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RESEARCH ARTICLE

# Response of the particulate matter capture ability to leaf age and pollution intensity

Xiang Niu [1,2,3] · Bing Wang [1,2,3] · Wenjun Wei [1]

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**Abstract**
Differences in leaf surface microstructure characteristics can lead to differences in the ability of trees to capture suspended particulate matter (PM). The influence of changes in leaf surface microstructure caused by growth and environmental pollution on the PM capture ability is poorly understood. This study assessed the influence of growth on leaf microstructure in leaves of different ages, and the influence of pollution intensity was assessed by studying trees growing under different pollution conditions. It was found that the ability of leaves of *Taxus cuspidata* var., *Platycladus orientalis*, and *Pinus tabuliformis* to absorb total suspended particles (TSP), $PM_{10}$, $PM_{2.5}$, and $PM_1$ increased with leaf age. The amounts of TSP and $PM_{10}$ captured by *P. orientalis*, *P. tabuliformis*, *Sophora japonica*, *Populus tomentosa*, and *Ginkgo biloba* were higher in heavily polluted areas than in clean areas. This may be because particle capture is influenced by leaf microstructure changes. With age increasing, the root mean square roughness ($R_q$) of three evergreen species leaves increased. Environmental pollution will change the leaf surface microstructure and its ability to capture PM. Compared with a clean area, in a heavily polluted area, the stomatal index of the leaves decreased, stomata were occluded, the leaf wax layer was degraded, the leaf surface contained more particles, the surface texture of *S. japonica* and *G. biloba* leaves became irregular, the boundaries of the epidermal cells became more irregular, and the trichrome of *S. japonica* became thinner, longer, and harder. The $R_q$ value was generally higher in the heavily polluted area, and the roughness of the abaxial surface increased more than on the adaxial surface. In the heavily polluted area, the leaf microstructure changes were the main reason for the increase in the $R_q$ value. With the increase in leaf roughness, the amount of PM on the leaf surface increased.

**Keywords** Leaf surface microstructure · Particulate matter capture ability · Leave ages · Pollution conditions

## Introduction

Particulate matter (PM) pollution has become an increasingly serious problem with the rapid development of industrialization and urbanization (Guerreiro et al. 2014; Andrade et al. 2017; Shi et al. 2017). Such pollution has always been a matter of great concern because of the adverse effect of PM on humans and plants (Rai et al. 2009). It reduces aerosol optical depth and produces photochemical smog (Wan et al. 2011). The sequences of several respiratory microbial allergens and pathogens have been identified and their relative abundance appears to have increased as levels of PM pollution have increased (Cao et al. 2014). Beijing is an international metropolis, and with the rapid development of its economy and the continuous expansion of the city, air pollution has reached serious levels (Zhang et al. 2011). Despite the remarkable achievements in air pollution control and the obvious improvements in air quality in recent years, there is still an issue

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due to the phenomenon of pollution rebound under the background of the increasingly serious regional air pollution (Yan et al. 2016; Hu et al. 2018). Trees are efficient scavengers of PM and are characterized by higher rates of dry deposition than other land use types (McDonald et al. 2007). Nowak et al. (2006) studied urban forests in the United States and found that they can remove about $71.1 \times 10^4$ t air pollutants per year. The model predicted that increasing total tree cover in the West Midlands, UK, from 3.7 to 16.5% would reduce the average primary $PM_{10}$ concentration by 10% from 2.3 to 2.1 mg $m^{-3}$, removing 110 t per year of primary $PM_{10}$ from the atmosphere. Overall health impacts included the avoidance of 30 incidences of human mortality and 22,000 incidences of acute respiratory symptoms across the West Midlands and Glasgow, UK (Nowak et al. 2014). Therefore, urban forest management can enable the provision of ecosystem services, especially air pollutant removal (Conway et al. 2019).

Forests are conducive to the formation of turbulence to promote dust capture, and meteorological factors can also affect dust capture. Precipitation can wash the particles attached to the leaves (Dawson et al. 2007). The particles captured can be washed by continuous precipitation of 15 mm (Fang et al. 2015). Proper wind speed can increase the capture effect of particles, and too high or too low wind speed will reduce the capture capacity of particles (Prusty et al. 2005). The ability of tree leaves to act as PM receptors depends upon their surface geometry, phyllotaxy, leaf pubescence, height, and canopy structure, as well as the prevailing meteorological conditions (Dzierzanowski et al. 2011; Hwang et al. 2011; Sæbø et al. 2012; Thaker and Gokhale 2016). Because leaves are the most important carriers of PM, the differences in leaf surface characteristics are important reasons for the differences among plants in their ability to absorb PM (Tallis et al. 2011). Neinhuis and Barthlott (1998) found that leaf surface characteristics had a strong influence on the retention of PM by leaf surfaces, e.g., leaves with complex shapes, waxy cuticles, trichomes, convex cells, and ridges may accumulate particles efficiently (Freer-Smith et al. 2004). The ultrastructure and chemical composition of wax are extremely complex (Wang et al. 2015b) and will have great influence on leaves roughness. Leaves can undergo several structural and functional changes when exposed to particulate-laden air (Rai et al. 2009). In dust-affected plants, the leaves have characteristic wrinkles, and the sinuous nature of epidermal cells and distinct cell boundaries are completely lost in the cuticle. These changes in the microstructure of leaves will have an impact on the ability to capture PM. Studies have shown that the microstructure of new to mature leaves can undergo great changes when exposed to PM (Wang et al. 2013). The microstructure of the leaves will change with their growth and exposure to environmental pollution. However, the influence of changes in the leaf surface microstructure caused by these factors on the PM retention capacity is still poorly understood. In this study, the effect of leaf age (i.e., the influence of growth) and pollution conditions (i.e., PM concentration) on leaf surface microstructure were investigated. The impacts of any leaf surface microstructure changes caused by leaf age and pollution conditions on their PM retention capacity were analyzed. The factors controlling the ability of leaves to capture PM were determined and data was provided to support scientific urban forest management measures that will improve the PM removal function of forests.

## Data and methods

### Study area

Beijing (39°N, 116°E) is located in the northwest part of the North China Plain. It is located within the warm temperate zone semi-humid region, the annual average temperature is 10 to 12 °C, and the annual average precipitation is 644 mm. The sampling sites were located in Beijing botanical garden and Chaoyang Park. The Beijing botanical garden is 23 km from the center of Beijing, and the sampling site was located far from any roads, and was therefore considered a relatively clean area. The area around Chaoyang Park has a high population density and a large number of vehicles. The sampling site was located alongside a road, and was therefore a heavily polluted area that was significantly affected by vehicle exhaust emissions. In 2017, the atmospheric $PM_{2.5}$ concentrations in Beijing botanical garden (clean area) and Chaoyang agricultural exhibition hall, which is near Chaoyang Park (heavily polluted area), were 58.32 and 75.43 μg $m^{-3}$, respectively, while the atmospheric $PM_{10}$ concentrations were 77.94 and 116.08 μg $m^{-3}$, respectively.

### Selection of tree species and leaf collection

New (1-year old) and old (more than 1-year old) leaves of three evergreen trees (*Platycladus orientalis*, *Pinus tabuliformis*, and *Taxus cuspidata* var.) in the clean area were selected for the determination of PM on the leaf surface and the observation of leaf microstructure. The new and old leaves are distinguished by the color of the leaves. The new leaves grew on the tip of the twig which seemed yellow green, and the old leaves grew on the bottom of the same twig which looked dark green. In both the clean and heavily polluted areas, two coniferous species (*P. orientalis* and *P. tabuliformis*) and three broadleaved species (*Sophora japonica*, *Populus tomentosa*, and *Ginkgo biloba*) were selected for the determination of PM on leaf surfaces and the observation of leaf microstructure under different PM concentrations. Growth of selected trees is in Table 1.

