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Influence of rainfall duration and intensity on particulate matter removal from plant leaves

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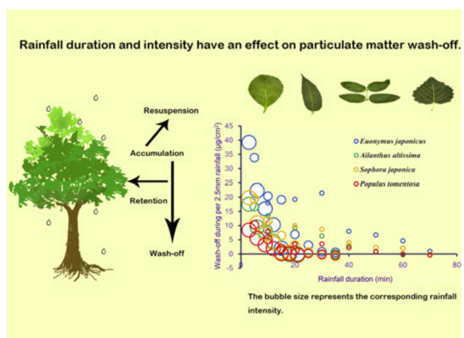
HIGHLIGHTS

- This study investigated wash off of PM accumulated on leaf surfaces.
- Plants with greatest PM accumulation have more PM wash-off and retention masses.
- Cumulative PM wash-off increment rates show exponential decay with rainfall amount.
- Duration of PM wash-off decreases with rainfall intensity increase.
- PM retention depends on rainfall intensity and plant species.

GRAPHICAL ABSTRACT



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ABSTRACT

Rainfall influences removal of airborne particulate matter (PM) from leaf surfaces through a process called wash off resulting in throughfall that carries PM to the ground. The present study examined the effects of rainfall characteristics on PM wash-off mass and rate from the foliage of four broadleaf species, to investigate retention of PM pollution. In a controlled rainfall simulation experiment, rainfall intensity was set to 15, 30, and 50 mm h^{-1}, and sampling intervals for the three rainfall intensities were divided into 10, 5, and 3 min, respectively. Of the plants examined, the evergreen shrub *Euonymus japonicus* had the greatest surface PM accumulation before rainfall (165 μg cm^{-2}), maximum wash-off during the first 2.5 mm of rain (30 μg cm^{-2}), and maximum surface PM retention after rainfall (24 μg cm^{-2}). Fitting observations with the Box Lucas regression model, cumulative PM wash-off rates increased with cumulative rainfall amount, until the curves tended to become steady after rain exceeded 12.5 mm. Wash off removed 51 to 70% of surface PM accumulation. As rainfall intensity increased, the duration of PM wash-off decreased, and wash-off rates were highest during the first rainfall interval. However, there was no significant difference between PM wash-off rates for rainfall intensities of 30 and 50 mm h^{-1} in each rainfall interval. In addition, rain did not remove all PM completely, and PM retention following rainfall differed with rainfall intensity, except for *Populus tomentosa*.

1. Introduction

Air pollution associated with rapid urbanization in recent decades is proving difficult to reduce in many cities around the world. Airborne particulate matter (PM), an important indicator of air pollution, consists

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of particles with aerodynamic diameters within the range 0.001–100 μm in a heterogeneous solid–liquid mixture (WHO, 2003). The chemical constituents of PM often include harmful substance, such as nitrates, sulfates, trace metals, polycyclic aromatic hydrocarbons and allergens (WHO, 2013). Airborne PM can pose a direct threat to human health because of various diseases linked to its association with pollutants (Kim et al., 2015). Therefore, resolving the problem of atmospheric particulate pollution is a matter of great concern to the international community, particularly in developing countries.

Plants often constitute a major part of a city landscape. For example, the average urban vegetation cover in Beijing is 48%, according to the Beijing Municipal Bureau of Landscape and Forestry (BMSB, 2016). Plants can reduce airborne PM through interception, impaction, sedimentation, and Brownian motion (Petroff et al., 2008). The reduction of PM is an important ecosystem service of plants that could reduce the threat to human health posed by particulate pollution (Escobedo et al., 2011).

Numerous studies of cities in China, the UK, and USA have confirmed that plants are important in PM reduction (e.g. Yin et al., 2011; Liu et al., 2013; McDonald et al., 2007; Tallis et al., 2011; Nowak et al., 2013). Most studies have focused on comparing PM accumulation of various urban plants that may mitigate atmospheric particulate pollution (Hwang et al., 2011; Sæbø et al., 2012; Dzierzanowski et al., 2011; Popek et al., 2012). It has been suggested that leaf surfaces may become saturated over time (Liu et al., 2013). However, most airborne PM captured by plants is stored temporarily on leaf surfaces before being resuspended in the air, washed off into the soil, or deposited on the ground with leaves when they drop from the canopy.

