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Experimental examination of effectiveness of vegetation as bio-filter of particulate matters in the urban environment

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Studies focused on pollutants deposition on vegetation surfaces or aerodynamics of vegetation space conflict in whether vegetation planting can effectively reduce airborne particulate matter (PM) pollution. To achieve a more comprehensive understanding of the conflict, we conducted experiments during 2013 and 2014 in Beijing, China to evaluate the importance of vegetation species, planting configurations and wind in influencing PM concentration at urban and street scales. Results showed that wind field prevailed over the purification function by vegetation at urban scale. All six examined planting configurations reduced total suspended particle along horizontal but not vertical direction. Shrubs and trees–grass configurations performed most effectively for horizontal PM2.5 reduction, but adversely for vertical attenuation. Trapping capacity of PMs was species-specific, but species selection criteria could hardly be generalized for practical use. Therefore, design of planting configuration is practically more effective than tree species selection in attenuating the ambient PM concentrations in urban settings.

1. Introduction

Rapid urbanization over past decades has increased urban population with inhalation exposure to hazardous air pollutants (Du et al., 2014). Widespread breakouts of smog events across China have drawn increasing public attention to airborne particulate pollutants. The fine (aerodynamic diameter of particles ≦2.5 μm) and ultrafine (particles<0.1 μm) particles originated from anthropogenic sources can be transported further in human pulmonary alveoli resulting in more serious health impacts (Hofman et al., 2013). Complications of chronic PM exposure include premature deaths, allergy, cardiovascular and respiratory diseases, even lung cancer (Cohen et al., 2005; Hofman et al., 2013; Remy et al., 2011). With realization of the adverse health effects, a number of measures have been taken to mitigate particulate air pollution at the source to constrain atmospheric concentration levels, including emission reductions, limitations and targets (e.g. WHO Air Quality Guidelines (WHO, 2006)). Exploration of the potential mitigation effect of vegetation is one of these efforts (Beckett et al., 1998; Litschke and Kuttler, 2008; Yang et al., 2005).

Vegetation captures gases, particulates and aerosols from the atmosphere more effectively than other land surfaces (Tallis et al., 2011). Therefore, vegetation surfaces can serve as a sink for atmospheric particles and an interface where some elemental nutrients adhering to the particulate matters (PMs) can be absorbed. Forests are efficient sinks for most atmospheric pollutants (Nowak et al., 2000; Nowak and Crane, 2002). Studies showed that trees can reduce concentrations of ammonia plume by deposition to plant cuticles and stomatal uptake (McDonald et al., 2007; Tiwary et al., 2006). Assessment found that urban vegetations in Guangzhou, China can eliminate 312.03 Mg of SO_2, NO_2 and total suspended particles (TSP) on an annual basis (Jim and Chen, 2008). PM removal by urban trees in the United States has been estimated at 711,000 tones (t) per year (Nowak et al., 2006). It has been estimated that existing urban forests in Chicago have removed 212 ton of PM_{10} each year (McPherson et al., 1994). Moreover, model results estimated that urban trees improve air quality by removing 0.2–1.0% for PM_{10} (Nowak et al., 2006).

However, some studies on aerodynamics demonstrated that vegetation can also be negative in reducing atmospheric pollution. For example, trees along the street canyon block effective ventilation and thus lead to higher local concentration of pollutant (Gromke and Ruck, 2007, 2009). It is known that vegetation design and structure can influence the microclimate. Meteorological

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parameters, such as precipitation, wind speed, turbulence and air humidity, are important factors (Litschke and Kuttler, 2008). Statistical analysis indicated that temperature and wind direction were significant factors influencing PM_{10} attenuation. Therefore, one thing should be considered is the spatial planting configuration. During dry periods, planting configurations influence wind speed that cause interception or re-suspension of particles. Another aspect that should be considered is the species selection. It is important to note that different species have different properties, such as leaf size, stomata, vegetation structure and leaf microstructure which will affect the capture efficiency (Freer-Smith et al., 2004; Mori et al., 2015; Räsänen et al., 2013). The inertia of particles travelling in an air stream as it curves around an object, such as a leaf or stem, forces them through the boundary layer and onto the object. For example, as a result of their large canopy surface area of leaves, stem and branches and the air turbulence created by their structure, trees are more effective in the uptake of these materials than shorter vegetation (Lovett, 1994). It was found that woodlands collected three times more PM_{10} than grassland in the West Midlands of England (Fowler et al., 2004).

