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Particulate matter deposited on leaf of five evergreen species in Beijing, China: Source identification and size distribution

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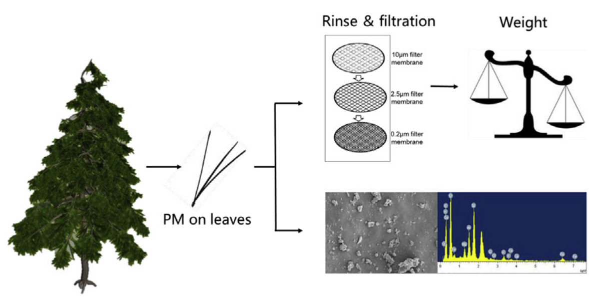
HIGHLIGHTS

- By SEM and EDX, we found PM on leaf surface mainly come from natural source.
- The number density and mass quality of particles per leaf square centimeter were compared between species.
- On leaf scale, the *Juniperus formosana* accumulated most PM for its complex leaf structure.
- For one tree, *Pinus bungeana*, with the most leaf area, was most effective at mitigating airborne PM.

GRAPHICAL ABSTRACT



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ABSTRACT

Airborne particulate matter (PM) has become a serious problem, and urban plants can play important roles in reducing PM concentrations in the air. The morphology, size, and elemental composition of PM on tree leaves (five evergreen species) from Beijing, China, were obtained, together with number density of PM size fraction, by using scanning electron microscopy (SEM) and energy dispersive X-rays (EDX). The rinse and weigh method was used to characterize PM in three size categories (0.2–2.5 μm, 2.5–10 μm, and 10–100 μm). The results showed that PM up to 2 μm can get into the stomatal cavity, and the most furrowed areas of the leaf surfaces were sites of maximum PM deposition. The leaf-deposited PM mainly comprised C, O, Si, and Fe. The number of particles per leaf per cm^2 was 1.95×10^7, and 96% of the particles were less than 2.5 μm. The mass concentration was 148.44 $\mu g/cm^2$, and $PM_{2.5}$ comprised only 2.09% by weight while PM larger than 10 μm comprised 79%. *Juniperus formosana* was most effective at mitigating airborne PM on the leaf scale. *Pinus bungeana* accumulated the most PM on the tree scale. The results showed that urban plants can play important roles in mitigating urban airborne PM.

1. Introduction

Airborne particulate matter (PM) is a serious environmental problem in most cities around the world (Nowak et al., 2006; Shridhar et al., 2010), especially in developing countries (Jim and

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Chen, 2008). Fine PM (with a diameter less than 2.5 μm) poses a great threat to human health in urban areas (Sæbø et al., 2012; Charron and Harrison, 2005; Putaud et al., 2010), which can reach the lungs and alveolar regions (Kampa and Castanas, 2008). Ultrafine PM (with a diameter less than 0.1 μm) can enter the blood stream (Kaiser, 2005; Nemmar et al., 2002). Heavy PM pollution has reduced projected life expectancies by one year (WHO, 2003) to 5.5 years (Chen et al., 2013).

Airborne PM is recognized internationally as a key environmental and health issue, and the potential phytoremediation has received increased attention. Many studies have identified a beneficial impact on PM through increased urban greening (Nowak et al., 2006; Tiwary et al., 2009; Jim and Chen, 2008). Pugh et al. (2012) reported that green walls interacted with the increased residence time of PM in street canyons, producing a PM decrease of up to 60%. Tallis et al. (2011) used the Urban Forest Effects Model and estimated that the urban trees in London deposited 852 to 2121 tons of PM_{10} annually. However, there is controversy regarding urban vegetation increased particulate matter concentrations (Vos et al., 2013; Wania et al., 2012; Gromke and Ruck, 2012).

Based on experimental methods, urban plants appear to act as sinks for PM (McDonald et al., 2007) because plants capture PM on leaf surfaces (Yin et al., 2011) and absorb ultrafine PM (<0.1 μm) (Treshow, 2002) into leaf tissues through their stomata. At the leaf scale, PM deposition on leaf surfaces (accounting for most of the PM capture) occurs by four depositing processes: sedimentation caused by gravity; diffusion derived by Brownian motion; and impaction and interception resulting from turbulent flow (Freer-Smith et al., 2005; Sternberg et al., 2010). Sedimentation principally affects the deposition of large PM (Freer-Smith et al., 2005), impaction and interception affect fine and coarse particle deposition, and Brownian motion leads to the deposition of ultrafine particles. Blade roughness (Dzierżanowski et al., 2011), trichomes (leaf hairs) (Wang et al., 2006), and the thickness of the wax layer may affect the interception and adherence of PM. At the branches scale, plant characteristics determine the efficiency of deposition (Mitchell et al., 2010; Beckett et al., 2000a). Complex leaf structures on the crown of the tree are ideal for absorbing PM because they produce turbulent air movement (Popek et al., 2013; Beckett et al., 2000b; Fowler et al., 1989). At the individual tree scale, the leaf area index (Beckett et al., 2000c), commonly used in modeling studies of leaf PM capture (Vos et al., 2013), a higher leaf area means more PM deposition.