Schaubroeck et al. (2014) using data from a *Pinus koraiensis* forest during a rain event focused on development of a multilayered model of PM behavior from deposition to removal. This demonstrated that rainfall may be important in mitigating airborne particulate pollution because PM wash-off allows continued removal from the atmosphere. Other recent research studied PM accumulation on foliage on both wet and dry days to assess the effects of rainfall (Nguyen et al., 2014; Rodríguez-Germade et al., 2014; Wang et al., 2015b; Kardel et al., 2011). In addition, a few studies investigated the efficacy of PM wash-off from evergreen plants under a certain amount of natural rainfall, but did not mention the rainfall intensity (Wang et al., 2006; Wang et al., 2015a). Experiments using natural rainfall can assess direct PM wash-off under field conditions, but it is difficult to analyze rainfall characteristics in such situations. Simulated rainfall, which has been used widely in studies of soil erosion, is an appropriate tool for the experimental control of rainfall characteristics (Zhao et al., 2013). Recent research investigated the effects of simulated rainfall on PM accumulation on shoots of Scots pine using sprayed distilled water equivalent to rainfall of 20 mm (Przybysz et al., 2014). However, this did not consider the effects of rainfall duration or intensity. It has been suggested that PM wash-off from leaf surfaces is closely related to both plant type and rainfall characteristics, such as rainfall duration and intensity (Wang et al., 2015a). However, few studies have focused on the effects of rainfall characteristics on PM wash-off from foliage, specifically in relation to the removal of airborne particulate pollution.

The objective of the present study was to quantify dynamic processes associated with PM accumulation before rainfall, wash-off via rainfall, and retention after rainfall in breezy and calm conditions at the leaf scale, as well as to explore the effects of rainfall characteristics. The results provide a theoretical basis for the development of artificial rainfall strategies intended to improve airborne PM reduction efficiency of plants, especially in regions or periods with infrequent rain.

2. Materials and methods

2.1. Site description and species selection

Beijing, in northern China, is the capital city. Frequent high concentrations of airborne PM have raised concerns among the public and the government. The rainfall experiment in our study was performed at the Hall of Key Laboratory of Soil and Water Conservation and Desertification Combating of the Ministry of Education, in the Jiufeng Mountains (40°04′N, 116°06′E, 145 m a.s.l.) of Beijing.

Experiments used an artificial rainfall simulation system (QYJY-503C, Xi'an Qingyuan measurement and control technology Corp., Xi'an, China) that included a cistern, pump, pipes, and nozzles. The cistern stored water from the rainfall, the pump propelled water through the pipes, and the rotating nozzles sprayed rainfall. The system was managed by a computer that controlled rainfall area, duration, and intensity. Experiments used one independent rainfall zone of 64 m^2. Raindrops fell from a height of 12 m with distribution uniformity >85%, as in natural rainfall.

The four plant types used were all broadleaf species, one of which was evergreen and the other three deciduous trees. They are all known for their extensive adaptability in street afforestation. *Sophora japonica* L., *Ailanthus altissima* (Mill.) Swingle., and *Populus tomentosa* Carrière. are tree species planted widely across Beijing (Yang et al., 2005) and *Euonymus japonicus Thunb.* is a shrub typical of the area. Saplings (15 pots of each species) in good condition with heights 0.8 m (for *E. japonicus*) and 1.5 m (for the other three trees) were planted in open space of the selected site six months earlier, at the same distance from roads. The open space was near roads connecting the Jiufeng Mountain Forest Park to the various scenic areas nearby, and had the widths of 3.0–5.0 m. It has been reported that PM accumulation on leaf surfaces maximize after 24 days, depending on the environment and plant species (Liu et al., 2013). Before the experiments, the plants were exposed to accumulating PM for 20 days, without any rain events.

2.2. Experiment design

The experimental device was been prepared before rainfall (Fig. 1). Thick foam board was fixed on a support with adhesive tape. Plastic funnels supported by the board were connected via PVC pipes to 50-mL plastic sampling bottles placed underneath the board. Samples of twigs (20–30 cm length) used in the rainfall experiments were harvested on September 19, 2015, before the onset of defoliation. Harvested twigs were inserted into a self-made experimental device, using metallic wire for twig reinforcement. After simulated rainfall stabilized, the experimental devices with twigs were placed in the rain area. It was ensured that leaves situated directly above the funnels so that the liquid flowed into the bottles.

Considering the accuracy of the rainfall simulator, rainfall intensity was set to 15, 30, and 50 mm h^{-1}. According to data from Beijing (2002 − 2011), average rainfall during the growing season is 2.3 mm d^{-1}. Therefore, sampling intervals for the three rainfall intensities were divided into 10, 5, and 3 min, respectively, to reflect a rainfall amount of 2.5 mm during each sampling interval. Based on a preliminary experiment, maximum rainfall was set to 17.5 mm. During rainfall, sampling bottles were replaced after each interval. Distilled water was used to wash the funnels to remove any residue at the end of each interval. Plastic bottles with wash-off and control (no leaves above the funnel) samples were labeled and kept at 4 °C in a laboratory refrigerator.

Leaf samples taken after rainfall (for surface PM retention analysis) and samples before the rainfall (after 20 dry days, for surface PM accumulation analysis) were placed in sealed plastic bags. Then, leaf samples were placed in glass beakers with 250 mL of ultrapure water and washed for 60 s with an ultrasonic cleaner (KQ2200, Kun Shan Ultrasonic Instruments Co., Ltd., Jiangsu, China) to remove particles from the leaf surfaces as soon as possible. The suspension liquids were marked and kept in plastic bottles as PM wash-off samples until analysis. Measurements were performed in three replicates.