As an important urban morphological mechanism that provides both social and ecosystem services in metropolitan areas, the conflicting influences of urban green spaces in reducing PM pollution poses a conundrum for using them in urban planning. To understand this confliction and facilitate effective use of vegetation in PM pollution control, this study was conducted during 2013 and 2014 in Beijing, China, aiming to evaluate the importance of species, spatial planting configuration and wind effect in influencing PM dispersion on urban and street scales specifically by answering two questions: (1) at urban scale, which is more effective in influencing PM pollution concentration, physical characteristics of large area of vegetation or the ventilation effect of urban wind field? If the previous is the case, maximization of green space can bring ideal effect. If the latter is the case, importance should be attached to the urban planning configurations that optimize pollution-diluting micrometeorology. (2) On the street scale, what are the roles of species differences and spatial planting configuration in removing air PM pollution? This also responds to practical needs in detailed green space design and further understanding under what circumstances and at what scale vegetation may capture enough PM to improve air quality and under what circumstances vegetation has no or maybe even a negative effect on air quality (Buccolieri et al., 2009).

2. Materials and methods

The study contained three major parts corresponding to the raised questions: 1) Exploration of the relationship between meteorological factors, vegetation coverage and PM2.5 concentration at urban scale. On a finer scale, we designed 2) Leaf-washing experiments to determine the role of species differences; and 3) on-site street-monitoring to test the differences of planting configurations in affecting air PM concentration.

2.1. Green space, wind data and PM concentration distribution at urban scale

The study was conducted in the city of Beijing, China, during 2013–2014. We included all blocky green space over 10 m^2 as a whole subject for study at urban scale. The original green space data within 5^{th} ring road was obtained from Google and extracted using ArcGIS 10.2 (Fig. 1). Combined with PM2.5 data, this enabled us to examine the correlation between vegetation layout and PM2.5 distribution across the urban area.

Daily PM2.5 concentration from June 2013 to May 2014 was collected from the website of Beijing Municipal Environmental Monitoring Center (http://www.bjmemc.com.cn/). The daily values were computed into seasonal average (Summer(2013): 1^{st} June to 31^{st} August; Autumn: 1^{st} September to 31^{st} November; Winter: 1^{st} December to 29^{th} Feburary; Spring (2014):1st March to 31st May). Intepolation analysis was conducted in ArcGIS 10.2 using data from all 21 sites (Fig. 1) and thus derived the spatial distribution characteristics of urban Beijing (within 5^{th} Ring Road). We used Original Kriging for the interpolation approach because of its proved flexibility and effectiveness in quantifing the spatial auto-correlation based on observed samples. Moreover, it had high accuracy in predicting normalized data (Zhao et al., 2014).

Corresponding to the PM data at urban scale, daily wind data (accuracy: 1 m/s) of urban Beijing from June 2013 to October 2014 were downloaded from China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/home.do). The monitoring instrumentation is not given by the system but the data were already processed to represent the whole area within the 5^{th} ring road when downloaded from the website. To study the seasonal relationship between the wind and the pollution distribution, daily data were divided into two periods, winter–spring (W–S) period which started from 1^{st} December to 31^{st} May next year and summer–autumn (S–A) period which lasted from 1^{st} June to 31^{st} November the same year.

2.2. PM comparison by different planting configurations

Traffic (47.9%) and combustion (29.7%) aerosol were found to dominate the particle number concentrations (Liu et al., 2014). Therefore, we chose road scenario to conduct on-site study. Previous analysis revealed seven structural types of urban green spaces in Beijing (Zhao et al., 2014), which included Tree (as a category), Shrub, Grass, Tree–Shrub, Shrub–Grass and Tree–Grass–Shrub. Therefore, six greenbelts of different planting configurations along the same main road were selected as the monitoring sites (Fig. 2). The greenbelts were over 50 m in length and 1 m in width. The species information can be found in Table 1.

The monitoring campaigns were conducted during daytime (7:00–19:00) when the relative humidity was low (RH<60%) and the wind speed was below 6 m/s from March to April. Study adopted stationary monitoring approaches to determine the effects of existing, mixed-species tree stand on near-road particulate matter concentrations. Wind direction and source pollution concentration influence the dry deposition on the plants. Given that the wind field in streets can be complicatedly various, only data from days without prevail wind direction was used. Moreover, we hypothesized that the source concentration along the main road is uniform because it is impossible to find a site with all sorts of planting configurations in real situation. Sites are 500 m away from each other in average (890 m from site A to site B, 360 m from site B to site C) and background differences among the sites are minimized. Parallel to the greenbelts and perpendicular to the main road, the PM monitoring equipments (Dustmate, Tunkey Co., UK) were deployed in alignment at 10 m and 20 m away from the curb (Fig. 3). At each monitoring point, two Dustmates were installed at the height of 1.5 m and 3 m, respectively, to sample PM concentration. A portable meteorological station (NK4500, Kestrel Co., USA) was also fixed at the height of 1.5 m to collect on-site environmental information. Linear regression was used to test the relationship between micrometeorological and PM data to explore the contributors to PM concentration changes.

In order to characterize the ability of greenbelt to remove PM, the PM removal ratio or reduction rate (P, purification efficiency) along the horizontal and vertical direction at each test point was calculated as follows: