Environmental Pollution 233 (2018) 315–322

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

# A dynamic processes study of PM retention by trees under different wind conditions☆

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ARTICLE INFO

*Article history:*
Received 10 June 2017
Received in revised form
22 September 2017
Accepted 18 October 2017

*Keywords:*
Particulate matter
Air pollution
PM retention processes
Wind tunnel
Leaves

ABSTRACT

Particulate matter (PM) is one of the most serious environmental problems, exacerbating respiratory and vascular illnesses. Plants have the ability to reduce non-point source PM pollution through retention on leaves and branches. Studies of the dynamic processes of PM retention by plants and the mechanisms influencing this process will help to improve the efficiency of urban greening for PM reduction. We examined dynamic processes of PM retention and the major factors influencing PM retention by six trees with different branch structure characteristics in wind tunnel experiments at three different wind speeds. The results showed that the changes of PM numbers retained by plant leaves over time were complex dynamic processes for which maximum values could exceed minimum values by over 10 times. The average value of PM measured in multiple periods and situations can be considered a reliable indicator of the ability of the plant to retain PM. The dynamic processes were similar for $PM_{10}$ and $PM_{2.5}$. They could be clustered into three groups simulated by continually-rising, inverse U-shaped, and U-shaped polynomial functions, respectively. The processes were the synthetic effect of characteristics such as species, wind speed, period of exposure and their interactions. Continually-rising functions always explained PM retention in species with extremely complex branch structure. Inverse U-shaped processes explained PM retention in species with relatively simple branch structure and gentle wind. The U-shaped processes mainly explained PM retention at high wind speeds and in species with a relatively simple crown. These results indicate that using plants with complex crowns in urban greening and decreasing wind speed in plant communities increases the chance of continually-rising or inverse U-shaped relationships, which have a positive effect in reducing PM pollution.



## 1. Introduction

Particulate matter (PM) pollution is one of the most serious environmental problems in many areas of the world (Akiko et al., 2015; Nowak et al., 2013). Similar to the London smog and Los Angeles smog problems, which took nearly half a century to be controlled, many cities in China have been beset by a major smog problem since 2013, especially in winter (Song et al., 2015; Xie et al., 2016). Some PM originates as point source pollution, which always has definite location and continuous pollution, e.g. factory emissions. However, some PM originates as non-point source pollution which always happen suddenly and are one-off pollution events, e.g. passing vehicles, incineration, and building construction. It is more difficult to control non-point pollution sources than point pollution sources, because of their wider range of types, higher frequency, and more uncertain occurrences. In particular, inhalable particles (aerodynamic equivalent diameter ≤10 μm) have a large specific surface area that can easily adsorb other substances such as heavy metals, organic matter, or bacteria. These can subsequently be deposited in the respiratory tract and deep alveoli and cause serious harm to human health (Dockery et al., 2013; Ito et al., 2006; Lippmann, 2012). Consequently, China is faced with the problem of controlling inhalable PM from non-point source pollution.

It has been confirmed by numerous studies that the reduction of PM by plants is an effective method of air purification (Beckett et al., 1998; Janhäll, 2015), especially for non-point source particulate pollution because of its wide distribution. Vegetation reduces PM within the atmosphere through a combination of processes. The

☆ This paper has been recommended for acceptance by Dr. Hageman Kimberly Jill.

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https://doi.org/10.1016/j.envpol.2017.10.073
0269-7491/

two most important of these are PM retention by leaves and branches and PM transfer from plants to the ground by rain or gravity. The retention of PM is the dynamic result of PM capture and resuspension over time. The PM can be captured by rough or hairy branches and leaves or in secretions, and also can be returned to the air by wind. The question of how to improve the efficiency of PM retention by plants is of great importance to improve air purification by vegetation in urban areas.

Related studies have focused on various aspects, e.g. the velocity and amount of particle deposition on different plants (Beckett et al., 2000a,b; Blanusa et al., 2015; Popek et al., 2013; Song et al., 2015); the effect of particle dispersion in different green areas, such as parks and greenbelt (Peachey et al., 2009), urban streets (Gromke et al., 2008; Jin et al., 2014), and rural and urban areas (Beckett et al., 2000a,b; Power et al., 2009); and the source identification and size distribution of particles on leaves (Song et al., 2015).

Earlier studies have also shown that many factors can affect the particle deposition and interception processes by trees (Janhäll, 2015). Those factors can be categorized into two groups: personal factors and external factors. Personal factors include characteristics of tree branches and leaves that are mainly dependent on species, such as canopy morphology, branch and leaf density, leaf angle, leaf surface roughness, amount of tomentum, and exudates (Blanusa et al., 2015; Pullman, 2009; Räsänen et al., 2013). External factors included particle concentration, particle size, temperature, humidity, and wind speed (Beckett et al., 2000a,b; Janhäll, 2015; Jin et al., 2014). In particular, wind speed plays a key role in PM retention by plants, e.g. by changing the form of branches, and promoting resuspension. Moreover, interaction effects between factors on deposition have been identified. The effects of those factors may be unsteady (e.g. fluctuate between positive and negative) under different conditions (Braaten, 1994; Gromke et al., 2008; Pullman, 2009). The level of PM retention by trees is a comprehensive effect of those factors.

