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



Frauke Weber <sup>a,\*</sup>, Ingo Kowarik <sup>a,b</sup>, Ina Säumel <sup>a,c</sup>

<sup>a</sup> Department of Ecology, Chair of Ecosystem Science/Plant Ecology, Technische Universität Berlin, Rothenburgstr. 12, D-12165 Berlin, Germany

<sup>b</sup> Berlin-Brandenburg Institute of Advanced Biodiversity Research (BBIB), 14195 Berlin, Germany

<sup>c</sup> Department of Ecology, Chair of Ecological Impact Research and Ecotoxicology, Technische Universität Berlin, Ernst Reuter Platz 1, D-10587 Berlin, Germany

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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.

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### 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).

\* Corresponding author.

E-mail addresses: [fraukeweber@web.de](mailto:fraukeweber@web.de), [frauke.weber@mailbox.tu-berlin.de](mailto:frauke.weber@mailbox.tu-berlin.de), [frauke.weber1@gmx.net](mailto:frauke.weber1@gmx.net) (F. Weber).

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 ( $\leq 0.1 \mu\text{m}$ ), fine (0.1–2.5  $\mu\text{m}$ ), coarse (2.5–10  $\mu\text{m}$ ), and supercoarse ( $> 10 \mu\text{m}$ ) (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  $-18^\circ\text{C}$  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 ( $1.8 \text{ mm}^2$  or  $1.08 \text{ mm}^2$ ). For statistical analyses, particle counts were averaged for  $1 \text{ mm}^2$ . Particle size was determined by using a net micrometer distinguishing six size classes: 3–10  $\mu\text{m}$ , 11–15  $\mu\text{m}$ , 16–30  $\mu\text{m}$ , 31–60  $\mu\text{m}$ , 61–120  $\mu\text{m}$ , 121–180  $\mu\text{m}$ . 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 mineralogic 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  $\text{mm}^2$ ) 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.

