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Review

Review on urban vegetation and particle air pollution – Deposition and dispersion

Sara Janhäll

Swedish National Road and Transport Research Institute-VTI, Sweden

HIGHLIGHTS

- Combining deposition and dispersion helps designing urban vegetation related to air quality.
- The dilution of emissions with clean air from aloft is crucial; limit high urban vegetation.
- High concentrations of air pollutants increase deposition; vegetation should be close to the source.
- Air floating above, and not through, vegetation barriers is not filtered; decides barrier porosity.
- Differently designed vegetation catch different particle sizes.

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ABSTRACT

Urban vegetation affects air quality through influencing pollutant deposition and dispersion. Both processes are described by many existing models and experiments, on-site and in wind tunnels, focussing e.g. on urban street canyons and crossings or vegetation barriers adjacent to traffic sources. There is an urgent need for well-structured experimental data, including detailed empirical descriptions of parameters that are not the explicit focus of the study.

This review revealed that design and choice of urban vegetation is crucial when using vegetation as an ecosystem service for air quality improvements. The reduced mixing in trafficked street canyons on adding large trees increases local air pollution levels, while low vegetation close to sources can improve air quality by increasing deposition. Filtration vegetation barriers have to be dense enough to offer large deposition surface area and porous enough to allow penetration, instead of deflection of the air stream above the barrier. The choice between tall or short and dense or sparse vegetation determines the effect on air pollution from different sources and different particle sizes.

1. Background

Urban vegetation is currently popular for the ecosystem services it can provide, such as reducing problems with flooding. Positive effects on air quality through filtration of polluted air are often mentioned, but without taking reduced dilution into account. As urban vegetation is also a way to abate the effects of climate change, e.g. rising sea level and global warming, many cities are increasingly including urban vegetation in their plans (Andersson-Sköld et al., 2015). A few reviews have been published in related areas, focussing on e.g. particle deposition on vegetation (Litschke and Kuttler, 2008); dry deposition on plant canopies (Petroff et al., 2008a); urban green space and social justice (Wolch et al., 2014); and dispersion without the complication of vegetation (Xia et al., 2014). Many studies have attempted to estimate the economic benefits of improving air quality, although the effect of vegetation on urban air quality is not yet fully understood (Tiwary et al., 2009; Escobedo et al., 2011).

The aim of this literature review was to appraise the physical effects linking vegetation to air quality from two perspectives, deposition and dispersion, and to provide input on the design of urban vegetation related to air quality. Particulate pollutants were considered in particular, as they have major health impacts and as physical processes differ for different size classes, introducing an extra complication compared with gaseous pollutants. The physical processes were reviewed at different scales, including the effects of particle properties and vegetation properties. Emissions from vegetation were excluded, as was transformation of pollutants in

E-mail address: sara.janhall@vti.se.

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the air. Dispersion was assessed by reviewing on-site measurements, wind tunnel studies and modelling approaches, with examples from both street canyons and vegetation barriers. Unfortunately, few experimental studies combining detailed descriptions of both dispersion and deposition were available for review.

This paper commences with a description of the deposition process, followed by vegetation and then dispersion within urban areas. Finally, the effects of vegetative barriers are described and recommendations on vegetation design are provided. All parts include measured and modelled data and each part ends with a short summary of the topic.

2. Deposition

Airborne particles and gas molecules can be deposited when they pass close to a surface. Most plants have a large surface area per unit volume, increasing the probability of deposition compared with the smooth, manufactured surfaces present in urban areas. For example, 10–30 times faster deposition has been reported for sub-micrometre (<μm) particles on synthetic grass compared with glass and cement surfaces (Roupsard et al., 2013). Particle size, among other parameters, has a great effect on deposition. Ultrafine particles, below ~0.1 μm, behave more like gas molecules and are deposited by diffusion; 1–10 μm particles impact on surfaces that force the air stream to bend; and particles >10 μm in diameter also fall to the ground by sedimentation (Hinds, 1999).

Deposition on vegetation is usually described as one-dimensional vertical deposition on a homogeneous layer of vegetation in the form of a forest or field. For urban applications, the vegetation is often merely single trees or bushes, or linear stands forming avenues and barriers, and the deposition process needs to be modelled in more detail. However, most of the physics can easily be described using the situation of an airstream passing a single leaf surface instead of a whole forest.