**Table 1** Growth of selected trees

| Sampling sites | Tree species | DBH/cm | Height/m | Crown depth/m |
|---|---|---|---|---|
| Beijing botanical Garden | *Platycladus orientalis* | 14.9 ± 2.7 | 12.3 ± 1.1 | 11.7 ± 0.5 |
| | *Pinus tabuliformis* | 11.4 ± 0.9 | 5.7 ± 0.7 | 3.5 ± 0.7 |
| | *Taxus cuspidata* var. | 6.3 ± 0.5 | 3.5 ± 0.2 | 2.8 ± 0.4 |
| | *Sophora japonica* | 16.2 ± 3.6 | 11.2 ± 1.0 | 7.3 ± 0.8 |
| | *Populus tomentosa* | 19.6 ± 2.5 | 18.2 ± 2.3 | 10.2 ± 1.5 |
| | *Ginkgo biloba* | 15.2 ± 1.9 | 15.9 ± 2.7 | 8.3 ± 0.7 |
| Chaoyang Park | *Platycladus orientalis* | 12.7 ± 1.6 | 11.3 ± 1.5 | 10.8 ± 0.3 |
| | *Pinus tabuliformis* | 12.6 ± 1.9 | 5.3 ± 1.0 | 3.6 ± 0.4 |
| | *Sophora japonica* | 13.5 ± 2.1 | 9.7 ± 1.1 | 5.9 ± 0.7 |
| | *Populus tomentosa* | 20.9 ± 3.7 | 21.5 ± 2.6 | 11.9 ± 1.3 |
| | *Ginkgo biloba* | 14.3 ± 2.3 | 13.7 ± 1.8 | 7.2 ± 0.5 |

To ensure that both new and old leaves, and leaves in both clean and heavily polluted area, were clean with the same "zero point" for observed of PM deposition on leaves, the samples were taken following August when the total precipitations exceed 200 mm. The leaves samples were collected after the rainfall more than 1 week. Leaf collection was conducted from September 5 to 6, 2017. Using overhead shears, leaves in the four directions (east, west, north, and south) and three heights (top, middle, and bottom) of the canopy were collected (Wang et al. 2016, 2017). Leaves were required to be complete and free from diseases, insect pests, and physical damage. About 100 g of leaves was collected from each tree. Three plants with good growth status and a mean diameter at breast height (DBH) were selected from each species as duplicates. The fresh leaves were placed into clean self-sealing bags, without any static charge, and transported to the laboratory for later use.

## Determination of leaf area

A 100-g sample of *P. tabuliformis* needles was collected. Needle diameters and lengths were measured. The average surface area of pine needles was calculated by assuming they were truncated cones, and the average surface area of pine needles was calculated using Equation (1) (Hwang et al. 2011).

$$A_{\text{needle}} = \frac{1}{2}\pi\cdot(D_1 + D_2)\cdot\left[\frac{1}{4}\cdot(D_2 - D_1)^2 + l^2\right]^{\frac{1}{2}} \quad (1)$$

where $D_1$ was the average diameter of pine needles at the upper tip, $D_2$ was the average diameter of pine needles at the lower tip, and $l$ was the average length. Thus, the total surface area of pine needles was calculated by multiplying the number of pine needles by the average surface area of pine needles.

The leaves of broad-leaved trees were scanned by an image scanner (Canon LIDE 110, Canon, Tokyo, Japan), and the images were converted into pictures that appeared black with a white background. The black area was obtained using Adobe Photoshop CS2 software and indicated the leaf surface area of these broad-leaved trees.

## Measurement of the amount of PM captured per unit leaf area

The principle of wind erosion was applied in the present study, with the PM on the leaves blown off and mixed to form aerosols again (Zhang et al. 2015b; Zhang et al. 2017) (Fig. 1). For each tree species, this process was repeated three times. The ability to capture PM was measured in a wind tunnel (size: 1 × 0.5 × 0.5 m) (Zhang et al. 2017; Zhang et al. 2018). The leaves were laid flat uniformly to ensure that most of the air stream could pass through them. The total length of the wind tunnel occupied by branches was 1 m. The experiment was implemented at a wind speed of 20 m $s^{-1}$, to ensure that the PM from each leaf could be resuspended to form an aerosol within the wind tunnel. The wind tunnel used filtered laboratory air. The aerosol concentration was fairly constant (< 1 μg $m^{-3}$) in the laboratory space of around 10 $m^3$. First, sampled leaves were placed in the wind tunnel; then, pure air without PM was introduced into the wind tunnel through a plenum with several openings. Second, a fan operating at a wind speed of 20 m $s^{-1}$ was used to blow air across the leaves in the tunnel. This process continued for about 6–10 min, to ensure that all of the PM on the leaf surface was suspended in the tunnel space. It has been confirmed that a wind speed of 20 m $s^{-1}$ and a duration of 6–10 min can remove > 80% of the PM deposited on leaves (Fang et al. 2015). Finally, a portable environmental dust detector (Dustmate, Turnkey, UK) was used to measure the total suspended particulate (TSP), $PM_{10}$, $PM_{2.5}$, and $PM_1$ concentrations of the tunnel space. Equation (2) was used to calculate the amount of PM per unit leaf area of different tree species (Wang et al. 2015):

$$M_{\mathrm{i}} = \sum_1^n m_{\mathrm{ij}}/S_{\mathrm{i}} \quad (2)$$

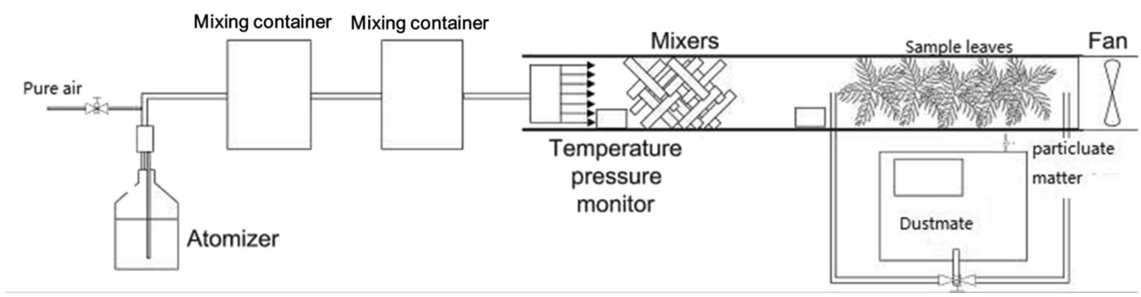


**Fig. 1** A sketch of the wind tunnel experimental setup (Zhang et al. 2015b; Zhang et al. 2017)

where $M$ represents the amount of captured PM per unit leaf area of the different tree species (g cm$^{-2}$), i represents the tree species, j represents the PM size, $n = 3$ replicates, and $m_{ij}$ represents the mass of the TSP, $PM_{10}$, $PM_{2.5}$, and $PM_1$ on leaves measured (μg), $S$ represents the leaf area (cm$^2$).

### Leaf microstructure observation

Fresh leaves were cut into 4 × 4-mm pieces from the middle of the leaves to avoid the veins, which were then fixed in 2.5% (volume fraction) glutaraldehyde solution. For dewatering, ethanol was then added in stages. After the leaf samples were sprayed with a conductive coating, the surface microstructure of the leaves was observed and analyzed by scanning electron microscopy (SEM) (S-3400, Hitachi, Tokyo, Japan), and images were taken at 300× magnification to observe the leaf surface microstructure.

### Determination of leaf surface roughness

Moisture was carefully removed from the leaf surfaces with absorbent paper, and then, the leaves were cut into 5 × 5-mm sections. At normal temperature, the leaf samples were scanned using an atomic force microscope (AFM) (Multimode 8, Bruker, Karlsruhe, Germany), with a maximum scanning range of 100 × 100 μm. All AFM images were obtained in the height mode and were not processed in any way. The sampled leaf surfaces were analyzed using NanoScope Analysis software (NanoScope Analysis 1.4, Bruker), which can obtain a three-dimensional structural image of the tested leaf surface and can determine leaf surface roughness, including the root mean square roughness ($R_q$), arithmetic mean deviation of the profile ($R_a$), and ten-point height of irregularities ($R_z$). The $R_q$ value was used to characterize the roughness of the leaf surface in this study.

### Data processing and analysis

The length of the guard cells, stomatal length and density, and trichome length and density were statistically analyzed in three random 300× leaf surface microstructure images. The stomatal index was calculated using Equation (3) (Brewer and Nun˜ez 2007). The stomatal length of *P. tomentosa* and *P. tabuliformis* were the guard cell length, while the stomatal length of *P. tabuliformis* was the longest diameter length.

$$S_I = S_D \times L_g \tag{3}$$

where $S_I$ is the stomatal index (mm$^{-1}$), $S_D$ is the stomatal density (n mm$^{-2}$), and $L_g$ is the guard cell length (mm).

Two-factor analysis of variance was applied to analyze leaf age and tree species on the particles capture capacity of leaves, as well as pollution intensity and tree species. The experimental data were processed and analyzed by Sigmastat 3.5 software, and the graph was drawn by Sigmaplot 10.0 software (Systat Software Inc. (SSI), San Jose, CA, USA).

## Results

### The ability of leaf surfaces to capture PM

#### Differences in the ability of leaf surfaces to capture PM at different leaf ages

The ability of old leaves to capture TSP, $PM_{10}$, $PM_{2.5}$, and $PM_1$ for the three evergreen trees (*P. orientalis*, *P. tabuliformis*, and *T. cuspidata* var.) was greater than that for new leaves (Fig. 2). With an increase in leaf age, the ability to capture PM of all sizes increased. Moreover, there were extremely significant differences between the capture capacity of different particle sizes for new leaves and old leaves (Fig. 2). When the leaves were new, the amount of TSP and $PM_{10}$ captured was highest in *P. orientalis*, followed by *T. cuspidata* var. and *P. tabuliformis*. The amount of $PM_{2.5}$ and $PM_1$ captured was highest in *T. cuspidata* var., followed by *P. orientalis*, and *P. tabuliformis*. When the leaves were old, the amount of TSP captured by leaves was highest in *T. cuspidata* var., followed by *P. orientalis* and *P. tabuliformis*. The amount of $PM_{10}$ captured was the same for all three tree species, although $PM_{2.5}$ and $PM_1$ had different capture dynamics. Among these four particle sizes, except $PM_{10}$, there were highly significant differences in particle capture capacity between different tree species (Fig. 2). The increase in the amount of TSP and PM of different sizes

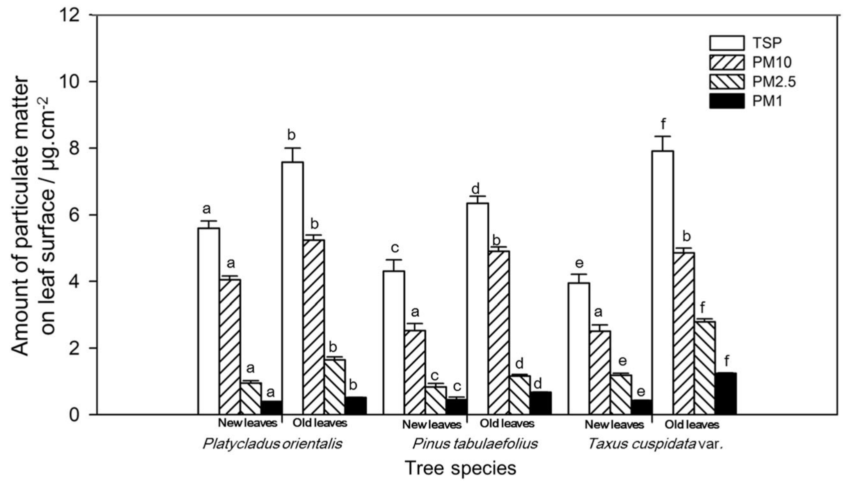


**Fig. 2** Particulate matters captured by leaves for different ages. Note: Different letters indicate significant differences between the treatments ($p < 0.05$)

captured by the different tree species varied with leaf age. This may be related to differences in leaf microstructure and roughness between tree species and changes in leaf microstructure with leaf age.

## Differences in the ability of leaf surfaces to capture PM in clean and heavily polluted areas

The amount of TSP and $PM_{10}$ captured by five tree species (*P. orientalis*, *S. japonica*, *P. tomentosa*, *P. tabuliformis*, and *G. biloba*) was higher in the heavily polluted area than in the clean area (Fig. 3). The amount of $PM_{2.5}$ and $PM_1$ captured by *P. orientalis*, *P. tabuliformis*, and *G. biloba* was higher in the heavily polluted area than in the clean area; however, the amounts captured by *S. japonica* and *P. tomentosa* were higher in the clean area than in the heavily polluted area. The particle retention capacity of different size classes, in addition to being affected by the PM concentration in the air, was also dependent on the influence of changes in the microstructure of leaves under different particle concentrations. Pollution intensity extremely significantly affected the capture capacity of TSP, $PM_{10}$, and $PM_{2.5}$ on leaves, as well as significantly affected the capture capacity of $PM_1$ (Fig. 3).

For different tree species, the amount of TSP and $PM_{10}$ captured in the clean area from high to low was *P. orientalis*, *P. tabuliformis*, *P. tomentosa*, *G. biloba*, and *S. japonica*, while the amounts of $PM_{2.5}$ and $PM_1$ captured were not consistent with this pattern (Fig. 3). The amount of TSP captured in the heavily polluted area followed the order of *P. orientalis* > *P. tabuliformis* > *P. tomentosa* > *S. japonica* > *G. biloba*, while the amount of $PM_{10}$ captured followed the order of *P. orientalis* > *P. tabuliformis* > *P. tomentosa* > *G. biloba* > *S. japonica.* There was highly significant difference in their particle capture capacity (Fig. 3).