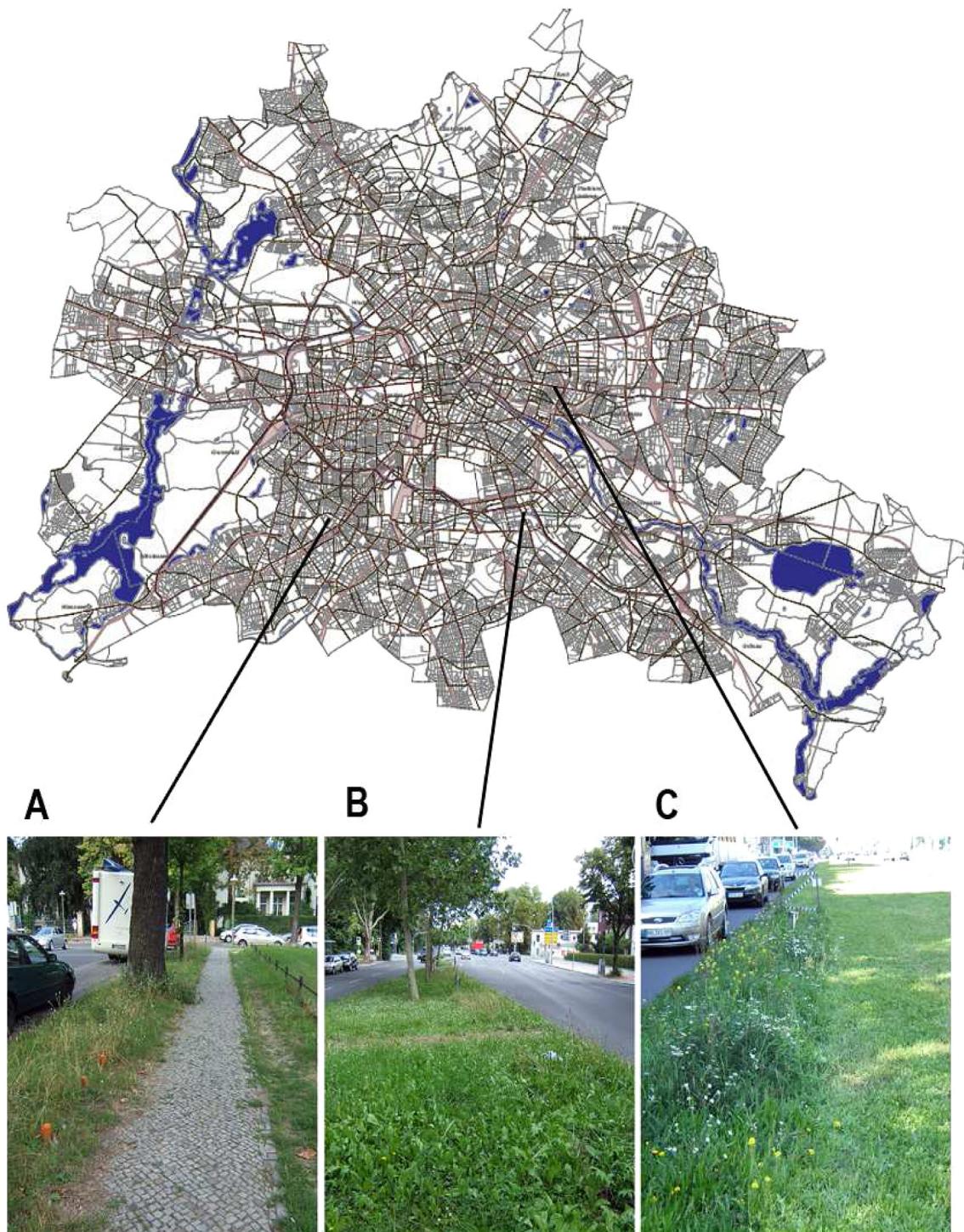
## 3. Results

Overall, the amount of PM on the leaves of roadside species (count/ $\text{mm}^2$  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, 1 = 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 |                        |                 |           |                   |
| <i>Achillea millefolium</i> | Common yarrow            | 5/3   | 5/3    | 5/3 | 0.32                   | 1               | Small     | l                 |
| <i>Artemisia vulgaris</i>   | Common wormwood          | ND  | 5/3    | 5/3 | 0.40                   | 6               | Medium    | k                 |
| <i>Berteroa incana</i>      | Hoary allysum            | 5/3   | 5/3    | 5/3 | 0.23                   | 2               | Small     | k                 |
| <i>Chenopodium album</i>    | Lambsquarters            | 5/3   | 5/3    | 3/3 | 0.25                   | 1               | Medium    | k                 |
| <i>Convolvulus arvensis</i> | Field bindweed           | 5/3   | ND     | ND  | 0.27                   | 5               | Medium    | k                 |
| <i>Elytrigia repens</i>     | Quackgrass               | 5/2   | ND     | 5/3 | 0.27                   | 3               | Small     | k                 |
| <i>Erodium cicutarium</i>   | Redstem stork's bill     | 5/3   | 5/3    | ND  | 0.01                   | 3               | Small     | m                 |
| <i>Festuca rubra</i>        | Red fescue               | ND  | 5/2    | 5/3 | 0.2                    | 3               | Small     | l                 |
| <i>Galinsoga parviflora</i> | Gallant soldier          | 5/3   | 5/3    | 4/3 | 0.31                   | 4               | Medium    | k                 |
| <i>Lolium perenne</i>       | Perennial ryegrass       | 5/3   | 5/2    | 5/3 | 0.05                   | 3               | Small     | l                 |
| <i>Plantago lanceolata</i>  | Narrowleaf plantain      | 5/3   | 5/3    | 5/3 | 0.01                   | 3               | Medium    | m                 |
| <i>Poa pratensis</i>        | Kentucky bluegrass       | ND  | 5/3    | ND  | 0.07                   | 4               | Small     | k                 |
| <i>Polygonum aviculare</i>  | Prostrate knotweed       | 5/3   | 4/2    | 4/2 | 0.17                   | 2               | Small     | k                 |
| <i>Sisymbrium loeselii</i>  | Small tumbleweed mustard | 5/3   | ND     | ND  | 0.43                   | 1               | Medium    | k                 |
| <i>Taraxacum officinale</i> | Common dandelion         | 5/3   | 5/3    | 5/3 | 0.01                   | 5               | Medium    | m                 |
| <i>Trifolium repens</i>     | White clover             | ND  | 5/3    | 5/3 | 0.08                   | 6               | Medium    | k                 |



**Fig. 1.** Urban road network of Berlin, Germany (black: roads with >5000 vehicles/day; gray: roads with <5000 vehicles/day, adapted from Senstadt, 2010) and location and impressions of study sites with low (A = Schmitt-Ott-Straße, a vegetated strip along a secondary road with <5000 vehicles/day), medium (B = Buschkrugallee, a median of a main road with 20,000–30,000 vehicles/day) and high (C = Frankfurter Allee, a median of an arterial road with 50,000–60,000 vehicles/day) traffic density within the city of Berlin, Germany.

particle type, and species (Fig. 2). A GLM revealed significant interactions of PM amounts with traffic density, particle type, and species (Table 3A). Overall, densely haired leaves captured significantly more particles than species with dispersed haired or glabrous leaves (Fig. 3).

The amount of PM captured on the plant leaves increased with traffic burden (Fig. 2). The amount of total non-transparent (NT)

and biogenic (B) PM on the leaves was significantly correlated with traffic density (NT:  $r = 0.598, p = 0.000$ ; B:  $r = 0.105, p = 0.016$ ). In contrast, the amount of transparent PM was not correlated with traffic density ( $r = -0.028, p = 0.524$ ).

Non-transparent particles made up the greatest fraction of the total PM, accounting for 97% of the total particle counts for the site with high traffic density, 86% for the site with medium traffic

**Table 2** Median (Med), mean and maximum (Max) particulate matter counts (per 1 mm<sup>2</sup>) for N leaf transects on plant leaves of frequent roadside species per species for particles of different size classes (I–IV) on sample sites with high (1), medium (2), and low (3) traffic burden. For further information on sampled species see Table 1.

