polluted Olympic park trees.

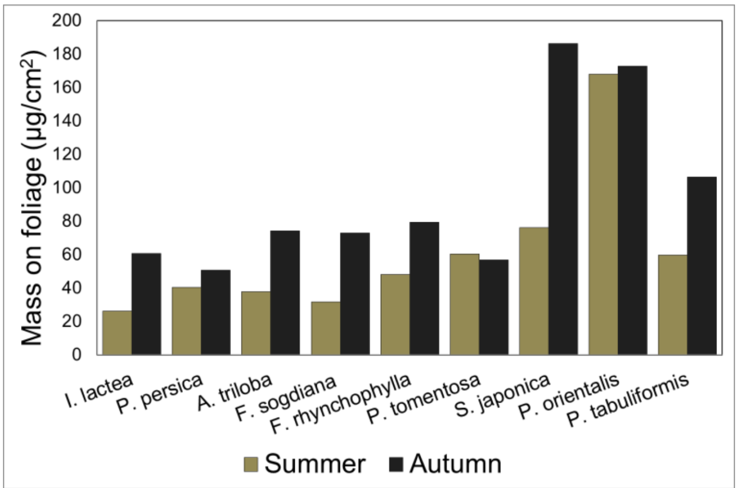

Fig. 1. The mass of particulate matter captured by the foliage of each species at each stage of leaf development over the same period.

The comparison of PM capturing ability on leaf surfaces and the epicuticular waxed layer of 9 urban forest species over 2 summers and autumns at Olympic Park, Beijing, show that in autumn, the quantity of PM accumulating on leaves of all species is higher than in summer. In summer, when rainfall is high, the quantity of PM on leaf surface and the epicuticular waxed layer among species varies. W-PM/S-PM absorbing ratio on leaf surfaces is higher in autumn than in summer 79.9% compared to 62.7% but there is no significant difference between the two seasons (P>0.1136). However, there is meaningful difference between S-PM and W-PM (P<0.0039). Among S-PM/W-PM of the species, there is also a statistically significant difference (P<0.0461).