## Changes in leaf surface microstructure in response to leaf age and pollution level

The SEM images showed that the adaxial surface of both the new and old leaves of *T. cuspidata* var. were smooth, with no prominent lines (Figs. 4a–d and 5). The abaxial surface was uneven, with nearly circular open stomata and irregular convex epidermal cells, although the surface structure of both old and new leaves was similar. Only a small number of particles were distributed on the adaxial and abaxial surfaces of the new leaves, while a large number of particles covered the surface of the old leaves. The particles were distributed in the grooves between the convex cells and stomata, especially on the adaxial surface. The 5-μm two-dimensional and three-dimensional AFM images showed that the adaxial and abaxial surfaces of

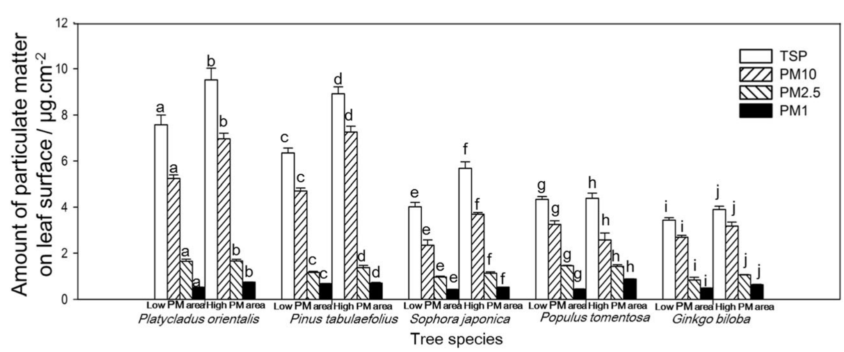


**Fig. 3** Particulate matters captured by leaves for different pollution level. Note: Low PM area was Beijing botanical Garden, and high PM area was Chaoyang Park. Different letters indicate significant differences between the treatments ($p < 0.05$)

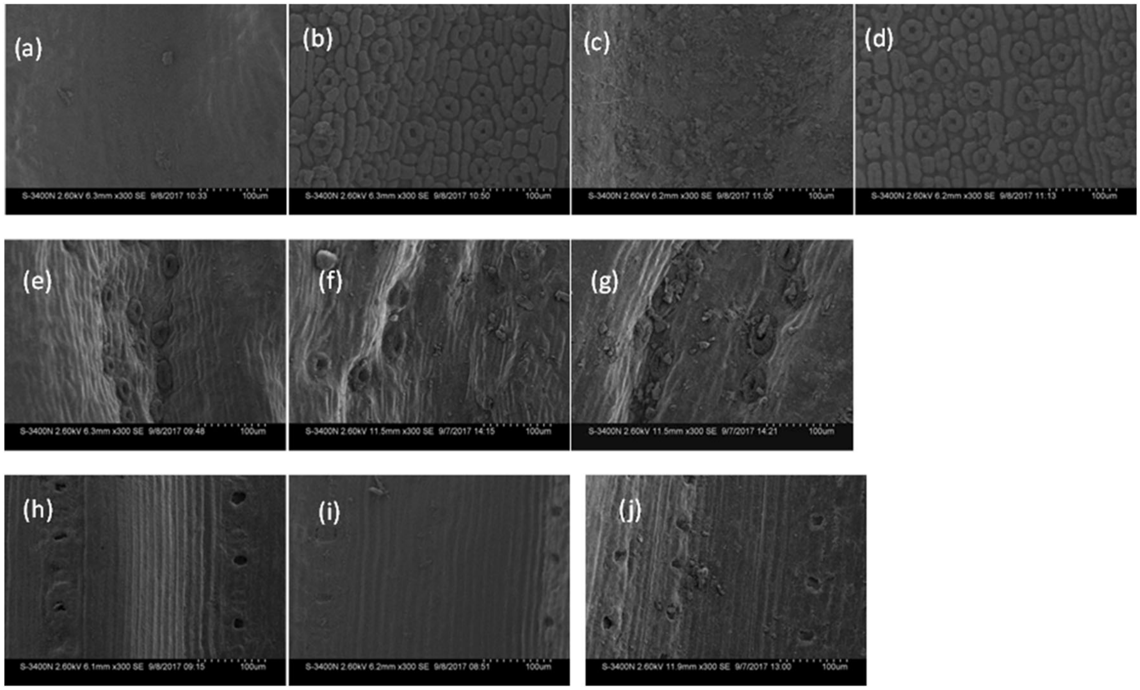


**Fig. 4** Leaf surface micrographs for evergreen tree species based on scanning electron micrographs. *Taxus cuspidata* var., new leaf **a** adaxial surface, **b** abaxial surface; old leaf, **c** adaxial surface; **d** abaxial surface. *Platycladus orientalis*, **e** new leaf in Beijing botanical garden, **f** old leaf in Beijing botanical garden, **g** old leaf in Chaoyang Park. *Pinus tabuliformis*, **h** new leaf in Beijing botanical garden, **i** old leaf in Beijing botanical garden, **j** old leaf in Chaoyang Park

the new leaves consisted of small convex grains, with tiny nanoparticles positioned on the abaxial surface. The surface of old leaves was more complex than that of new leaves, with uneven peaks and valleys. The $R_q$ values of the adaxial and abaxial surfaces of the new and old leaves were 98.7, 4.46, 297, and 290 nm, respectively (Fig. 6). As the leaf age increased, the roughness of the adaxial and abaxial surfaces gradually became similar.

The texture of the new leaves of *P. orientalis* and *P. tabuliformis* was clearly different to that of the old leaves (Figs. 4e–j and 5). The stomata of *P. orientalis* were elliptic and open, but were unevenly distributed. The stomata of *P. tabulaeformis* were regularly distributed and open. There were very few particles on the surface of new leaves of *P. orientalis* and *P. tabuliformis*. The texture of the old leaves of both species was not as smooth as that of the new leaves. There was PM distributed in the grooves, and the amount of PM on leaf surfaces in the heavily polluted area was clearly greater than in the clean area. Stomatal apertures in the heavily polluted area were smaller than those in the clean area. Particulate matter occluded some of the stomata. The wax layer on the leaf surface of *P. orientalis* and *P. tabuliformis* in the heavily polluted area was damaged due to the exposure

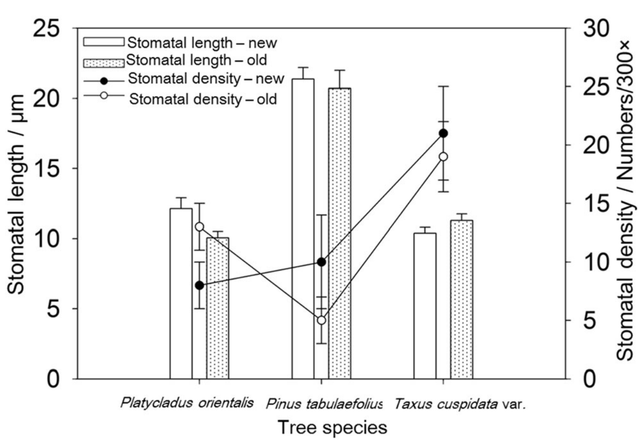


**Fig. 5** Stomatal length and density on leaf surface for different ages based on scanning electron micrographs

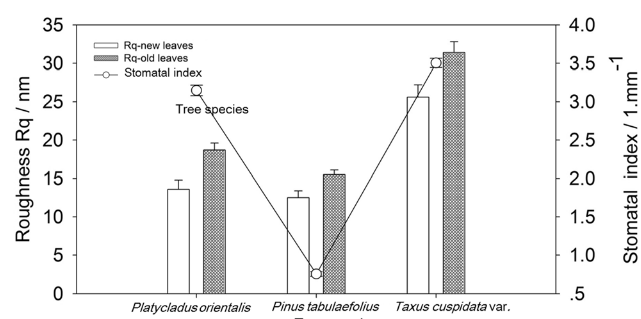


**Fig. 6** The roughness $R_q$ and stomatal index on leaf surface for different ages based on atomic force microscope

to more serious levels of pollution. The AFM diagram showed that the $R_q$ values of the leaves of the two species did not increase significantly with the increase in leaf age (Fig. 6). However, the roughness of the leaves in the heavily polluted area was significantly greater than in the clean area (Fig. 9).

Compared with the clean area, the trichomes on the adaxial and abaxial surfaces of the leaves of *S. japonica* in the heavily polluted area were thinner, longer, and harder (Figs. 7a–d and 8). In the clean area, they were prostrate on the leaf surface, but they were erect in the heavily polluted area. The cuticular wax in the heavily polluted area was severely damaged. In addition, the structure changed from a regular to irregular arrangement of convex cells. More particles were distributed on the surface of leaves in the heavily polluted area, with particles on the abaxial surface mainly distributed on leaf ridges and in areas with a large density of trichomes. The stomatal apertures were small in the heavily polluted area. AFM images showed that the adaxial surface of leaves had similar peaks and valleys in the heavily polluted and clean areas, and the measured $R_q$ value was also similar in both areas (Fig. 9). On the abaxial surface, the $R_q$ values in the heavily polluted area were much higher than in the clean area.

In the heavily polluted and clean areas, the adaxial surface of *P. tomentosa* leaves had a smooth cuticle, the grain was shallow, and there was a larger coverage of particles (Figs. 7e–h and 8). The distribution of stomata on the abaxial surface of leaves was dense, the stomatal guard cells had irregular rough edges, and the particles were mainly distributed around the stomata and leaf ridges. The wax layer of the adaxial surface of the leaves from both study sites was damaged to a certain extent. In the clean area, it was more damaged than in the heavily polluted area. The wax layer on the abaxial surface of the leaves in the heavily polluted area was damaged, while in the clean area, it was well preserved. The roughness of the adaxial surface of leaves in the clean and heavily polluted areas was similar, while the abaxial surface of the leaves in the heavily polluted area was more uneven and had greater roughness (Fig. 9).

On the adaxial surface, the *G. biloba* leaves had a clear grain and groove structure (Figs. 7i–l and 8). Particles were adhered to the grooves. The wax layer in the heavily polluted area had been damaged. The leaf stomatal guard cells and epidermis on the abaxial surface consisted of regular convex cells. In the heavily polluted area, the convex stomatal guard cells on the abaxial surface were more degenerated than in the clean area. The convex cells on the leaf surface were also irregular gully structures. The number of particles attached to the abaxial surface of the leaf was significantly less than on the adaxial surface. There were more particles on the adaxial and abaxial surfaces of *G. biloba* leaves in the heavily polluted area than in the clean area. The roughness of the adaxial and abaxial surfaces of *G. biloba* leaves in the heavily polluted and clean areas was similar (Fig. 9).

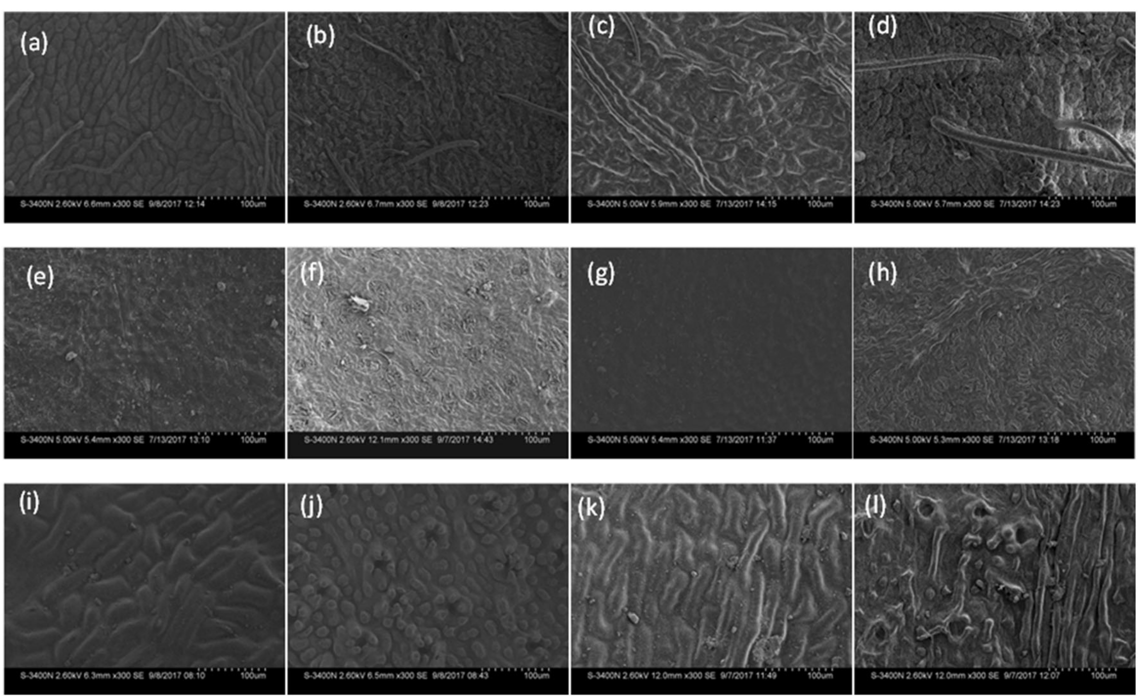


**Fig. 7** Leaf surface micrographs for deciduous tree species based on scanning electron micrographs. *Sophora japonica*, in Beijing botanical garden **a** adaxial surface, **b** abaxial surface; in Chaoyang Park, **c** adaxial surface, **d** abaxial surface. *Populus tomentosa*, in Beijing botanical garden **e** adaxial surface, **f** abaxial surface; in Chaoyang Park, **g** adaxial surface, **h** abaxial surface. *Ginkgo biloba*, in Beijing botanical garden **i** adaxial surface, **j** abaxial surface; in Chaoyang Park, **k** adaxial surface, **l** abaxial surface

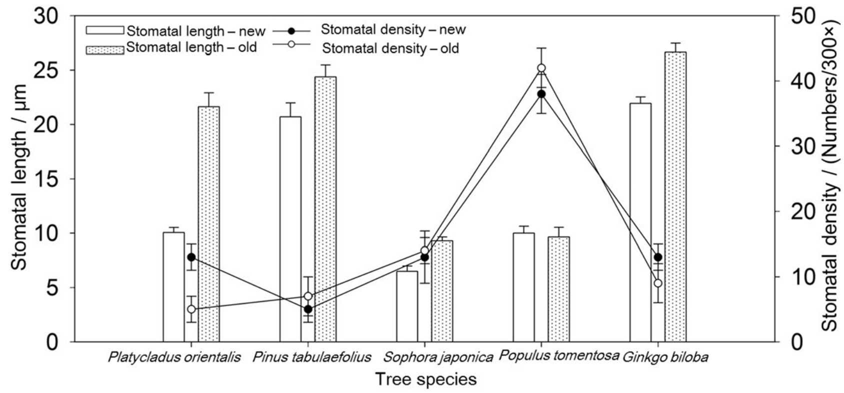


**Fig. 8** The stomatal length and density on leaf surface for different pollution level based on scanning electron micrographs

## Discussion

### The dynamics of the amount of PM captured on leaves

The ability of leaves from different tree species to capture PM varied among the different growth periods. In a previous study, the ability of 2-year-old Norway spruce (*Picea abies*) to capture PM was found to be higher than that of 1-year-old trees (Räsänen et al. 2014), and this has also been reported for stone pine (*Pinus pinea*) (Terzaghi et al. 2013). Many more particles have been reported to be deposited on the adaxial leaf surfaces of various species, including *S. japonica*, in April than in October (Wang et al. 2013). The results of these studies were consistent with the results reported here for TSP, $PM_{10}$, $PM_{2.5}$, and $PM_1$ particles captured by the three evergreen tree species, *P. orientalis*, *P. tabuliformis*, and *T. cuspidata* var., which increased as the leaf age increased.

