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Herbaceous plants as filters: Immobilization of particulates along urban street corridors

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ABSTRACT

Among air pollutants, particulate matter (PM) is considered to be the most serious threat to human health. Plants provide ecosystem services in urban areas, including reducing levels of PM by providing a surface for deposition and immobilization. While previous studies have mostly addressed woody species, we focus on herbaceous roadside vegetation and assess the role of species traits such as leaf surface roughness or hairiness for the immobilization of PM. We found that PM deposition patterns on plant surfaces reflect site-specific traffic densities and that strong differences in particulate deposition are present among species. The amount of immobilized PM differed according to particle type and size and was related to specific plant species traits. Our study suggests that herbaceous vegetation immobilizes a significant amount of the air pollutants relevant to human health and that increasing biodiversity of roadside vegetation supports air filtration and thus healthier conditions along street corridors.

1. Introduction

Many cities suffer from excessive air pollution, and particulate matter (PM) is considered to be the air pollutant affecting human health most seriously (Dockery et al., 1993; Samet et al., 2000; WHO, 2007; UNEP, 2007). Particulate matter originates from natural (e.g., volcanism, sea spray, bioaerosols such as volatile organic compounds) or anthropogenic sources (e.g., combustion of fossil fuels, industrial emissions, vehicular traffic, tire abrasion; Gorbachevskaya et al., 2007). In urban areas, road traffic is one of the major sources of PM (Janssen et al., 1997; Jain and Khare, 2008; Belis et al., 2013) with the highest toxicity (WHO, 2005). Currently political pressure to act is increasing as established emission limits have been severely exceeded in many urban areas (UNEP, 2007). The ecosystem services of plants such as air filtration are increasingly being taken into consideration as a means of preventing and ameliorating ambient air pollution (Gorbachevskaya et al., 2007; Jim and Chen, 2008; Litschke and Kuttler, 2008; Escobedo et al., 2011; Langner et al., 2011; Speak et al., 2012).

Since the mass of dust deposited per unit leaf area decreases exponentially with increasing distance from the emission source (Freer-Smith et al., 1997; Kaur et al., 2005; Litschke and Kuttler, 2008), vegetation should be as near as possible to the source of pollution, and the leaf surface should be as large as possible to maximize the efficiency of immobilization effects (Jim and Chen, 2008; Litschke and Kuttler, 2008). Hence, roadside vegetation is expected to have a considerable effect at reducing environmental particulate pollution because it is situated very near to both motor vehicle traffic and exposed pedestrians.

Previous studies have mostly confirmed the functioning of trees and some shrubs as dust filters, although with differing methods and results (Beckett et al., 1998; Freer-Smith et al., 2004, 2005; Nowak et al., 2006; Jim and Chen, 2008; Sæbø et al., 2012; Hofman et al., in press). Trees in particular have been promoted as biological filters because of their large leaf areas and physical surface properties (Beckett et al., 1998), while the capacity of herbaceous vegetation to immobilize PM has been understudied so far. There is growing evidence, however, that trees in urban street corridors can also increase local air pollution due to reduced near-surface air exchange windspeed (Thönnessen, 2000; Ries and Eichhorn, 2001; Gromke and Ruck, 2007; Buccolieri et al., 2009). Urban roadside vegetation consists of a variety of vegetative structures beyond trees, including lawns and other types of herbaceous vegetation which could contribute to the immobilization of PM (Litschke and Kuttler, 2008).

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Since the surface properties of objects are known to influence particle immobilization (Beckett et al., 1998), it has been hypothesized that plant species will differ in their ability to scavenge dust-laden air due to their differing features such as habitus; canopy height; or position, size, and morphology of leaves (Beckett et al., 1998; Gorbachevskaya et al., 2007; Litschke and Kuttler, 2008). In particular, the shape and surface of individual leaves (or needles) have been studied as predictors of particulate deposition in a few woody species (Litschke and Kuttler, 2008). An increased roughness of leaf surface due to the presence of three-dimensional leaf structures such as hairs, scales, glands, furrows, and veins, has been found to increase particulate accumulation (Yunus et al., 1985; Pyatt and Haywood, 1989; Pfanz and Flohr, 2007; Litschke and Kuttler, 2008; Jamil et al., 2009; Mitchell et al., 2010). Moreover, characteristics of the vegetation such as flow-through due to plant architecture, phenology, and the position within the urban environment are expected to influence air filtration by plants (Gorbachevskaya et al., 2007; Litschke and Kuttler, 2008).

Particulate matter size is classified as ultra fine ($\leq$0.1 μm), fine (0.1–2.5 μm), coarse (2.5–10 μm), and supercoarse (>10 μm) (EPA, 2009) and is directly linked to potential health risks. The ultra fine and fine particulates in particular have been the focus of research (e.g., Cohen et al., 2005), since they can be inhaled into the alveoli of the lungs and hence are particularly harmful. Effects of coarse airborne particles on health are gaining increasing attention, as there is reason to believe the related health effects may have been underappreciated in the past (Brunekreef and Forsberg, 2004; Yeatts et al., 2007; Cho et al., 2009).

In our study we assessed deposition of coarse PM on herbaceous plant surfaces quantitatively and qualitatively by using light microscopy. We focused on the role of spontaneous (i.e., non-planted) herbaceous roadside vegetation for immobilizing traffic-related particles in urban areas. We aimed to answer the following questions: 1) Do PM deposition patterns on plant surfaces reflect site-specific traffic densities? 2) Do the rates of accumulated particles differ with particle type (i.e., transparent, biogenic, or non-transparent particles) or particle size? 3) Does the amount of accumulated PM on plant leaves differ among different species of plants? 4) Do leaf traits (e.g., size, roughness, or presence of hairs) affect the amount of captured matter?