| Particle size class species | I (3–10 µm) |       |        |      | II (11–15 µm) |       |      |     | III (16–30 µm) |     |      |      | IV (31–60 µm) |     |      |     | V (61–120 µm) |     |      |     | VI (121–180 µm) |     |      |     | N    | Sample sites |  |  |
|-----------------------------|-------------|-------|--------|------|---------------|-------|------|-----|----------------|-----|------|------|---------------|-----|------|-----|---------------|-----|------|-----|-----------------|-----|------|-----|------|--------------|--|--|
|                             | Med         |       | Mean   |      | Med           |       | Mean |     | Med            |     | Mean |      | Med           |     | Mean |     | Med           |     | Mean |     | Med             |     | Mean |     |      |              |  |  |
|                             | Med         | Max   | Med    | Max  | Med           | Max   | Med  | Max | Med            | Max | Med  | Max  | Med           | Max | Med  | Max | Med           | Max | Med  | Max | Med             | Max | Med  | Max |      |              |  |  |
| <i>Achillea millefolium</i> | 5.5         | 176.4 | 3917.6 | 8.3  | 35.0          | 313.0 | 0.5  | 0.9 | 6.5            | 0   | 0.2  | 2.8  | 0.0           | 0.0 | 0.5  | 0.0 | 0.0           | 0.0 | 0.0  | 0.0 | 0.0             | 0.0 | 0.0  | 0.0 | 45   | 1–3          |  |  |
| <i>Artemisia vulgaris</i>   | 10.6        | 100.4 | 992.6  | 11.6 | 17.0          | 78.7  | 0.7  | 1.4 | 10.2           | 0   | 0.4  | 2.8  | 0.0           | 0.0 | 0.9  | 0.0 | 0.0           | 0.0 | 0.0  | 0.0 | 0.0             | 0.0 | 0.0  | 0.0 | 30   | 2–3          |  |  |
| <i>Berteroa incana</i>      | 7.4         | 145.4 | 2152.8 | 8.3  | 23.8          | 312.0 | 0.9  | 2.4 | 24.1           | 0   | 0.5  | 3.7  | 0.0           | 0.0 | 0.9  | 0.0 | 0.0           | 0.0 | 0.0  | 0.0 | 0.0             | 0.0 | 0.0  | 0.0 | 20.4 | 1–3          |  |  |
| <i>Chenopodium album</i>    | 15.6        | 193.3 | 3053.7 | 10.2 | 21.0          | 154.6 | 0.9  | 1.8 | 13.0           | 0   | 0.32 | 71.3 | 0.0           | 0.0 | 0.5  | 0.0 | 0.0           | 0.0 | 0.0  | 0.0 | 0.0             | 0.0 | 0.0  | 0.0 | 36.9 | 1–3          |  |  |
| <i>Convolvulus arvensis</i> | 2.8         | 220.4 | 1288.0 | 10.2 | 27.4          | 133.3 | 0.0  | 1.1 | 7.4            | 0   | 0.4  | 4.6  | 0.0           | 0.0 | 0.0  | 0.0 | 0.0           | 0.0 | 0.0  | 0.0 | 0.0             | 0.0 | 0.0  | 0.0 | 12.0 | 249.3        |  |  |
| <i>Elytrigia repens</i>     | 4.6         | 49.0  | 619.4  | 4.6  | 9.6           | 59.2  | 0.0  | 0.5 | 5.5            | 0   | 0.2  | 1.8  | 0.0           | 0.0 | 0.0  | 0.0 | 0.0           | 0.0 | 0.0  | 0.0 | 0.0             | 0.0 | 0.0  | 0.0 | 11.1 | 59.3         |  |  |
| <i>Erodium cicutarium</i>   | 11.6        | 74.5  | 1099.0 | 7.4  | 13.8          | 60.2  | 0.9  | 2.2 | 8.3            | 0   | 0.8  | 3.7  | 0.0           | 0.0 | 0.9  | 0.0 | 0.0           | 0.0 | 0.0  | 0.0 | 0.0             | 0.0 | 0.0  | 0.0 | 19.0 | 1164.8       |  |  |
| <i>Festuca rubra</i>        | 1.8         | 144.4 | 1.8    | 3.4  | 26.7          | 0.0   | 0.2  | 3.3 | 0              | 0.2 | 4.4  | 0.0  | 0.0           | 0.0 | 0.0  | 0.0 | 0.0           | 0.0 | 0.0  | 0.0 | 0.0             | 0.0 | 0.0  | 0.0 | 4.6  | 174.4        |  |  |
| <i>Galinsoga parviflora</i> | 15.5        | 109.5 | 1498.1 | 10.6 | 22.7          | 141.7 | 0.9  | 1.7 | 11.1           | 0   | 0.7  | 7.8  | 0.0           | 0.0 | 1.1  | 0.0 | 0.0           | 0.0 | 0.0  | 0.0 | 0.0             | 0.0 | 0.0  | 0.0 | 28.5 | 134.7        |  |  |
| <i>Lolium perenne</i>       | 11.1        | 60.6  | 599.0  | 10.2 | 16.8          | 75.5  | 0.5  | 1.5 | 12.8           | 0   | 0.7  | 8.8  | 0.0           | 0.0 | 0.5  | 0.0 | 0.0           | 0.0 | 0.0  | 0.0 | 0.0             | 0.0 | 0.0  | 0.0 | 25.0 | 79.7         |  |  |
| <i>Plantago lanceolata</i>  | 6.5         | 36.6  | 335.1  | 7.4  | 12.1          | 60.5  | 0.9  | 2.2 | 15.5           | 0   | 0.9  | 9.4  | 0.0           | 0.0 | 1.1  | 0.0 | 0.0           | 0.0 | 0.0  | 0.0 | 0.0             | 0.0 | 0.0  | 0.0 | 17.6 | 52.0         |  |  |
| <i>Poa pratensis</i>        | 3.0         | 48.2  | 305.0  | 1.9  | 7.2           | 40.0  | 0.0  | 0.6 | 6.1            | 0   | 0.3  | 2.8  | 0.0           | 0.0 | 0.0  | 0.0 | 0.0           | 0.0 | 0.0  | 0.0 | 0.0             | 0.0 | 0.0  | 0.0 | 5.3  | 336.1        |  |  |
| <i>Polygonum aviculare</i>  | 6.5         | 430.5 | 4158.3 | 7.4  | 22.4          | 174.0 | 0.5  | 1.8 | 38.0           | 0   | 0.1  | 1.8  | 0.0           | 0.0 | 0.0  | 0.0 | 0.0           | 0.0 | 0.0  | 0.0 | 0.0             | 0.0 | 0.0  | 0.0 | 13.9 | 4371.3       |  |  |
| <i>Sisymbrium loeselii</i>  | 10.2        | 518.4 | 2412.0 | 8.3  | 24.8          | 104.6 | 0.0  | 2.6 | 15.7           | 0   | 0.2  | 1.8  | 0.0           | 0.0 | 0.0  | 0.0 | 0.0           | 0.0 | 0.0  | 0.0 | 0.0             | 0.0 | 0.0  | 0.0 | 21.3 | 69.5         |  |  |
| <i>Taraxacum officinale</i> | 10.2        | 545.7 | 763.9  | 8.3  | 12.7          | 58.3  | 0.9  | 1.7 | 11.1           | 0   | 0.5  | 6.1  | 0.0           | 0.0 | 0.5  | 0.0 | 0.0           | 0.0 | 0.0  | 0.0 | 0.0             | 0.0 | 0.0  | 0.0 | 23.9 | 813.9        |  |  |
| <i>Trifolium repens</i>     | 12.1        | 22.0  | 129.6  | 10.1 | 14.0          | 62.2  | 1.1  | 2.1 | 10.5           | 0   | 0.4  | 2.8  | 0.0           | 0.0 | 0.5  | 0.0 | 0.0           | 0.0 | 0.0  | 0.0 | 0.0             | 0.0 | 0.0  | 0.0 | 25.0 | 38.6         |  |  |

density and 78% with low traffic density. Particles of the smallest size class (3–10 µm) were more frequent than larger particles (Table 2).