The ability of leaves to capture PM is related to leaf age, while the pollution level and ability of the leaf surface to capture $PM_{2.5}$ have been shown to be positively correlated (Lu et al. 2018). High concentrations of atmospheric PM resulted in the surface of *Ligustrum compactum* and *Viburnum odoratissinum* leaves becoming saturated with PM after 4–5 days (Wang et al. 2015a). Traffic flows and the distance from a tree to the closest road have been shown to significantly influence the $PM_{2.5}$ retention on the *L. compactum* leaf surface. A significant positive correlation has been reported between leaf $PM_{2.5}$ retention and traffic flow (Wang et al. 2014). For $PM_{10}$ capturing, needle-leaved species showed higher capacity under all traffic pressures except under the low traffic pressure. For $PM_{2.5}$ capturing, needle-leaved species accumulated more PM only under the high traffic pressure (He et al. 2020a). In the present study, the amounts of TSP and $PM_{10}$ captured by five tree species (*P. orientalis*, *P. tabuliformis*, *S. japonica*, *P. tomentosa*, and *G. biloba*) were higher in the heavily polluted area than in the clean area. The amounts of $PM_{2.5}$ and $PM_1$ captured by *P. orientalis*, *P. tabuliformis*, and *G. biloba* were higher in the heavily polluted area than in the clean area. This may be due to the differing retention capacity of particles with different sizes, which in addition to being affected by the concentration of PM in the air, is also dependent on the influence of changes in the microstructure of leaves at different particle concentrations. The greatest accumulation of air pollutants occurred on the foliage of plants protected from the rain at a site exposed to traffic-related pollution and the smallest accumulation at a rural site (Przybysz et al. 2014).

Contrasts between evergreen and deciduous tree species have been reported with regard to leaf PM accumulation. Freer-Smith et al. (2004) observed that the leaf PM captured by the needles of evergreen species was greater than that captured by the leaves of deciduous species, which was also reported by Moreno et al. (2003). He et al. (2020b) highlights

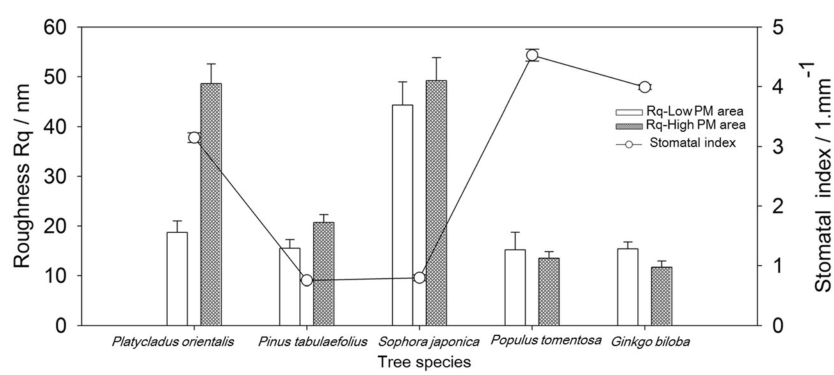


**Fig. 9** The roughness $R_q$ and stomatal index on leaf surface for different pollution level based on atomic force microscope

the importance of evergreen roadside plants for PM pollution management during winter. One-year-old needles of *Cedrus deodara* did not have a greater ability to accumulate PM than the leaves of the deciduous species *S. japonica* and *Platanus acerifolia* during their lifespan. However, because atmospheric PM removal occurs principally during the in-leaf period, evergreen species that grow throughout the year could contribute more to PM removal than deciduous species, with the difference being particularly pronounced in winter (Wang et al. 2013). In our study, it was found that the amount of PM captured by mature leaves of *P. tomentosa* in the clean area was higher than that of 1-year-old *T. cuspidata* var. and *P. tabuliformis*, and the amount of PM on mature leaves of *G. biloba* was also higher than that on 1-year-old *P. tabuliformis*. Therefore, the influence of leaf age cannot be ignored when evaluating the ability of evergreen leaves to capture PM.

## Effect of the microstructure changes of leaves on the amount of PM captured

There exist functional adaptations of plant surface structures to environmental conditions (Koch et al. 2009). Differences in leaf surface characteristics and roughness are important determinants of the ability of plants to capture PM (Lu et al. 2018). The roughness on the leaf surface is determined by morphological parameters, such as cuticular ornamentations, raised epidermal cell boundaries, stomatal ledges, trichomes, and epicuticular and cuticular waxes (Pal et al. 2002; Nairn et al. 2011). With an increase in leaf age, the $R_q$ values of *T. cuspidata* var., *P. orientalis*, and *P. tabuliformis* increased. The number of particles on the leaf surface in the scanned images of leaves and the measured amounts of fine PM on the leaves both displayed an increasing trend. The contact angles of water droplets on leaves decrease with leaf age (Wang et al. 2013), and the ability to capture PM increases with the decreased leaf contact angle. The increase in wettability, which is probably caused when epicuticular wax was destroyed by mechanical and chemical abrasion, seems to be the main factor leading to seasonal variations in leaf PM accumulation (Wang et al. 2013).

In the three coniferous tree species, compared with the new leaves, the old leaves of *T. cuspidata* var. displayed the most obvious increase in the amount of particles captured, with the increase in the amount of PM captured by the leaves of *T. cuspidata* var. being higher than that captured by *P. orientalis* and *P. tabuliformis*. Some large particles on the leaf surface were easily removed under the action of external forces, such as rainfall and wind. The higher $R_q$ values and stomatal index on the leaf surface of *T. cuspidata* var. could increase the strength of attachment of PM and prevent them from being removed by external forces. In addition, the wax layer on the adaxial surface of the old leaves of *T. cuspidata* var. was more damaged than that of the new leaves. Due to the increase in wettability of the damaged leaf wax layer, the amount of particulate captured on the adaxial surface of the old leaves increased significantly. With an increase in leaf age, the roughness of the abaxial surface also increased. The roughness of the adaxial and abaxial surfaces gradually became similar, which also improved the ability of leaves to capture particles.

In addition to the variation of the microstructure of the leaf surface with the growth of leaves, the influence of leaf age on the surface microstructure of leaves is also important because old leaves are affected by pollutants for a longer time than new leaves. Environmental pollution will change the structure and properties of leaf surface, and thus alter their ability to capture PM. Compared with clean areas, the changes to the leaf surface microstructure in heavily polluted areas have been reported to result in a decrease of the stomatal index (Pourkhabbaz et al. 2010), occlusion of stomata, degradation of the leaf wax layer (Rai et al. 2009), and the coverage of the leaf surface with more particles (Zhang et al. 2015a). The surface texture of leaves of *S. japonica* and *G. biloba* has been reported to become irregular, and the boundaries of the epidermal cells also become more irregular (Pal et al. 2002; Zhang et al. 2015a). Additionally, the trichomes on the leaf surface become thinner (Rai et al. 2009; Zhang et al. 2015a), longer (Pal et al. 2002; Zhang et al. 2015a), and harder. The results of the present study were different from those of Zhang et al. (2015a). More samples will be taken in future studies to determine the reasons for these variations. Most of the results in our study were consistent with the results of the particle spray experiments reported by Rai et al. (2009). It was also found that seedling leaves sprayed with PM had smaller epidermal cells and stomata (Rai et al. 2009), the leaf structure exposed to the polluted environment changed significantly, and the number of stomata doubled with the contraction of epidermal cells (Pal et al. 2002). The results of leaf studies involving both PM spraying and exposure to polluted environments confirmed that pollutants also had a great impact on the leaf surface microstructure. The $R_q$ values were generally higher in the heavily polluted area than in clean area, and the roughness of the abaxial surface increased more obviously than that of the adaxial surface. The main reason for this was that the stomata are mainly distributed on the abaxial surface of the leaf. On the abaxial surface of the leaves of *P. tomentosa* and *G. biloba*, compared with the clean area, the number, shape, size, and aperture of stomata of leaves in the heavily polluted area changed greatly. Haines et al. (1985) found that the higher the wettability of the leaf surface, the more vulnerable the epicuticular wax layer is to environmental factors and air pollution, in particular. Mechanical damage and chemical corrosion of the adaxial surface have been reported to be more obvious than those of the abaxial surface (Burkhardt et al. 1995).