Simplified one-dimensional deposition is divided into transport from free air to the surface; across the laminar layer adjacent to the surface; and processes relating to surface properties. The deposition velocity, v_d, is often described as the reciprocal of resistance to deposition, R_{tot} (equation (1)). R_{tot} can be divided into a sum of resistances relating to each of these transport processes, namely R_a = aerodynamic resistance, R_b = boundary resistance and R_c = surface resistance (Davidson and Wu, 1990).

$$v_d = \frac{1}{R_{tot}} = \frac{1}{R_a} + \frac{1}{R_b} + \frac{1}{R_c} \tag{1}$$

The aerodynamic resistance is normally considered small compared with the other types and is thus set to zero, unless the study is focussing on particles with high settling velocity[1] (Hinds, 1999), i.e. with a particle diameter above 10 μm diameter (Slinn, 1982; Davidson et al., 1982). The deposition velocity is always larger than the settling velocity (Petroff et al., 2008a). In this context, the aerodynamic resistance is also related to dispersion. For aerodynamic resistance, R_a, meteorology is important and both R_a and the boundary layer resistance, R_b, depend on the reciprocal of the friction, or shear, velocity (Bruse, 2007; Petroff et al., 2008a).

Vong et al. (2010) showed that the deposition velocity measured for 0.2–0.5 μm particles depends on the atmospheric stability of the boundary layer, described by the Monin-Obukov length, L, and linearly on the particle diameter, D_p (equation (2)). Other dependencies are collected within the empirical constant A, which is 0.63 over pine forest (Vong et al., 2010), 1.35 over forests (Gallagher et al., 1997) and 0.2 over grass (Wesely et al., 1985).

$$v_d = A^* u_*{}^* D_p{}^* \left(1 + \left(-\frac{300}{L}\right)^{2/3}\right) \tag{2}$$

The deposition velocity for super-micrometre particles increases with size due to increasing impaction rate and, for vertical deposition, settling velocity, while for sub-micrometre particles it decreases with size. The minimum deposition velocities reported in the literature are 0.1–0.3 μm (Slinn, 1982; Davidson et al., 1982; Litschke and Kuttler, 2008; Petroff et al., 2008a; Lin and Khlystov, 2011). Particulate matter (PM) size is often reported in large size classes, e.g. PM_{10} includes particles <10 μm in diameter which have an average diameter of either 5.0 or 0.1 μm, giving deposition velocities differing by about 100-fold (Litschke and Kuttler, 2008). Number of particles emphasises smaller particles, while particle mass emphasises larger particles.

Discrepancies can also arise depending on the complexity of the measurements. For example, Freer-Smith et al. (2005) divided particles into size fractions obtained from samples in solution and attributed all dissolved particle mass to the sub-micrometre particle size range, i.e. to airborne sub-micrometre particle mass, which thus got a huge deposition velocity. Litschke and Kuttler (2008) reported that hygroscopic particles (marine) can increase their deposition velocity by 5- to 6-fold, changing the relative humidity from 40% to 99%, and with deposition 16- to 25-fold faster in 99.9% relative humidity. Thus if humidity is not stated in the literature source, the deposition velocity for hygroscopic particles might be difficult to use. Deposition velocity data obtained from net transport of particles to surfaces indicate that sticky surfaces have greater deposition velocity than dry surfaces, e.g. as shown for 18 μm particles by Petroff et al. (2008a). Many discrepancies between published deposition velocity values are due to differences not included in the analysis (Litschke and Kuttler, 2008; Petroff et al., 2008a).

Deposition velocity, v_d, for different types of vegetation is often measured in wind tunnels, which normally force all available air to pass through the vegetation. However, this is usually not the case under ambient conditions, where the air stream can pass above or around the vegetation (see section on Barriers). In a study where the particles tested were 0.01–0.1 μm in diameter and the wind speed was 0.3–1.5 m s^{-1} , cypress (*Cupressus leylandii*) and pine (*Pinus sylvestris* L.) hedges were found to be filters with an effective filter diameter in the same range as pine needles (Lin et al., 2012). Those results confirm earlier findings that deposition velocity decreases with size for sub-micrometre particles (Petroff et al., 2008a).

$$Deposited\ amount\left(g/m^2\right) = LAI^* v_d{}^* C^* t \tag{3}$$

The amount of material deposited per unit ground area and time is often calculated by equation (3), where LAI is Leaf Area Index, i.e. the amount of vegetation surface area per m^2 of ground area; v_d is the deposition velocity; C is the air concentration of the pollutant; and t is the time. The definition of LAI varies slightly, see below. A detailed model for transport and deposition on needles was successfully applied to three different datasets by Petroff et al. (2008b), who found slight over-prediction of capture efficiency for super-micrometre particles in light winds. The model is based on a data review (Petroff et al., 2008a) and has been further developed for broad-leaved canopies (Petroff et al., 2009). These models include all different kinds of deposition of particles (diffusion, interception, impaction, sedimentation) but exclude some processes, e.g. interactions among particles and between particles and gases,

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[1] Velocity of a falling particle under zero acceleration.