Particle counts on the leaves also differed according to selected species traits. A GLM revealed significant interactions of particle concentrations and leaf surface roughness, leaf hairiness, and sampling height (Table 3). Herbs did not collect significantly more particulates on the leaves than grasses ( $p = 0.229$ ).

Sampling height of plant leaves ranged from 1 to 71 cm and showed significant interactions with PM amounts on the leaves (Table 3A). Leaves harvested above the median sampling height (15 cm) accumulated greater amounts of PM than leaves located below this position. Species and sample height showed no significant interaction with PM amounts on the leaves. Leaf size and distribution along stem showed no significant interaction with PM amounts on the leaves.

*Sisymbrium loeselii*, a species with rough dispersed haired leaves, captured the greatest amount of PM on the leaves, in terms of both highest mean and maximum (Table 2). *Polygonum aviculare*, a rather low-growing species with small hairy leaves, had the second highest amount of PM on the leaves, followed by *Convolvulus arvensis*, a creeper with rough leaves (Table 2). Other high PM accumulators were *Chenopodium album*, a species with glandular hairs on the leaves, which thus appear mealy, *Achillea millefolium*, with pinnate hairy leaves, *Berteroa incana* with dense stellate hairs, and *Galinsoga parviflora*, a species with dispersed haired leaves (Table 2). *Artemesia vulgaris*, a species with smooth adaxial leaves, and *Erodium cicutarium*, a rather low-growing species with pinnate dispersed haired leaves, captured fewer particles than the above-mentioned high accumulating species (Table 2, Fig. 2).

Considerably fewer particles were captured on the leaves of the grass *Lolium perenne*, of *Taraxacum officinale*, a rosette plant with smooth glabrous leaves, and by other species such as *Elytrigia repens*, *Poa pratensis*, *Plantago lanceolata*. The fewest particles were captured by the herb *Trifolium repens*, which has smooth leaves, and the grass *Festuca rubra*, which has dispersed haired rough leaves (Table 2).

#### 4. Discussion

The influence of species traits such as leaf morphology on PM deposition on plant surfaces has been investigated thus far mainly in woody species (Litschke and Kuttler, 2008). To our knowledge this is the first study focusing on filtration capacities of grasses and herbaceous species that frequently grow along roadsides, the main sites of human exposure to particulate matter in urban environments. Our main results can be summarized as follows: Particulate matter deposition on plant surfaces corresponded to site-specific traffic densities, differed in terms of particle types and sizes and among plant species, and was related to plant species traits.

Overall, our results illustrate the capacity of herbaceous plants to immobilize locally occurring air pollutants that are highly relevant for human health. Although previous research has largely focused on fine particles (PM < 2.5 µm), the relevance of coarse particles, the subject of our study, for human health is increasingly acknowledged (Brunekreef and Forsberg, 2004; Yeatts et al., 2007; Cho et al., 2009). A Canadian study found that higher daily mean levels of coarse particulates were associated with increased cardiovascular mortality, whereas PM < 2.5 µm did not predict mortality significantly (Villeneuve et al., 2003). In another study, coarse particles were more toxic to alveolar macrophages than were fine particles (Kleinman et al., 2005). Non-transparent particles are primarily of anthropogenic origin and frequently consist of combustion residues and abrasion materials (VDI, 1997); they have been shown to have the most significant effects on public health

(CAFE, 2004). Thus far, it has not been possible to establish threshold concentrations below which PM pollution showed no effects on public health; thus any reduction in PM concentrations is beneficial to people (WHO, 2005). Our results thus suggest beneficial effects of PM immobilization on plant leaves for human health. Yet further research should consider whether such effects are diminished by resuspension of PM from living or dead plant surfaces. In our study, traffic burden was reflected in particulate deposition on herbaceous plant leaves (Fig. 2). This result suggests that herbaceous plant leaves immobilize particulates where they actually mostly occur, thus providing relief from air pollution next to busy roads. Also earlier studies report larger amounts of PM being captured on plant leaves at highly polluted sites compared to less polluted sites (Beckett et al., 2000; Freer-Smith et al., 2005; Säumel et al., 2012) analogously for trace metals).

Non-transparent particles made up the greatest share of captured particles by all species on all sites, which was probably due to the higher proportion of anthropogenic sources in urban agglomerations in general and of traffic-induced non-transparent particles in particular (Janssen et al., 1997; Lenschow et al., 2001; Keukens et al., 2013). In contrast a study conducted in a woodland showed more organic than inorganic particles on oak leaves (Freer-Smith et al., 1997). Particles of the smallest size range (3–10 µm) were captured most frequently on the plant leaves. This result adds evidence to some previous studies finding mean particle diameters of 6.0–9.0 µm on oak leaves (Freer-Smith et al., 1997). Another study found that large particles (>10 µm) on plant leaves are rather rare compared to those <10 µm (Ottelé et al., 2010). These contradictory results might be due to differing study sites and particle assessment methods.

#### 4.1. Biodiversity matters in PM deposition on plant leaves

All sampled species contributed to particle immobilization, but the amount of captured PM significantly depended on leaf traits and plant height (Table 3B). Moreover, individual species captured PM of different size classes and particle types (Table 2, Fig. 2). One important result of our study thus was that species diversity of roadside vegetation matters in immobilizing PM. Species with densely haired leaves proved to be most effective at retaining PM (Fig. 3). This result suggests that mechanisms determining plant leaves' efficiency at capturing particulates in woody species (e.g.