Although many researchers reported that vegetation plays an important role in the deposition of airborne PM, there were few studies on the source identification of PM on leaf surface. Much is known about the mass quality of PM accumulated on the leaf surface, but less is known about the number density of PM on the leaf surface. The number density is another important indicator used to express the volume of PM detention by plants, but was applied only a few times. In our study, we measured the number density and mass quality of fine (0.2–2.5 μm), coarse (2.5–10 μm), and large PM (10–100 μm) on the leaf surface of five evergreen species.

Beijing is the capital of China and has a population of 19.6 million (The Sixth National Population Census, Beijing, 2010). The airborne PM pollution is a serious problem concerned by the public and scientists. Urban plants can effectively reduce airborne PM by capturing particles on the leaf surface, but few studies were conducted in Beijing.

Our aims in this study were to examine the location and the elemental composition of PM deposited on urban leaf surfaces, determine the number density and mass quality of PM in three size fractions, and compare the accumulation of PM deposited on the leaf surface of five typical evergreen species in Beijing.

2. Materials and methods

2.1. Sampling site

All of the test plants were grown on the campus of the research center for eco-environment sciences (RCEES), Chinese Academy of Sciences (40°0′ 28.40″ N, 116°20′ 23.47″ E) Beijing, China. The sampling sites were all located on the campus of the research center with distances less than 100 m, so the PM concentration, temperature, relative humidity, etc., of the different sites were nearly same. There were two motorways south and west of the RCEES (Fig. 1). There were no high polluting factories or power plants within 5 km, and the $PM_{2.5}$ average in 2010 was 95.5 $\mu m/m^3$ (Wang et al., 2012). Plant leaves were collected from five typical evergreen species: *Juniperus formosana*, *P. bungeana*, *Platycladus orientalis*, *Pinus tabulaeformis*, and *Euonymus japonicus*. For each species, we had four individuals as replicates which had good growth conditions, an average size, and no defections. The basic information of the trees used for testing is listed in Table 1. We sampled intact leaves, with no damage from insects and pests, from four directions of each tree at a height of 1.5 m. The samples were cut off with scissors, placed in paper bags, labeled, transported to the laboratory, and kept at an ambient temperature until analysis. We carefully conducted all of these processes and kept the PM deposited on the leaf from falling off. The date of the sampling and the dry periods before the sampling are listed in Table 2. There were at least 30 days with no precipitation before sampling. According to Liu et al. (2013), after 26 days of no rainfall, the plant leaves attained the maximum dust-retaining capabilities. We assumed the quality of PM on the leaf surface had approached the saturated value.

2.2. SEM and EDX analysis

For the needle leaves of *P. bungeana* and *P. tabulaeformis*, two 1 cm long needle sections were cut with scissors from the middle of whole needles. For *J. formosana* and *Platycladus orientalis*, whole leaves were small enough to be mounted intact on the field emission scanning electron microscope stub. For *E. japonicus*, 1 cm^2 were cut from the center of the leaf. The prepared samples were attached to the stub with double-sided adhesive tape. The samples were gold-coated (with a thickness of less than 10 nm) to enhance electrical conductivity before analyzing them using a field emission scanning electron microscope (SEM, Hitachi S4800, Tokyo, Japan), Photographs were taken of randomly chosen spots at 1000× magnification, at 5 kV. Particle counting was performed using Image J software (for more information about this software please see http://rsbweb.nih.gov/ij), according to the method described by Ottelé et al. (2010). Only particles larger than 0.2 μm were counted, as we were limited by the image resolution. The PM composition was investigated by energy dispersive X-ray (EDX) analysis, with lower limits of 0.1 wt%.

2.3. The rinse and weigh method

The methods for rinse and weigh were those described by Dzierżanowski et al. (2011). The PM was rinsed off leaves with distilled water, resulting in the almost complete removal of the leaf-deposited PM (Fig. A.2). The rinse water was filtered using a sieve (bore diameter 100 μm) to remove PM larger than 100 μm. The water was then filtered sequentially, using 10 μm, 3 μm, and 0.2 μm filters (Millipore, USA), capturing large, coarse, and fine PM, respectively. Before and after their use, the filters were dried for 2 h at 60 °C, stabilized over 24 h (20–23 °C, and 30–40% relative humidity), and weighed using a BT25S balance (Sartorius Scientific Instruments Co. Ltd, Germany).