Compared with the amounts of TSP and $PM_{10}$ on leaf surfaces in the clean area, the amounts on the leaves of each tree species in the heavily polluted area were higher. In the heavily polluted area, with its higher PM concentration, changes in leaf microstructure were observed. This resulted in an increase in leaf surface roughness, and with the increase of roughness, the amount of PM captured on the leaf surface increased. Therefore, after the leaves were dusted and their growth and physiological characteristics were seriously affected, but the morphological adaptability of leaves surface microstructure could enhance their ability to capture particles to a certain extent. However, the relationship between fine PM ($PM_{2.5}$ and $PM_1$) and leaf surface roughness is complex, mainly because the retention of fine particles depends more on the adhesion conditions of the particles, such as stomatal density, stomatal aperture, groove width, trichomes, epidermal cell contour, and leaf wax layer. Especially, leaves with groove seem that there was sufficient room on the leaf to capture PM (He et al. 2020b). Moreover, another important reason was that the fine particles are usually further transported from their long distance emission source.

Leaf traits including leaf form, leaf shape, leaf surface area, leaf surface hydrophilicity, and leaf surface characteristics all have notable effects on the PM capturing capacity of the roadside plant species (He et al. 2020c) Among the different tree species, the amounts of TSP and $PM_{10}$ captured in the clean area followed the order of *P. orientalis* > *P. tabuliformis* > *P. tomentosa* > *G. biloba* > *S. japonica*. The amount of TSP captured in the heavily polluted areas varied from high to low in the order of *P. orientalis*, *P. tabuliformis*, *P. tomentosa*, *S. japonica*, and *G. biloba*, while for $PM_{10}$, the amount captured varied from high to low in the order of *P. orientalis*, *P. tabuliformis*, *P. tomentosa*, *G. biloba*, and *S. japonica*. The main reason for this was that the $R_q$ values of the leaves of *S. japonica* in the heavily polluted area were much higher than in the clean area, while there was little variation in the roughness of *G. biloba* leaves between the heavily polluted and clean areas. The scanned images of leaves showed that the contours of epidermal cells on the adaxial surface of *G. biloba* leaves became unclear, the stomatal guard cells on the abaxial surface became irregular, and the epidermal convex cells degenerated. The leaf roughness of *P. tomentosa* did not vary much between the heavily polluted and clean areas, but the irregular stomatal guard cells and leaf ridges of *P. tomentosa* were more beneficial to the retention of PM. Therefore, due to the high concentration of atmospheric PM in the heavily polluted area, the amount of PM on the leaf surfaces was higher than in the clean area. However, the amounts of $PM_{2.5}$ and $PM_1$ captured were not of the same order, which was similar to the results of Zhang et al. (2015a), mainly due to more complex factors affecting the adhesion conditions of fine particles such as $PM_{2.5}$ and $PM_1$. Needle-leaved plants were more sensitive to the change of traffic pressures, its PM capturing capacity changed notably between different traffic pressures because its leaf wax is more susceptible to be corroded. Leaf surface contact angle was slightly affected by the change of traffic pressure for broad-leaved species, but for needle-leaved species, it changed greatly (He et al. 2020a). Therefore, further studies are still required to fully explain how leaves capture fine particles and what factors play a major role in the process.

## Conclusions

The increase of roughness $R_q$ value of the old leaves of *P. orientalis*, *P. tabuliformis*, and *T. cuspidata* var. were the main reason that led to the increase of the particle capture capacity on leaves. The particle capture of mature leaves of *P. tomentosa* was higher than that of *T. cuspidata* var. and *P. tabuliformis*. The mature leaves of *G. biloba* were higher than the new leaves of *P. tabuliformis*. When comparing the particle capture capacity of evergreen and deciduous species, the influence of old and new evergreen needle leaves should not be ignored. Compared with the relatively clean area, in the heavily polluted area, the stomatal index of leaves was reduced, the waxy layer was degraded, the surface texture and cell boundary were more irregular, and the trichomes were longer and harder. These changes in the microstructure of the leaves surface made the roughness $R_q$ value of the heavily polluted area higher than that of the relatively clean area. Moreover, the increase of the abaxial surface of the leaves was more obvious than that of the adaxial surface; therefore, the capture capacity of particulate matter on leaves was significantly enhanced in heavily polluted areas. After leaves were dusty, before leaf growth and physiological characteristics were seriously affected, the morphological adaptability of the surface microstructure could enhance their particle capture capacity to some extent.

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## References

Andrade MF, Kumar P, de Freitas ED, Ynoue RY, Martins J, Martins LD, Nogueira T, Perez-Martinez P, de Miranda RM, Albuquerque T, Gonçalves FLT, Oyama B, Zhang Y (2017) Air quality in the megacity of São Paulo: evolution over the last 30 years and future perspectives. Atmos Environ 159:66–82

Brewer CA, Nuñez CI (2007) Patterns of leaf wettability along an extreme moisture gradient in Western Patagonia, Argentina. Int J Plant Sci 168:555–562

Burkhardt J, Peters K, Crossley A (1995) The presence of structural surface waxes on coniferous needles affects the pattern of dry deposition of fine particles. J Exp Bot 46:823–831

Cao C, Jiang W, Wang B, Fang J, Lang J, Tian G, Jiang J, Zhu TF (2014) Inhalable microorganisms in Beijing's PM2.5 and PM10 pollutants during a severe smog event. Environ Sci Technol 48:1499–1507

Conway TM, Almas AD, Coore D (2019) Ecosystem services, ecological integrity, and native species planting: how to balance these ideas in urban forest management? Urban For Urban Gree 41:1–5

Dawson J, Adams P, Pandis S (2007) Sensitivity of PM2.5 to climate in the Eastern US: a modeling case study. Atmos Chem Phys 7(16): 4295–4309

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

Fang YY, Wang B, Niu X (2015) Effects of surface roughness on leaf particulate matter capture capability and rain wash-off characteristics. J Soil Water Conserv 29:110–115

Freer-Smith PH, El-Khatib AA, Taylor G (2004) Capture of particulate pollution by trees: a comparison of species typical of semi-arid areas (*Ficus nitida* and *Eucalyptus globulus*) with European and North American species. Water Air Soil Pollut 155:173–187

Guerreiro CBB, Foltescu V, de Leeuw F (2014) Air quality status and trends in Europe. Atmos Environ 98:376–384

Haines BL, Jernstedt JA, Neufeld HS (1985) Direct foliar effects of simulated acid rain II. Leaf surface characteristics. New Phytol 99:407–416