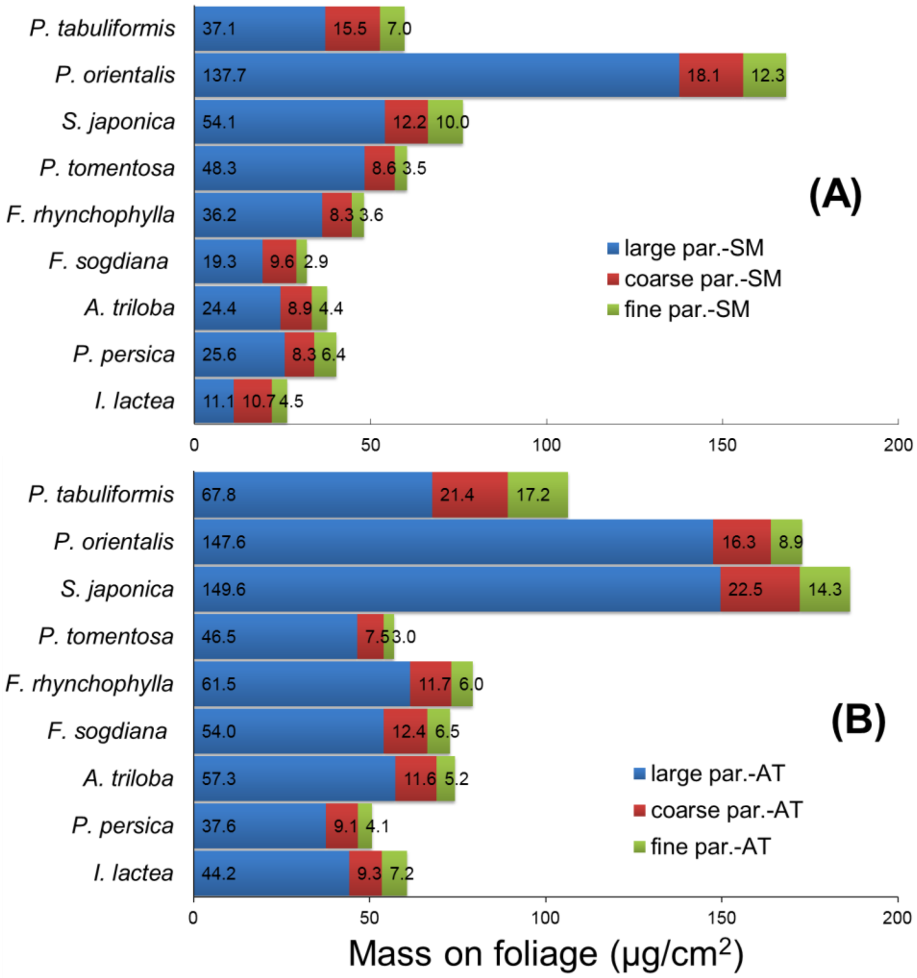

Fig. 2. Accumulation of particulate matter on leaves of urban tree species in Beijing, China in summer (SM) and autumn (AT) seasons (2013), presented as the sum of surface and wax-deposited particulate matter in three particle size fractions.

In summer, the highest absorbing S-PM is *P. orientalis* (72.85 µg/cm^2), next is *S. japonica* (49.67 µg/cm^2), the lowest are *I. lactea* (19.83 µg/cm^2) and *A. triloba* (20.75 µg/cm^2). The highest in-wax value is *P. orientalis* (95.27 µg/cm^2), next is *P. tabuliformis* (28.40 µg/cm^2) and the lowest are *I. lactea* (6.46 µg/cm^2) và *F. sogdiana* (6.51 µg/cm^2). In autumn, the highest S-PM is *S. japonica* (156.25 µg/cm^2), next are *P. orientalis* (91.14 µg/cm^2) and *P. tabuliformis* (79.14 µg/cm^2). In contrast, the highest W-PM is *P. orientalis* and *S. japonica* and the lowest are *I. lactea* và *P. tomentosa*. Both seasons show that shrubs are less effective than conifers. *P. tomentosa* (large leaf) shows that the ability to absorb W-PM is effective in summer but is not as high in autumn. Meanwhile shrubs, small trees and grass are all effective in autumn.

In autumn the amount of PM on leaves of all species is higher than in summer. This may be caused by specific meteorological events during the vegetative period related to rainfall and wind direction, especially directly before sample collection in each season (Dzierżanowski et al., 2011). Summer with more rainfall, may have a big amount of PM washed off by rain water. After the dry season from September to November, over a long accumulation period, the amount of PM on the leaf surface in autumn shows a higher result because it is not washed off as much. The higher S-PM/W-PM ratio in autumn than in summer is also explained by this reason.

Comparison of differences between seasons showed that the amount of PM deposited on the leaves of tested species was in general higher in autumn than in summer, when on average for all species the amounts of PM were similar, except for *S. japonica* and *P. orientalis*. *P. orientalis* and *S. japonica* showed high total PM accumulation calculated as mean value for the two seasons, being 175.20 and 194.40 µg/cm^2 (Figs. 1, 2). *P. persica*, *P. tomentosa*, *F. sogdiana* and *F. rhynchophylla* with smooth leaf surfaces had considerably lower total accumulation of PM (31.64 – 51.74 µg/cm^2), while the remaining species showed intermediate PM accumulation. Weak to moderate positive correlations between accumulations of the different PM fractions (large particles, coarse particles, fine particles) were observed across the species.

The nine plant species were tested in both seasons and could be clustered according to how much PM was captured. Of these, shrubs and grass had low accumulation of PM during both seasons. *P. persica*, *F. rhynchophylla* and *P. tomentosa* species with large leaf surface areas had intermediate accumulation and *P. orientalis* and *S. japonica* were in the cluster with the largest PM accumulation. In summer, data showed that *P. orientalis* had the highest PM accumulation (mean 168.12 µg/cm^2) but not in autumn. *S. japonica* had the highest PM accumulation (mean 186.42 µg/cm^2) in autumn and was the species with the highest accumulation (Table 1). White wax and *A. triloba* were in the medium cluster in autumn and in the cluster with least accumulation in summer. The level of PM deposited on the leaves was lower in all species in summer than in fall, reflecting the difference in exposure to pollutants in the two seasons.

3.2 PM concentration deposited on different urban forest species

Plants possess an ability to filter contaminants from the air and retain them on leaves (Beckett et al., 1998). Leaves of some species are equipped with specific morphological features like trichomes (leaf hair) that may increase the number of captured particles (Bakker et al., 1999). The epicuticular wax layer, its thickness and composition are important factors for PM accumulation as well, because some particles penetrate inside it and are deposited there (Kaupp et al., 2000; Jouraeva et al, 2002). There was a positive relationship between PM accumulation and hair density on the leaves (Sæbø et al, 2012). Due to greater leaf area index, trees are able to capture more PM than other vegetation using the same ground area (Fowler et al., 1989). Levels of air pollution tolerance vary from species to species, depending on the capacity of plants to withstand the effect of pollutants without showing any external damage.

Trees are effective in the capture of particles from urban air to the extent that they can significantly improve urban air quality. As a result of their aerodynamic properties, conifers with their smaller leaves and more complex shoot structures, have been shown to capture larger amounts of particulate matter than broadleaved trees. Conifers have been demonstrated to be capable of coarse particles capture up to ten times that of broadleaf species but their ability to retain particles remains in question (Nowak et al., 1994; Beckett et al., 2000a; Freer-Smith et al., 2004; Freer-Smith et al., 2005).

Data on the total PM accumulated on the leaves of the eight tree species studied are presented in Fig. 3 and Tables 1. All tested species captured some particles on their leaves, but the quantity of PM differed significantly between the species.

All tested species captured some particles on their leaves, but the quantity of PM differed significantly between the species. *S. japonica* and *P. orientalis* have leaves with a ridged and hairy morphology and were found to be the most effective in PM capture, while the large, smooth leaves of the branchy trees *P. persica and A. triloba* were least effective, with over a twofold difference between these species. Similarly, significant differences in the quantity of particulate matter deposited on leaves were reported for five tree species by Beckett et al. (2000) and Freer-smith (2005).