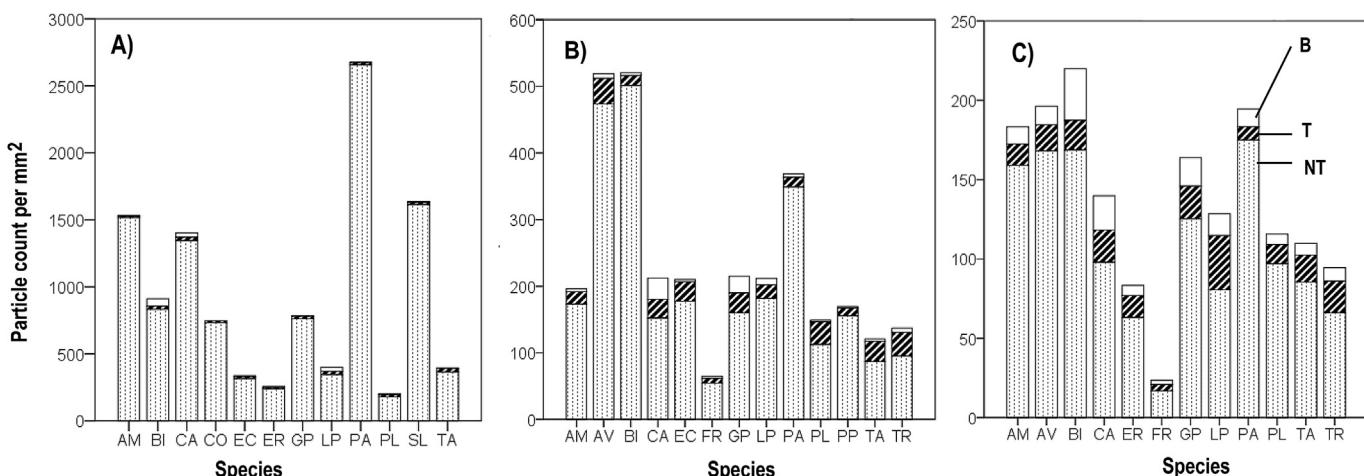
Pyatt and Haywood, 1989; Beckett et al., 2000; Jamil et al., 2009; Sæbø et al., 2012) apply equally for herbaceous species.

In contrast to former studies that found grasses to collect less PM than herbs (Pyatt, 1973; Jonas, 1984) and a recent study that found grasses to be more effective than perennial herbs at filtering dust on green roofs (Speak et al., 2012), we found no significant differences between the two groups of plants. Rather, individual plant characteristics appear to be more relevant for air filtration capacities than membership in the group of grasses or herbs.

Accumulated PM amounts significantly depended on sampling height of plant leaves, whereby tall-growing herbs with leaves regularly distributed along the whole stem collected more particles than low-growing species. Thus, structurally diverse and abundant roadside vegetation with large leaf areas at different heights is expected to foster immobilization effects. Earlier studies on shrubs and trees (Steubing and Klee, 1970; Pyatt, 1973; Prusty et al., 2005; Wang et al., 2006) or sticky collection plates (Helbing, 1973) found decreasing numbers of particles with increasing sampling height. Other authors described higher PM densities on plants at low sampling heights (e.g. Wang et al., 2006; Sæbø et al., 2012) compared to taller woody species and attributed this effect to the resuspension of road dust or soil splash. A maximum concentration of airborne pollutants at a height of 2 m and a minimum concentration at a height of 4 m were observed for an urban green façade (Thönnissen, 2000), while there was no effect of sampling height on the amount of accumulated PM on a free-standing noise protection wall next to a road (Ottelé et al., 2010). Since the mentioned studies differed widely in methodological approaches, standardized approaches are needed to shed light on general patterns of particulate immobilization in relation to plant heights.

#### 4.2. Enhancing air filtration capacity of roadside vegetation beyond trees

For reducing traffic-born PM emissions, technical approaches (e.g., particulate filters) and non-technical approaches (e.g., shaping of traffic flows) have been applied to reduce health risks for urban residents (UBA, 2009). Greening measures could complement air pollution mitigation policies effectively due to the potential of urban vegetation to remove air pollution (Jim and Chen, 2008; Escobedo and Nowak, 2009).



**Fig. 2.** Mean biogenic (B), transparent (T) and non-transparent (NT) particulate matter (count/mm<sup>2</sup>) of different size classes (I = 3–10 µm, 11–15 µm, 16–30 µm, 31–60 µm, 61–120 µm, 121–180 µm) on the leaves of common roadside species (AM = Achillea millefolium, AV = Artemisia vulgaris, BI = Berteroia incana, CA = Chenopodium album, CO = Convolvulus arvensis, EC = Erodium cicutarium, ER = Elytrigia repens, FR = Festuca rubra, GP = Galinsoga parviflora, LP = Lolium perenne, PA = Polygonum aviculare, PL = Plantago lanceolata, PP = Poa pratensis, SL = Sisymbrium loeselii, TA = Taraxacum officinale, TR = Trifolium repens) on study sites with A) high, B) medium and C) low traffic density. Please note the different scales of y-axis. For further information on sampled species, see Table 1.

**Table 3**

Generalized linear model (GLM) results with number of particles of different size classes as the response variable and A) species (sp) and sample height (h) of the plant leaves, traffic density (td), and particle type (pt) as explanatory variables:  $\sim h + td + pt + sp + td^*pt + td^*sp + pt^*sp + td^*pt^*sp$ ; and B) leaf morphology (struc = surface roughness, leaf hairiness) of the plant leaves, traffic density (td), and particle type (pt) as explanatory variables:  $\sim struc + pt + td + struc^*pt + struc^*td + pt^*td + struc^*pt^*td$ . Given are main effects and interactions of factors. GLM algorithm is Pillai's Trace. The significance level is  $p < 0.05$ . Mean squares (MS), F values, degrees of freedom (Df) and p values (P) are given. For further information on sampled species, see Table 1.