He C, Qiu KY, Pott R (2020a) Reduction of traffic-related particulate matter by roadside plants: effect of traffic pressure and sampling height. Int J Phytoremediat 22(2):184–200

He C, Qiu KY, Alahmad A (2020b) Particulate matter capturing capacity of roadside evergreen vegetation during the winter season. Urban For Urban Green 48:126510

He C, Qiu KY, Pott R (2020c) Reduction of urban traffic-related particulate matter-leaf trait matters. Environ Sci Pollut Res 27:5825–5844

Hu ZZ, Tang XG, Zheng C, Guan ML, Shen JW (2018) Spatial and temporal analyses of air pollutants and meteorological driving forces in Beijing–Tianjin–Hebei region, China. Environ Earth Sci 77:1–19

Hwang HJ, Yook SJ, Ahn KH (2011) Experimental investigation of submicron and ultrafine soot particle removal by tree leaves. Atmos Environ 45:6987–6994

Koch K, Bhushan B, Barthlott W (2009) Multifunctional surface structures of plants: an inspiration for biomimetics. Prog Mater Sci 54(2): 137–178

Lu SW, Yang XB, Li SN, Chen B, Jiang Y, Wang D, Xu L (2018) Effects of plant leaf surface and different pollution levels on PM2.5 adsorption capacity. Urban For Urban Gree 34:64–70

McDonald AG, Bealey WJ, Fowler D, Dragosits U, Skiba U, Smith RI, Donovan RG, Brett HE, Hewitt CN, Nemitz E (2007) Quantifying the effect of urban tree planting on concentrations and depositions of PM10 in two UK conurbations. Atmos Environ 41:8455–8467

Moreno E, Sagnotti L, Dinarès-Turell J, Winkler A, Cascella A (2003) Biomonitoring of traffic air pollution in Rome using magnetic properties of tree leaves. Atmos Environ 37:2967–2977

Nairn JJ, Forster WA, van Leeuwen RM (2011) Quantification of physical (roughness) and chemical (dielectric constant) leaf surface properties relevant to wettability and adhesion. Pest Manag Sci 67:1562–1570

Neinhuis C, Barthlott W (1998) Seasonal changes of leaf surface contamination in beech, oak, and ginkgo in relation to leaf micromorphology and wettability. New Phytol 138:91–98

Nowak DJ, Crane DE, Stevens JC (2006) Air pollution removal by urban trees and shrubs in the United States. Urban For Urban Gree 4:115–123

Nowak DJ, Hirabayashi S, Bodine A, Greenfield E (2014) Tree and forest effects on air quality and human health in the United States. Environ Pollut 193:119–129

Pal A, Kulshreshtha K, Ahmad KJ, Behl HM (2002) Do leaf surface characters play a role in plant resistance to auto-exhaust pollution? Flora - Morphol Dis Funct Ecol Plants 197:47–55

Pourkhabbaz A, Rastin N, Olbrich A, Langenfeld-Heyser R, Polle A (2010) Influence of environmental pollution on leaf properties of urban plane trees, Platanus orientalis L. Bull Environ Contam Toxicol 85:251–255

Prusty BA, Mishra PC, Azeez PA (2005) Dust accumulation and leaf pigment content in vegetation near the national highway at Sambalpur, Orissa, India. Ecotox Environ Safe 60(2):228–235

Przybysz A, Sæbø A, Hanslinb HM, Gawroński SW (2014) Accumulation of particulate matter and trace elements on vegetation as affected by pollution level, rainfall and the passage of time. Sci Total Environ 481:360–369

Rai A, Kulshreshtha K, Srivastava PK, Mohanty CS (2009) Leaf surface structure alterations due to particulate pollution in some common plants. Environmentalist 30:18–23

Räsänen JV, Holopainen T, Joutsensaari J, Pasanen P, Kivimäenpää M (2014) Particle capture efficiency of different-aged needles of Norway spruce under moderate and severe drought. Can J For Res 44:831–835

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

Shi PJ, Bai XM, Kong F, Fang JY, Gong DY, Zhou T, Guo Y, Liu YS, Dong WJ, Wei ZA, He CY, Yu D, Wang JA, Ye Q, Yu RC, Chen DL (2017) Urbanization and air quality as major drivers of altered spatiotemporal patterns of heavy rainfall in China. Landsc Ecol 32: 1723–1738

Tallis M, Taylor G, Sinnett D, Freer-Smith P (2011) Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments. Landsc Urban Plan 103:129–138

Terzaghi E, Wild E, Zacchello G, Cerabolini BEL, Jones KC, Di Guardo A (2013) Forest filter effect: role of leaves in capturing/releasing air particulate matter and its associated PAHs. Atmos Environ 74:378–384

Thaker P, Gokhale S (2016) The impact of traffic-flow patterns on air quality in urban street canyons. Environ Pollut 208:161–169

Wan JM, Lin M, Chan CY, Zhang ZS, Engling G, Wang XM, Chan IN, Li SY (2011) Change of air quality and its impact on atmospheric visibility in central-western Pearl River Delta. Environ Monit Assess 172:339–351

Wang HX, Shi H, Li YY, Yu Y, Zhang J (2013) Seasonal variations in leaf capturing of particulate matter, surface wettability and micromorphology in urban tree species. Fron Environ Sci Eng 7:579–588

Wang HX, Shi H, Wang YH, Yu Y (2014) PM2.5 removal by plant leaves: taking Ligustrum lucidum as an example. Ecol Sci 33:749–753

Wang HX, Shi H, Wang YH (2015a) Dynamics of the captured quantity of particulate matter by plant leaves under typical weather conditions. Acta Ecol Sin 35:1696–1705

Wang ZS, Li YT, Chen T, Zhang DW, Sun F, Pan LB (2015b) Spatial-temporal characteristics of PM2.5 in Beijing in 2013. Acta Geogra Sinica 70:110–120

Wang B, Niu X, Jiang YX, Wang XS, Wang D, Song QF, Lu SW, Zhou M, Ding FJ, You WZ, Li HJ, Li SN, Wei JS, Wei WJ, Liu ZY (2016) Methodology for field long-term observation of forest ecosystem(GB/T33027–2016). Standard Press, Beijing

Wang B, Niu X, Jiang YX, Guo QS, Liu SR, Yang FW, Song QF (2017) Indicators system for long-term observation of forest ecosystem (GB/T35377–2017). Standard Press, Beijing

Yan S, Cao H, Chen Y, Wu C, Hong T, Fan H (2016) Spatial and temporal characteristics of air quality and air pollutants in 2013 in Beijing. Environ Sci Pollut Res Int 23:13996–14007

Zhang J, Ouyang ZY, Miao H, Wang XK (2011) Ambient air quality trends and driving factor analysis in Beijing, 1983–2007. J Environ Sci 23:2019–2028

Zhang WK, Wang B, Niu X (2015a) Adsorption capacity of the air particulate matter in different urban landscape plants of Beijing. Environ Sci 36:2381–2388

Zhang WK, Wang B, Niu X (2015b) Study on the adsorption capacities for airborne particulates of landscape plants in different polluted regions in Beijing (China). Int J Environ Res Public Health 12: 9623–9638

Zhang WK, Wang B, Niu X (2017) Relationship between leaf surface characteristics and particle capturing capacities of different tree species in Beijing. Forests 8:92

Zhang WK, Zhang Z, Meng H, Zhang T (2018) How does leaf surface micromorphology of different trees impact their ability to capture particulate matter? Forests 9:681

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