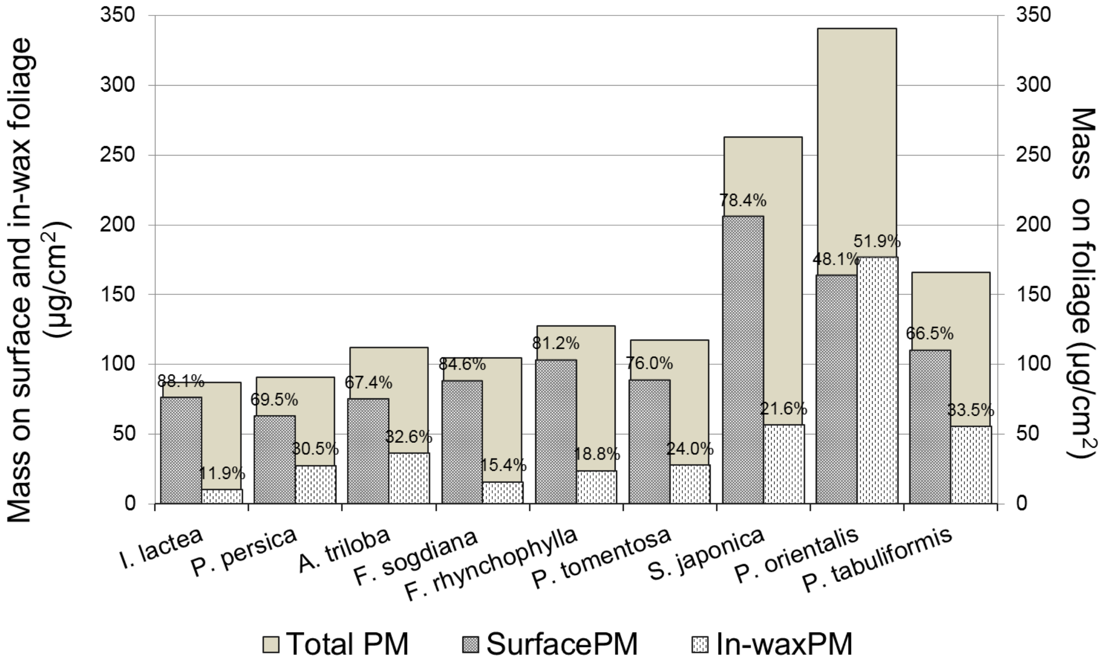

Fig. 3. Mass (μg/cm^2) of surface PM and in-wax PM accumulated on leaves of the nine plant species.

P. tabuliformis and *P. orientalis* were more effective in capturing fine particles on foliage than the other species. *S. japonica* accumulated the same amount of surface PM as these species, and are similar to in-wax PM. *P. tomentosa and P. persica* appeared to have the smallest amount of fine PM deposited, both on leaf surfaces and in the wax layer (Fig. 3).

The results show that *S. japonica* and *P. orientalis* accumulated the highest quantity of large particles (surface large particles). For all species there was also a large quantity of particles of this size deposited in epicuticular waxes, but there were no large differences between the species (P<0.035).

The species with the largest accumulation (12.09 and 12.15 μg/cm^2) of the fine particles fraction included *S. japonica* and *P. tabuliformis*. *P. tomentosa* were at the lower end of the scale and accumulated considerably less of the smallest PM fraction (3.22 μg/cm^2). Summer data showed that *P. tabuliformis* had the highest coarse particles accumulation (mean 18.09 μg/cm^2) but not in autumn, and was the only species in the high accumulation cluster (Table 1). The species with the highest accumulations of coarse particles (17.19–18.42 μg/cm^2) were *P. tabuliformis* and *P. orientalis* (conifers). The species with the lowest accumulations of this fraction (8.03 – 8.70 μg/cm^2) were *P. tomentosa* and *P. persica* (large leaf). Large particles appeared mainly on the leaf surfaces. This means that most of this fraction can easily be washed off during rain events or dislodged by wind and thus these large particles may ultimately be deposited on the ground (Dzierżanowski et al., 2012).

The results of clusters of plants: conifers (*P. orientalis* and *P. tabuliformis*) showed absorbed PM (all 3 sizes of dust) higher than the other trees, shrubs and grass. No correlations were found between PM accumulation and leaf surface roughness and leaf size of the tested species (Sæbø, 2012).

The results showed that the species examined accumulated large quantities of particulate matter. The largest quantity of PM occurred in the form of large particles (10–100 μm diameter) followed by a significantly smaller amount of coarse ones (3.0–10 μm). The quantity of fine PM (0.45–3.0 μm) was the smallest. Similarly, Beckett et al. (2000) found more coarse than fine PM deposited on the leaves of five tree species studied. However, Freer-Smith et al. (2005), in a similar study, reported that when leaves of two conifer species were harvested for analysis in winter time, more fine than coarse PM was found on needles. In contrast, Ottel´e et al. (2010) reported particles ≥ 10 μm to be rather rare in visual counts of PM on ESEM photographs of *H. helix* leaves. They found the greatest number of particles with the smallest diameter (0.5–1.0 μm), with twofold to eightfold fewer particles with diameter 1.0–5.5 μm and very few with diameter 5.5–10 μm. However, in preliminary microscopic studies, Mitchell et al. (2010) observed particles of all fractions studied, with the large particles (10–100 μm) being present quite frequently. It should be borne in mind, however, that comparisons of data collected using different methods may be of little relevance, for example due to lack of a direct relationship between the number of particles in a given size fraction and their mass. This indicates that the surface particles dominate the leaf magnetic signature. It seems likely that waxy evergreen leaves capture ambient particles at a slower rate than the deciduous tree species investigated here, and hence evergreens may incorporate a larger proportion of particles within the leaf structure, rather than upon the leaf surface. Deciduous trees therefore appear more suitable for monitoring of ambient particulate pollution than evergreen species. Particles appear to accumulate around ridges in the leaf surface (Mitchell et al., 2010). Additionally, trees such as lime and birch attract aphids which secrete a 'honeydew' waste product making the surface of the leaf sticky, possibly enhancing particle retention. Other species such as field maple directly secrete honeydew to the same effect.