| Effect      | MS    | F       | Df  | P     |
|-------------|-------|---------|-----|-------|
| <b>A</b>    |       |         |     |       |
| Intercept   | 0.188 | 54.215  | 6   | 0.000 |
| h           | 0.021 | 5.132   | 6   | 0.000 |
| td          | 0.244 | 32.688  | 12  | 0.000 |
| pt          | 0.563 | 91.994  | 12  | 0.000 |
| sp          | 0.433 | 7.329   | 90  | 0.000 |
| td*pt       | 0.381 | 24.772  | 24  | 0.000 |
| td*sp       | 0.509 | 6.893   | 114 | 0.000 |
| pt*sp       | 0.738 | 6.608   | 180 | 0.000 |
| td*pt*sp    | 0.773 | 5.502   | 228 | 0.000 |
| <b>B</b>    |       |         |     |       |
| Intercept   | 0.513 | 264.301 | 6   | 0.000 |
| struc       | 0.143 | 7.399   | 30  | 0.000 |
| pt          | 0.503 | 84.387  | 12  | 0.000 |
| td          | 0.222 | 31.313  | 12  | 0.000 |
| struc*pt    | 0.263 | 6.938   | 60  | 0.000 |
| struc*td    | 0.210 | 6.093   | 54  | 0.000 |
| pt*td       | 0.342 | 23.521  | 24  | 0.000 |
| struc*pt*td | 0.303 | 4.469   | 108 | 0.000 |

The prevailing focus on ecosystem services provided by tree species (Jim and Chen, 2008; Escobedo and Nowak, 2009) is mostly justified by the large biomass and related leaf surface areas of trees. Yet tree plantings can be challenging under some urban conditions because (i) they can reduce near-surface air exchange and affect windspeed, thereby increasing local air pollution by up to 20% in some cases (Litschke and Kuttler, 2008; Salim et al., 2011; Vos et al., 2012); (ii) urban street trees are exposed to multiple stressors resulting in poor vitality and tree decline (Pauleit, 2003) as roadside habitats are characterized by harsh living conditions, e.g., high pollution loads, drought, and high disturbance frequency (Tubby

and Webber, 2010). Conifers in particular, which have been shown to be most effective in capturing particles in some studies due to the complex spatial structure of their shoots and needles (Jonas, 1984; Beckett et al., 2000; Freer-Smith et al., 2005; Steubing and Klee, 1970; Reznik and Schmidt, 2008; Räsänen et al., 2013), are often unsuitable for urban areas due to their poor resistance to pollutants.

Our results highlight the functional role of herbaceous vegetation in street corridors because this type of vegetation might supplement the benefits provided by trees. The main reasons for enhancing herbaceous roadside vegetation are that herbaceous vegetation (i) is situated closer to motor vehicle traffic and exposed pedestrians compared to the canopies of street trees, thus maximizing the immobilization effect (Jim and Chen, 2008; Litschke and Kuttler, 2008), (ii) does not affect air exchange in urban street corridors, (iii) can supplement woody vegetation by binding particulates that have been resuspended or washed off trees (Gorbachevskaya et al., 2007; Pfanz and Flohr, 2007), and (iv) can be easily incorporated into existing infrastructure and readily adapted to local priorities.

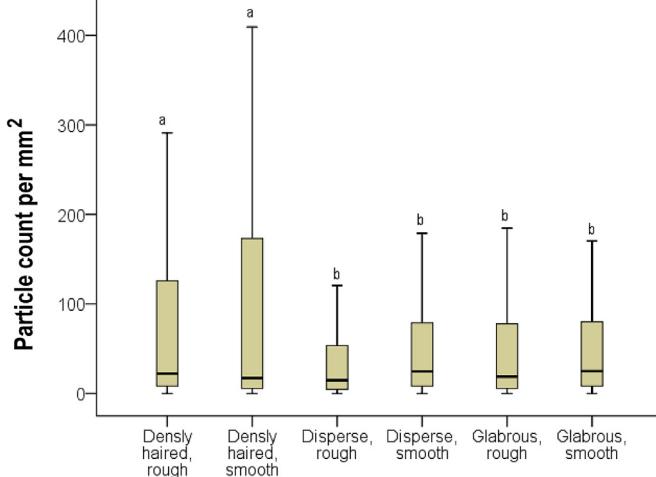
Our results suggest that the structural diversity of heterogeneous species assemblages along roadsides, with a variety of species, plant architectures, and surface morphologies, fosters the immobilization of a wide range of PM. Enhancing biodiversity in urban road corridors is thus expected to contribute to human health by binding relevant local air pollution. In addition plants in urban road corridors can link people with biodiversity since they are directly perceptible elements of urban nature even in neighborhoods undersupplied with parks or gardens.

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## References

- Beckett, K.P., Freer-Smith, P., Taylor, G., 1998. Urban woodlands: their role in reducing the effects of particulate pollution. Environ. Pollut. 99, 347–360.
- Beckett, K.P., Freer-Smith, P., Taylor, G., 2000. Effective tree species for local air-quality management. J. Arboricul. 26, 12–19.
- Belis, C.A., Karagulian, F., Larsen, B.R., Hopke, P.K., 2013. Critical review and meta-analysis of ambient particulate matter source apportionment using receptor models in Europe. Atmos. Environ. 69, 94–108.
- Brunekreef, B., Forsberg, B., 2004. Epidemiological evidence of effects of coarse airborne particles on health. Eur. Respir. J. 26, 309–318.
- Buccolieri, R., Gromke, C., Di Sabatino, S., Ruck, B., 2009. Aerodynamic effects of trees on pollutant concentration in street canyons. Sci. Total Environ. 407, 5247–5256.
- CAFE, 2004. Second Position Paper on Particulate Matter. [http://ec.europa.eu/environment/archives/cafe/pdf/working\\_groups/2nd\\_position\\_paper\\_pm.pdf](http://ec.europa.eu/environment/archives/cafe/pdf/working_groups/2nd_position_paper_pm.pdf).
- Cho, S.-H., Tong, H., McGee, J.K., Baldauf, R.W., Krantz, Q.T., Gilmour, M.I., 2009. Comparative toxicity of size fractionated airborne particulate matter collected at different distances from an urban highway. Environ. Health Perspect. 117, 1682–1689.
- Cohen, A.J., Anderson, H.R., Ostra, B., Pandey, K.D., Krzyzanowski, M., Künzli, N., Gutschmidt, K., Pope, A., 2005. The global burden of disease due to outdoor air pollution. J. Toxicol. Environ. Health A 68, 1–7.
- Dockery, D.W., Pope, C.A., Xu, X., Spengler, J.D., Ware, J.H., Fay, M.E., Ferris, B.G., Speizer, F.E., 1993. An association between air pollution and mortality in six U.S. cities. New Eng. J. Med. 329, 1753–1759.
- Escobedo, F.J., Nowak, D.J., 2009. Spatial heterogeneity and air pollution removal by an urban forest. Landsc. Urban Plan. 90, 102–110.
- Escobedo, F.J., Kroeger, T., Wagner, J.E., 2011. Urban forests and pollution mitigation: analyzing ecosystem services and disservices. Environ. Pollut. 159, 2078–2087.
- EPA, 2009. Integrated Science Assessment for Particulate Matter (First external review draft). U.S. Environmental Protection Agency, Washington, DC. EPA/600/R-08/139, 2008.