2. Methods

We analyzed randomly sampled herbaceous plant leaves on three sites in Berlin with low, medium, and high traffic densities (for site description see Table 1, Fig. 1) by light microscopy. Site selection was based on results of vehicle counts by local authorities (Senstadt, 2010). We harvested spontaneous, i.e., non-planted, species occurring frequently along roadsides. The plant species had different leaf traits (leaf size, leaf distribution, leaf surface roughness, and hairiness) that are expected to influence particle accumulation (for description of leaf characteristics, see Table 1). We classified species' adaxial leaf structure according to the presence of three-dimensional leaf structures such as hairs, scales, glands, furrows, and veins in 1 = densely haired rough leaves; 2 = densely haired smooth leaves; 3 = dispersed haired rough leaves; 4 = dispersed haired smooth leaves; 5 = glabrous rough leaves; 6 = glabrous smooth leaves) and species' leaf distribution as: i) regularly distributed, ii) half-rosette or iii) rosette; see Table 1). Plant leaves were harvested after one growing season, i.e., in the beginning of October, and frozen in collection tubes at −18 °C after collection. For each sample the height at which the collected leaf was attached to the plant axis was noted. Samples were handled carefully to minimize any disruption or removal of particles. In total, we randomly sampled 16 species (Tables 1 and 2).

Particles deposited on the samples were determined quantitatively (number and size of particles) and qualitatively (type of particles) under a microscope with magnification 1:200 by adapting approaches used in passive sampling and determination of coarse particles (VDI, 1997). For each sampled plant leaf, we counted attached particles on the upper sides of leaves on two or three transects of a defined surface area (1.8 mm^2 or 1.08 mm^2). For statistical analyses, particle counts were averaged for 1 mm^2. Particle size was determined by using a net micrometer distinguishing six size classes: 3–10 μm, 11–15 μm, 16–30 μm, 31–60 μm, 61–120 μm, 121–180 μm. We classified particles according to Feret's statistical diameter (Walton, 1948) as the distance between the tangents perpendicular to the measuring direction. Particles were distinguished into three types based on optical and morphological features according to VDI (1979), and McCrone et al. (1979): i) transparent: inorganic minerogenic particles; ii) biogenic: pollen grains or other organic particles, and iii) non-transparent: anthropogenic sooty combustion residues or tire abrasion particles.

The interactions of particulate count (per mm^2) on the leaves, roadside species, and local traffic burden were analyzed by generalized linear models (GLM). Particulate count of different size classes on the leaves was taken as the response variable, and parameters which characterized the local particle burden (traffic density, particle type) and leaf-related parameters (surface roughness, hairiness, size, and leaf distribution along stem) were taken as explanatory variables. Correlation between traffic density and amount of PM on plant leaves was analyzed by Spearman's rank correlation. Particle number on leaves of herbs versus grasses at a definite time was analyzed by Mann–Whitney test. All statistical analyses were done using PASW Statistics 19.

3. Results

Overall, the amount of PM on the leaves of roadside species (count/mm^2 leaf surface) differed according to traffic density,

Table 1
Description of sampled herbaceous roadside species including leaf morphology with adaxial leaf structure and hairiness (1 = densely haired rough leaves; 2 = densely haired smooth leaves; 3 = dispersed haired rough leaves; 4 = dispersed haired smooth leaves; 5 = glabrous rough leaves; 6 = glabrous smooth leaves), leaf distribution (*k* = regularly distributed, l = half-rosette, m = rosette) and mean sampling height. Number of samples per site and counted sampled per leaf are given. ND: not determined.

Species name	Common name	Samples per site/transects per leaf and traffic density			Mean sample height (m)	Leaf morphology	Leaf size	Leaf distribution
		High	Medium	Low				
Achillea millefolium	Common yarrow	5/3	5/3	5/3	0.32	1	Small	l
Artemisia vulgaris	Common wormwood	ND	5/3	5/3	0.40	6	Medium	k
Berteroa incana	Hoary allysum	5/3	5/3	5/3	0.23	2	Small	k
Chenopodium album	Lambsquarters	5/3	5/3	3/3	0.25	1	Medium	k
Convolvulus arvensis	Field bindweed	5/3	ND	ND	0.27	5	Medium	k
Elytrigia repens	Quackgrass	5/2	ND	5/3	0.27	3	Small	k
Erodium cicutarium	Redstem stork's bill	5/3	5/3	ND	0.01	3	Small	m
Festuca rubra	Red fescue	ND	5/2	5/3	0.2	3	Small	l
Galinsoga parviflora	Gallant soldier	5/3	5/3	4/3	0.31	4	Medium	k
Lolium perenne	Perennial ryegrass	5/3	5/2	5/3	0.05	3	Small	l
Plantago lanceolata	Narrowleaf plantain	5/3	5/3	5/3	0.01	3	Medium	m
Poa pratensis	Kentucky bluegrass	ND	5/3	ND	0.07	4	Small	k
Polygonum aviculare	Prostrate knotweed	5/3	4/2	4/2	0.17	2	Small	k
Sysimbrium loeselii	Small tumbleweed mustard	5/3	ND	ND	0.43	1	Medium	k
Taraxacum officinale	Common dandelion	5/3	5/3	5/3	0.01	5	Medium	m
Trifolium repens	White clover	ND	5/3	5/3	0.08	6	Medium	k