Particles on the leaf surface, rather than particles incorporated into the leaf structure, dominate the magnetic signature for the entire in-leaf season for deciduous species. Deciduous trees, demonstrating relatively rapid equilibration with ambient large particles concentrations, appear preferable for monitoring purposes compared with more slowly accumulating evergreen species (Mitchell et al., 2010).

3.3 Urban plant species differ in particulate matter accumulation on Surface PM and Waxed PM concentration

Wax quantity was an important predictor for accumulation of all PM size fractions, while both surface leaf area (SLA) and leaf surface hair density were found to be significant predictors of accumulation of the total sum of PM, the large particles and coarse particles fractions (Fig. 3). An increase in surface leaf area predicted a decrease in particle accumulation, whereas increased hair density predicted an increase. Total PM accumulation was also predicted to increase with increasing quantity of wax, a trend that was found for all PM size fractions, both in wax and on leaf surfaces.

The amounts of these three size fractions in surface PM and in-wax PM are presented in Fig. 4 (A, B and C).

P. orientalis accumulated the highest quantity of large particles (surface large particles), and was significantly different to the other species, but there was no difference between *P. orientalis* and *S. japonica*.

For all species there was less amount of particles of this size deposited in epicuticular waxes, but there were large differences between the species. *S. japonica* and *P. orientalis* had about three-fourfold more large particles in waxes than the other species (Fig. 4 – Chart A). The large fraction (>10 μm) mainly appeared as surface PM, except that *P. orientalis* accumulated more of these particles in epicuticular waxes. Smaller particles (diameter below 10 μm) are considered to be more harmful for human health, with fine ones being more dangerous than coarse (Dockery et al. 1993). Therefore, selection of plants for urban air purification should be based on their ability to collect these PM fractions. The coarse fraction (3.0–10 μm) mainly appeared as surface PM (Fig. 4). *P. tabuliformis* was most effective in accumulating this fraction and was significant higher than the remaining species (Fig. 4 – Chart A). Fine particles (0.4–10 μm in diameter) appeared mainly on the leaf surfaces (Fig. 4 – Chart B,C) in rainy summer more than in drier autumn. This means that most of this fraction can easily be washed off during rain events or dislodged by wind and thus these large particles may ultimately be deposited on the ground. This is shown clearly observed through the two seasons examined.

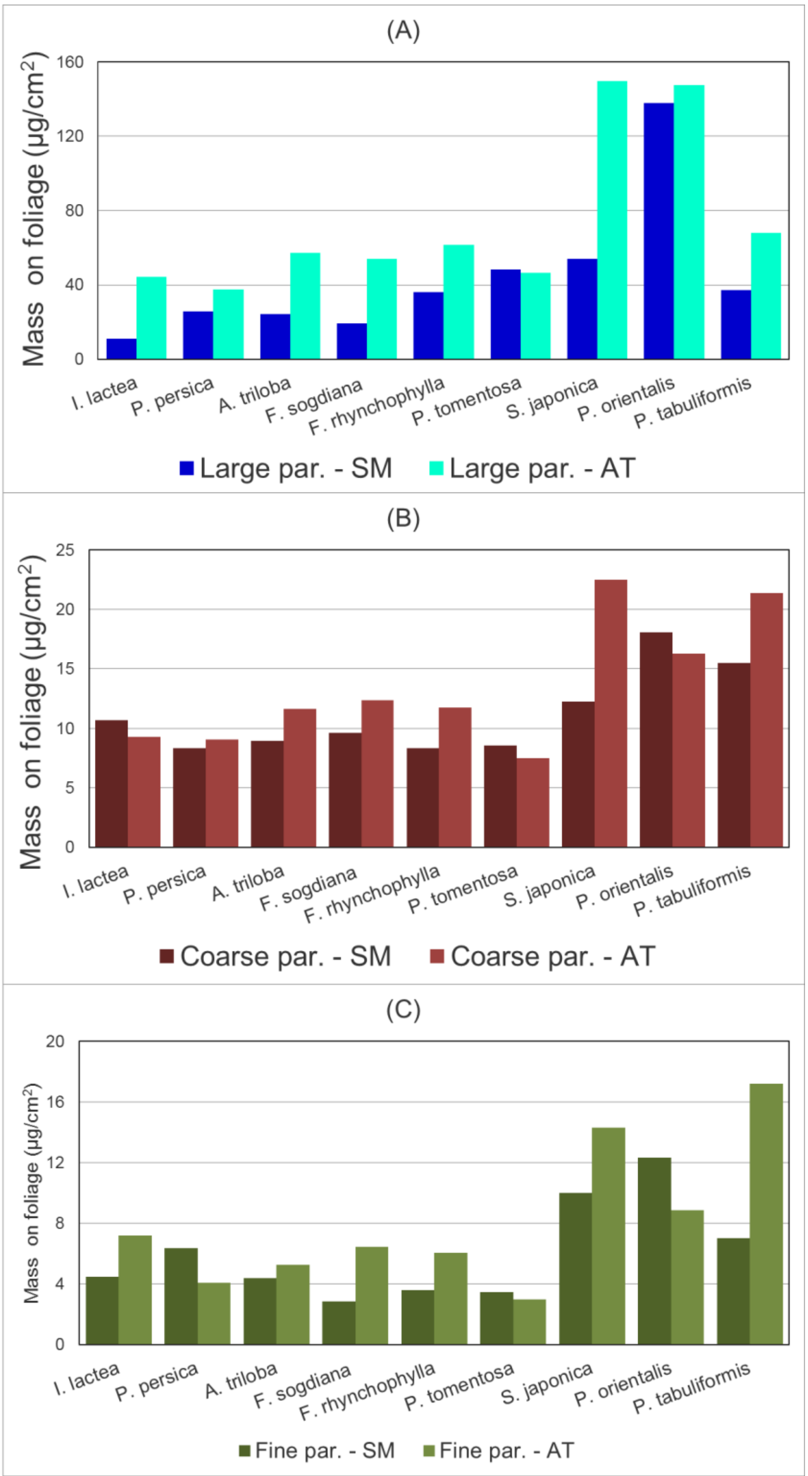

Fig. 4. Compare mass (µg/cm^2) of surface PM and in-wax PM with particle diameter (A) 10–100 µm, (B) 3.0–10 µm, and (C) 0.45–3.0 µm accumulated on leaves of the nine plant species.

In autumn, when rainfall is low, PM content of the 3 particle sizes on the leaf surfaces is definitely higher than in summer. In particular, conifers and *S. japonica* with small hairy leaves show that there is PM deposition on the leaf surface higher in autumn but is stored in the epicuticular wax layer in summer.

In all plant species examined in the present study, particles of all size fractions were found in the epicuticular wax layer. However, the quantity of large particles was always smaller in the wax layer than on the surface. For the smaller PM fractions, this difference was much less evident. Moreover, there were species in which the total amount of in-wax PM was either nearly the same or even greater than surface PM (Fig. 3 and 4).

3.4 Surface PM and Waxed PM concentration ratio

In all species and all years of study, particulate matter was found both as surface (S-PM) and in-wax (W-PM). With few exceptions, more PM was deposited on the leaf surface (on average for all species 48.1-88.1% of total PM) than was immobilized in waxes. Only in one of eight determinations was the proportion of W-PM greater than 51.9% (Table 2 and Fig. 3). In which, *P. orientalis* accumulated 51.9 % of PM in the wax fraction, whereas *I. lactea* accumulated only 11.9% in the waxes and the rest on the surface. In *S. japonica*, which was among the most efficient species in terms of PM accumulation, the proportion of PM in wax was also low (21.6%).

Table 1: Total mass of PM (μg/cm^2) accumulated on leaves of the nine urban plant species examined in summer (SM) and autumn (AT).

	Large particles-SM	**Coarse particles-SM**	**Fine particles-SM**	**Large particles-AT**	**Coarse particles-AT**	**Fine particles-AT**
I. lactea	11.14	10.69	4.46	44.20	9.30	7.21
P. persica	25.63	8.33	6.37	37.57	9.07	4.06
A. triloba	24.38	8.93	4.40	57.29	11.64	5.24
F. sogdiana	19.32	9.61	2.85	53.97	12.38	6.46
F. rhynchophylla	36.24	8.34	3.58	61.54	11.72	6.04
P. tomentosa	48.26	8.57	3.46	46.49	7.48	2.98
S. japonica	54.07	12.22	10.01	149.62	22.49	14.30
P. orientalis	137.71	18.09	12.32	147.59	16.29	8.86
P. tabuliformis	37.15	9.75	12.72	67.83	21.37	17.19

Table 2. Surface PM and Waxed PM with total of PM concentration capture on leaves of nine examined species. Mean of two examined seasons.

Species	**S-PM** μg/cm^2	**W-PM** μg/cm^2	**Sum-PM** μg/cm^2	**S-PM/PM** %	**W-PM/PM** %	**SPM/ WPM**
I. lactea	38.32	5.18	43.50	88.1	11.9	**7.41**
P. persica	31.64	13.87	45.51	69.5	30.5	**2.28**
A. triloba	37.68	18.26	55.94	67.4	32.6	**2.06**
F. sogdiana	44.27	8.04	52.30	84.6	15.4	**5.51**
F. rhynchophylla	51.74	12.00	63.74	81.2	18.8	**4.31**
P. tomentosa	44.55	14.07	58.63	76.0	24.0	**3.17**
S. japonica	102.96	28.40	131.36	78.4	21.6	**3.63**
P. orientalis	82.00	88.43	170.43	48.1	51.9	**0.93**
P. tabuliformis	55.18	27.83	83.01	66.5	33.5	**1.98**

The ratio between surface PM and that bound in waxes differed significantly between the species, with the highest value observed for *I. lactea* (7.41) and the lowest for *P. orientalis* (0.93) (Table 2).

The result of large particles deposition on leaf surfaces and waxed layer shows that difference is significantly between species but there is no difference between species in the same cluster, except for conifers (Table 2). *P. orientalis* were at the other end of the scale, with a ratio of 0.83 with more large particles in their epicuticular waxes than on their surfaces. The other species had a ratio between 1.83 – 8.32. large particles uptake on leaf surfaces and waxed layers showed no significant difference, *P. orientalis* in-wax large particles has good absorption and higher accumulation on surfaces in rainy conditions.

Analysis of the ratio between PM on the surface and in-wax for coarse particles showed that on average for the two seasons studied, *P. tomentosa, F. rhynchophylla, I. lactea* and *F. sogdiana* (smooth leaf surface) had a significantly higher ratio (14.25, 8.74, 7.59 and 6.41, respectively) than the other species (rough leaves, hairy and conifers). coarse particles and fine particles shows a very clear difference between the surface PM and in wax PM. But not with *P. tabuliformis*, fine particles captured in wax is lower than that on the leaf surface.

The percentage of S-PM in comparison with W-PM in autumn is higher than in summer. It could be because there is more rain in summer, a proportion of PM on leaf surfaces is washed off, meanwhile there is less rain in autumn therefore PM deposition is higher on the leaf surfaces.

In summer, the S-PM/W-PM ratio is quite high among the species studied, and among them, *P. orientalis* shows the highest deposition into the waxed layer, and is even higher for S-PM (0.76). The ability to deposit PM into the waxed layer of *P. orientalis* is also effective in autumn (1.12). In the same conifers cluster, *P. tabuliformis* also show effective absorption of in-wax PM for the leaves. The S-PM/W-PM ratio is high in summer due to wind and rain water. Some of the PM is washed off the leaf surfaces and some of the PM deposited into the waxed layer remains. In autumn, PM is not washed away by rain water and only a little is lost due to the impact of wind.

The species also differed significantly in terms of surface PM and PM immobilized by epicuticular waxes (S-PM). On average for all 9 species and the two seasons of study, S-PM contributed about 70% to total PM deposition (Table 2). This result is higher than the proportions of S-PM and W-PM (about 60% and 40%, respectively) reported by Popek et al (2012) for 13 wood species, Dzierżanowski (2011) for five tree and tree shrub species and by Popek et al (2011) for 19 shrub species. This is maybe because in Beijing, air pollution levels are more than in Poland (on average PM 13.1 µg/m^3 and 32.0 µg/m^3 for June and August 2011 in Poland)

4. Summary

Plants of all species tested accumulated particulate matter (PM) of large (10–100 μm), coarse (3.0–10 μm), and fine (0.4–3.0 μm) fraction sizes. The PM was deposited on leaf surfaces and trapped in waxes. The largest quantity of deposited PM observed consisted of large particles, while there were smaller quantities of coarse and fine particles. The quantities of in-wax PM depended on species and particle size fraction.

In autumn, when rainfall is low, PM content of the 3 particle sizes on the leaf surface is definitely higher than in summer.

The nine species examined differed significantly in their ability to capture particulate matter. *S. japonica* and *P. orientalis* were most effective while *I. lactea* and *P. persica* were least effective. Conifers (*P. orientalis* and *P. tabuliformis*) showed absorption of PM (all 3 sizes of dust) higher than broad leaved trees, shrubs and grass.

P. orientalis holds an order of magnitude more particulates per square meter of needles than *P. tabuliformis*. *P. tabuliformis* of the Mixed trees type shows that the PM content is higher than that of conifer type. PM deposition process on leaf surfaces and waxed layers depends on many elements: deposition time, rain and wind. Urban forest types also have impact on this deposition process.

Acknowledgments

This work was fund by The Forestry Public Welfare Project of China NO.201304301. The authors gratefully acknowledge the contributions of Xu Hui Liu, Zhi Hua Tu, Vinh Thai Nguyen, for their assistance with the field measurements and instrumentation maintenance.

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Supporting information

Figure. 1. The mass of particulate matter captured by the foliage of each species at each stage of leaf development over the same period.

Fig. 2. Accumulation of particulate matter on leaves of urban tree species in Beijing, China in summer (SM) and autumn (AT) seasons (2013), presented as the sum of surface and wax-deposited particulate matter in three particle size fractions.

Fig. 3. Mass (µg/cm^2) of surface PM and in-wax PM accumulated on leaves of the nine plant species.

Fig. 4. Compare mass (µg/cm^2) of surface PM and in-wax PM with particle diameter (A) 10–100 µm, (B) 3.0–10 µm, and (C) 0.45–3.0 µm accumulated on leaves of the nine plant species.

Table 1. Total mass of PM (µg/cm^2) accumulated on leaves of the nine urban plant species examined in summer (SM) and autumn (AT).

Table 2. Surface PM and Waxed PM with total of PM concentration capture on leaves of nine examined species. Mean of two examined seasons.