**Fig. 3.** Particulate matter (count/ $\text{mm}^2$ ) (y-axis) on the leaves of roadside species with different leaf morphologies (densely haired rough leaves; densely haired smooth leaves; dispersed haired rough leaves; dispersed haired smooth leaves; glabrous rough leaves; glabrous smooth leaves). The box plots indicate medians and the 25th and 75th percentiles of the distribution. Lowercase letters indicate significant differences in total particle counts per  $\text{mm}^2$  leaf area. For further information on sampled species, see Table 1.

- Freer-Smith, P.H., Holloway, S., Goodman, A., 1997. The uptake of particulates by an urban woodland: site description and particulate composition. *Environ. Pollut.* 95, 27–35.
- Freer-Smith, P.H., El-Khatib, A.A., 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.
- Freer-Smith, P.H., Beckett, K.P., Taylor, G., 2005. Deposition velocities to *Sorbus aria*, *Acer campestre*, *Populus deltoides* x *trichocarpa* 'Beaupré', *Pinus nigra* and x *Cupressocyparis leylandii* for coarse, fine and ultra-fine particles in the urban environment. *Environ. Pollut.* 133, 157–167.
- Gorbachevskaya, O., Schreiter, H., Kappis, C., 2007. Wissenschaftlicher Erkenntnisstand über das Feinstaubfilterungspotential von Pflanzen (qualitativ und quantitativ) – Ergebnisse der Literaturstudie. Berliner Geographische Arbeiten 109, pp. 71–82.
- Gromke, C., Ruck, B., 2007. Influence of trees on the dispersion of pollutants in an urban street canyon—experimental investigation of the flow and concentration field. *Atmos. Environ.* 41, 3287–3302.
- Helbing, C.-D., 1973. Staubemissionen im Bonner Stadtgebiet und deren artspezifische Ablagerungen auf Blättern ausgewählter Gehölze (Dissertation, Bonn, Germany).
- Hofman, J., Stokkaer, I., Snauwaert, L., Samson, R., 2012. Spatial distribution assessment of particulate matter in an urban street canyon using biomagnetic leaf monitoring of tree crown deposited particles. *Environ. Pollut.* 183, 123–132.
- Jain, S., Khare, M., 2008. Urban air quality in mega cities: a case study of Delhi City using vulnerability analysis. *Environ. Monit. Assess.* 136, 257–265.
- Jamil, S., Abhilash, P.C., Singh, A., Singh, N., Behl, H.M., 2009. Fly ash trapping and metal accumulating capacity of plants: implication for green belt around thermal power plants. *Landscape. Urban Plan.* 92, 136–147.
- Janssen, N.A.H., Van Mansum, D.F.M., Van Der Jagt, K., Harssema, H., Hoek, G., 1997. Mass concentration and elemental composition of airborne particulate matter at street and background locations. *Atmos. Environ.* 31, 1185–1193.
- Jim, C.Y., Chen, W.Y., 2008. Assessing the ecosystem service of air pollutant removal by urban trees in Guangzhou (China). *J. Environ. Manage.* 88, 665–676.
- Jonas, R., 1984. Ablagerung und Bindung von Luftverunreinigungen an Vegetation und an anderen atmosphärischen Grenzflächen (Dissertation, Aachen, Germany).
- Kaur, S., Nieuwenhuijsen, M.J., Colvile, R.N., 2005. Pedestrian exposure to air pollution along a major road in Central London, UK. *Atmos. Environ.* 39, 7307–7320.
- Keukens, M.P., Moerman, M., Voogt, M., Blom, M., Weijers, E.P., Rockmann, T., Dusek, U., 2013. Source contributions to PM2.5 and PM10 at an urban background and a street location. *Atmos. Environ.* 71, 26–35.
- Kleinman, M.T., Sioutas, C., Chang, M.C., Boere, A.J.F., Cassee, F.R., 2005. Ambient fine and coarse particle suppression of alveolar macrophage functions. *Source Toxicol. Lett.* 137, 151–158.
- Langner, M., Kull, M., Endlicher, W.R., 2011. Determination of PM10 deposition based on antimony flux to selected urban surfaces. *Environ. Pollut.* 159, 2028–2034.
- Lenschow, P., Abraham, H.-J., Kutzner, K., Lutz, M., Preu, J.-D., Reichenbacher, W., 2001. Some ideas about the sources of PM10. *Atmos. Environ.* 35, 23–33.
- Litschke, T., Kuttler, W., 2008. On the reduction of urban particle concentration by vegetation – a review. *Meteorol. Z.* 17, 229–240.
- McCrone, W.C., Delly, J.G., Palenik, S.J., 1979. The Particle Atlas: an Encyclopedia of Techniques for Small Article Identification. Ann Arbor Science Publishers, Ann Arbor, USA.
- Mitchell, R., Maher, B.A., Kinnersley, R., 2010. Rates of particulate pollution deposition onto leaf surfaces: temporal and inter-species magnetic analyses. *Environ. Pollut.* 158, 1472–1478.
- Nowak, D.J., Crane, D.E., Stevens, J.C., 2006. Air pollution removal by urban trees and shrubs in the United States. *Urban For. Urban Green.* 4, 5–123.
- Ottelé, M., van Bohemen, H.D., Fraaij, A.L.A., 2010. Quantifying the deposition of particulate matter on climber vegetation on living walls. *Ecol. Eng.* 36, 154–162.
- Paulté, S., 2003. Urban street tree plantings: identifying the key requirements. In: Proceedings of the ICE – Municipal Engineer 156, pp. 43–50.
- Pfanz, H., Flohr, S., 2007. Die Wirkung von Holzgewächsen auf Stäube und die mögliche Rückwirkung der Stäube auf Pflanzen. In: Roloff, A., Thiel, D., Weiß, H. (Eds.), *Forstwissenschaftliche Beiträge Tharandt*, Beiheft 6, pp. 58–66.
- Prusty, B.A.K., Mishra, P.C., Azeezb, P.A., 2005. Dust accumulation and leaf pigment content in vegetation near the national highway at Sambalpur, Orissa, India. *Ecotoxicol. Environ. Saf.* 60, 228–235.
- Pyatt, F.B., 1973. Some aspects of plant contamination by air borne particulate pollutants. *Int. J. Environ. Stud.* 5, 215–220.
- Pyatt, F.B., Haywood, W.J., 1989. Airborne particulate distribution and their accumulation in tree canopies. *Nottingham, U.K. Environmentalist* 9, 291–298.
- Räsänen, J.V., Holopainen, T., Joutsensaari, J., Ndamb, C., Pasanen, P., Rinnan, Å., Kivimäenpää, M., 2013. Effects of species-specific leaf characteristics and reduced water availability on fine particle capture efficiency of trees. *Environ. Pollut.* 183, 1–7.
- Reznik, G., Schmidt, E., 2008. Abscheidung von Feinstaub an Pflanzen bei niedrigen Strömungsgeschwindigkeiten. *Chem. Ing. Tech.* 80, 1849–1853.
- Ries, K., Eichhorn, J., 2001. Simulation of effects of vegetation on the dispersion of pollutants in street canyons. *Meteorol. Z.* 10, 229–233.
- Sæbø, A., Popek, R., Nawrot, B., Hanslin, H.M., Gawronski, H., Gawronski, S.W., 2012. Plant species differences in particulate matter accumulation on leaf surfaces. *Sci. Total Environ.* 427–428, 347–354.
- Säumel, I., Kotyuk, I., Hölscher, M., Lenkereit, C., Weber, F., Kowarik, I., 2012. How healthy is urban horticulture in high traffic areas? Trace metal concentrations in vegetable crops from plantings within inner city neighbourhoods in Berlin, Germany. *Environ. Pollut.* 165, 124–132.
- Salim, S.M., Cheah, S.C., Chan, A., 2011. Numerical simulation of dispersion in urban street canyons with avenue-like tree plantings: comparison between RANS and LES. *Build. Environ.* 46, 1735–1746.
- Samet, J.M., Dominici, F., Curriero, F.C., Coursac, I., Zeger, S.L., 2000. Fine particulate air pollution and mortality in 20 U.S. cities, 1987–1994. *N. Engl. J. Med.* 343, 1742–1749.
- Senstadt, 2010. Luftgütemessdaten 2010. <http://www.stadtentwicklung.berlin.de/umwelt/luftqualitaet/de/messnetz/download/jahresbericht2010.pdf>.
- Speak, A.F., Rothwell, J.J., Lindley, S.J., Smith, C.L., 2012. Urban particulate pollution reduction by four species of green roof vegetation in a UK city. *Atmos. Environ.* 61, 283–293.
- Steubing, L., Klee, R., 1970. Vergleichende Untersuchung zur Staubfilterung von Laub- und Nadelgehölzen. *Angew. Bot.* 44, 73–85.
- Thönnessen, M., 2000. Staubfilterung und immissionshistorische Aspekte am Beispiel fassadenbegrenzenden Wilden Weins (*Parthenocissus tricuspidata*). *Umweltwiss. Schadstoff-Forsch.* 18, 5–12.
- Tubby, K.V., Webber, J.F., 2010. Pests and diseases threatening urban trees under a changing climate. *Forestry* 83, 451–459.
- UBA, 2009. Feinstaubbelastung in Deutschland. Hintergrundpapier. <http://www.umweltbundesamt.de/uba-info-medien/3565.html>.
- UNEP, 2007. Global Environment Outlook: Environment for Development (GEO-4).
- VDI, 1997. VDI 2119 Part 4. Measurement of Particulate Precipitations - Microscopic Differentiation and Size Fractionated Determination of Particle Deposition on Adhesive Collection Plates Sigma-2 Sampler. Beuth-Verlag, Berlin, Germany.
- Villeneuve, P.J., Burnett, R.T., Shi, Y.L., Krewski, D., Goldberg, M.S., Hertzman, C., Chen, Y., Brook, J., 2003. A time-series study of air pollution, socioeconomic status, and mortality in Vancouver, Canada. *J. Expo. Anal. Environ. Epidemiol.* 13, 427–435.
- Vos, P.E.J., Maiheu, B., Vankerkom, J., Janssen, S., 2012. Improving local air quality in cities: to tree or not to tree? *Environ. Pollut.* 183, 113–122.
- Walton, W.H., 1948. Feric's statistical diameter as a measure of particle size. *Nature* 162, 329–330.
- Wang, L., Liu, L.-U., Gao, S.-Y., Hasi, E., Wang, Z., 2006. Physiochemical characteristics of ambient particles settling upon leaf surfaces of urban plants in Beijing. *J. Environ. Sci.* 18, 921–926.
- WHO, 2005. Air Quality Guidelines Global Update 2005.
- WHO, 2007. Improving Public Health Responses to Extreme Weather/heat-waves – EuroHEAT.
- Yeatts, K., Svendsen, E., Creason, J., Alexis, N., Herbst, M., Scott, J., Kupper, L., Williams, R., Neas, L., Cascio, W., Devlin, R.B., Peden, D.B., 2007. Coarse particulate matter (PM2.5–10) affects heart rate variability, blood lipids, and circulating eosinophils in adults with asthma. *Environ. Health Perspect.* 115, 709–714.
- Yunus, M., Dwivedi, A.K., Kulshreshtha, K., Ahmad, K.J., 1985. Dust loading on some common plants near Lucknow City. *Environ. Pollut. Ser. B* 9, 71–80.