Although studies mentioned above have quantified the effectiveness and amount of PM retained by plants and described the influencing factors, these research efforts have been limited by the lack of assessment of the temporal dynamic processes of PM retention by plants. The temporal aspect should be considered to increase insight into removal of atmospheric PM by trees and accurately estimate the potential of urban greenery to reduce PM. Related works have focused on the dynamic processes of PM retention by sward (Giess et al., 1997) and flooring materials (Goldasteh et al., 2013; Qian and Ferro, 2008). However, there are likely to be more complex processes involved in PM retention by trees than by sward and flooring materials because of the more complex and variable structure of branches. The amount of PM retention by trees is consistently unstable, with complex changes occurring during the deposition and dispersion processes as a result of the impact of changeable factors, especially wind conditions (Pullman, 2009).

To identify the most effective plants and improve the benefit of green space in air purification, it is necessary to first establish the relation between PM reduction by trees and temporal dynamic processes. This research aimed to fill this gap in our current knowledge by determining the differences and common factors between PM retention by different plants under different wind conditions and assess the reasons for these variations. We also seek to determine which types of plant and which wind conditions produce positive efficiency in PM retention. In this study, a one-off particle pollution event was simulated, and the temporal dynamic processes of PM on six trees with different characteristics of branch structure and leaf surface were studied in wind tunnel experiments at three different wind speeds. The influencing mechanisms of wind speed, species and exposure time on the PM retention processes were analyzed. Ultimately, these results will improve understanding of PM retention processes by plants and may be applied to guide the practice of urban greening.

## 2. Methods and materials

### 2.1. Species and samples selection

Three species of broad-leaved and three species of coniferous trees were chosen for this study (Table 1): the broad-leaved trees were *Magnolia grandiflora* L. (Lotus Magnolia), *Acer palmatum* Thunb (Japanese Maple), and *Buxus sinica* (Rehder et E. H. Wilson) M. Cheng (Common Boxwood); and the coniferous trees were *Metasequoia glyptostroboides* (Dawn Redwood), *Sabina chinensis* (L.) Ant (Dragon Juniper) and *Cedrus deodara* (Roxb. et Lamb.) G. Don (Cedrus Deodara). These species have been frequently used as greening materials in the Shanghai region. They have significantly different characteristics and represented a range of leaf widths, leaf areas, and branch and leaf densities (leaf numbers and sub-branch numbers). These characteristics represent canopies from simple to complex in structure, which determines the physical reaction of the tree to increasing wind speed.

A total of 342 branch samples of the six species were collected from identified trees in the center of Shanghai Jiao Tong University campus one day after rainfall. For each species, 57 similar tips of branches about 25 cm in length were cut, and then randomly assigned to the control group (9 branches), experimental groups for three different wind speeds (15 branches for each wind speed), and a reserve group (3 branches) which were also used as samples for the measurement of branch characteristics.

The single leaf area, leaf number, and sub-branch number of each sample was measured and recorded before the start of the experiments. A general rule was observed that species with smaller single leaf area always had a bigger number of leaves and sub-branches (Table 1), indicating that the structure of the crown was more complex.

### 2.2. Wind speed settings

Variable wind speed influences ground objects differently; according to the wind scale, there are differences in the effects of varied wind forces on tree branches. In light air (wind speed $< 1.5$ m/s), leaves are always motionless. In light breeze or gentle breeze ($1.6$ m/s $<$ wind speed $< 5.4$ m/s), the leaves would be shaken, while branches stay almost still. In moderate breeze or fresh breeze ($5.5$ m/s $<$ wind speed $< 10.7$ m/s), the branches also would be shaken. Given the influence of wind speed on the branches we set three experimental wind speeds of 1, 3.5 and 8 m/s, which are the medians of the above wind scales.

### 2.3. Measurement of the total leaf area of branches

The total leaf area of branches was used to standardize the PM retained by different branches so that they were comparable. The PM number per leaf area was determined by the total PM number and the total leaf area.

The total leaf area of the branch was determined empirically through a set relationship between fresh weight and surface area determined in preliminary work. Digital leaf images of the reserve branches were analyzed using a scanner, then the amount of leaf surface areas (S) of each branch was calculated using Photoshop CS5 (Adobe, CA, USA). The fresh weight (W) of leaves was measured in g using a Sartorius BS423S balance (Gottingen, Germany) with 0.0001 accuracy. The coefficient (C) of leaf area and fresh weight was obtained by averaging S/W. All the leaf fresh weight ($W_1$) of