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Spatial distribution assessment of particulate matter in an urban street canyon using biomagnetic leaf monitoring of tree crown deposited particles

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ABSTRACT

Recently, biomagnetic monitoring of tree leaves has proven to be a good estimator for ambient particulate concentration. This paper investigates the usefulness of biomagnetic leaf monitoring of crown deposited particles to assess the spatial PM distribution inside individual tree crowns and an urban street canyon in Ghent (Belgium). Results demonstrate that biomagnetic monitoring can be used to assess spatial PM variations, even within single tree crowns. SIRM values decrease exponentially with height and azimuthal effects are obtained for wind exposed sides of the street canyon. Edge and canyon trees seem to be exposed differently. As far as we know, this study is the first to present biomagnetic monitoring results of different trees within a single street canyon. The results not only give valuable insights into the spatial distribution of particulate matter inside tree crowns and a street canyon, but also offer a great potential as validation tool for air quality modelling.

1. Introduction

To date, a continuously increasing urbanization has resulted in health-threatening concentrations of air pollutants, especially in urban areas. Urban outdoor air pollution is estimated to cause 1.3 million deaths worldwide per year (WHO, 2011). Particulate matter (PM) is of particular interest because it affects more people than any other pollutant (WHO, 2011). In three Belgian cities (Antwerp, Brussels and Liège), evidence suggested that 5.5% of the mortality is attributable to PM_{10} concentrations higher than the reference level (20 $\mu g/m^3$) (Remy et al., 2011). PM consists of a complex mixture of both liquid and solid particles of organic and inorganic substances suspended in the air, and is divided into different fractions based on its aerodynamic diameter. The coarse fraction represents particles smaller than 10 μm and is health related because of its ability to enter the respiratory tract (Langner, 2007). Within the PM_{10} fraction, fine particles represent particles smaller than 2.5 μm and ultrafine particles are smaller than 0.1 μm. While the coarse fraction largely consists of particles that originate from natural sources, the fine and ultrafine particles originate from anthropogenic sources. The smaller the particles, the further they are transported in our pulmonary alveoli, which will result in more serious health impacts (Donaldson et al., 2001). Health impacts of chronic PM exposure involve cardiovascular and respiratory diseases, as well as lung cancer (Donaldson et al., 2001; Remy et al., 2011).

Because of the adverse health effects, the mitigation of particulate air pollution is mainly aimed at source measures, where emission reductions, limitations and targets are pursued to constrain atmospheric concentration levels (e.g. WHO Air Quality Guidelines (WHO, 2006)). Although source regulations are indispensable in the mitigation of air pollution, growing interest has heightened the need for exposure measures that influence atmospheric pollutant concentrations by stimulating deposition and/or dispersion processes. In this context, former research concentrated on the potential mitigation effect of vegetation (Beckett et al., 1998; Yang et al., 2005; Litschke and Kuttler, 2008). In addition to already known ecosystem services like carbon sequestration, micro-climate regulation, noise reduction, rainwater drainage, psychological and recreational values (Ulrich, 1984; Bolund and Hunhammar, 1999; Chen and Jim, 2008; Jim and Chen, 2009; Li et al., 2010), the mitigation of air pollution can serve as an important additional ecosystem service of urban green. Because of its high leaf area relative to the ground area it covers, vegetation (especially trees) can influence local atmospheric PM concentrations through both direct and indirect effects. While vegetation will lower ambient particle concentration by stimulating deposition on its surface (direct effect), vegetation will also affect wind speed and direction and therefore the dispersion of PM polluted air (indirect effect) (Langner, 2007). Research indicated that this indirect effect is able

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to reduce, but also concentrate atmospheric particles. Several studies namely suggest that trees in street canyons reduce the air circulation and therefore lead to higher local PM concentrations (Vardoulakis et al., 2003; Gromke and Ruck, 2007; Wesseling et al., 2011). In the literature, this effect is referred to as the reduced ventilation hypothesis. So far, investigations of this hypothesis have been mainly restricted to model studies and wind tunnel experiments while field data are still missing.

In the last few years, biomonitoring, which can be defined as the measurement of the response of living organisms to changes in their environment (Nali and Lorenzini, 2007), has been proposed as a solution to the air pollution monitoring problem (Moreno et al., 2003). As plants are immobile and more sensitive in terms of their physiological reaction to the most prevalent air pollutants than humans and animals, they better reflect local conditions (Nali and Lorenzini, 2007). Biomonitoring can be based on the evaluation of anatomical, morphological and physiological characteristics, or the analysis of trace elements in plants like lichens, mosses, grasses or tree leaves (Matzka and Maher, 1999; Balasooriya et al., 2009; Kardel et al., 2010, 2011, 2012a; Wuytack et al., 2010; Ares et al., 2012). Iron, which often occurs as an impurity in fossil fuels during industrial, domestic or vehicle combustion, can be considered as such a trace element. During the combustion process, carbon and organic material are lost by oxidation whilst the iron forms a non-volatile residue, often comprising glassy spherules (due to melting). Depending on the fuel type and temperature of combustion, spherules contain variable amounts and grain sizes of magnetite (Fe_3O_4) and/or haematite (Fe_2O_3) (Matzka and Maher, 1999; Goddu et al., 2004). In addition to combustion, vehicles also generate non-spherical Fe-rich particles in manners of exhaust emissions, abrasion/corrosion of engine and vehicle body materials (Lu et al., 2008). The ferro(i)magnetic PM fraction can be quantified by the Saturated Isotherm Remanent Magnetization (SIRM), which represents the magnetization retained by a sample after exposure to a large magnetic field, e.g. 300 mT or 1 T (Matzka and Maher, 1999). A magnetic study of urban dusts in the centre of Munich (Matzka, 1997) identified a high correlation between total PM_{10} dust mass and its SIRM concentration while Lu et al. (2008) found strong correlations between magnetic properties of dusts on urban tree leaves and heavy metal concentrations of Fe, Mn and Cu ($r > 0.885$), derived from combustion, industrial activities and vehicle exhaust processes. Within the field of biomonitoring, magnetic properties offer a rapid, cost-effective and non-destructive method to investigate the spatial and temporal pattern of urban dust loadings on leaves of roadside trees (Matzka and Maher, 1999; Kardel et al., 2011; Zhang et al., 2012). Especially in urban areas, where the spatial resolution of active PM monitoring is limited due to high investment and maintenance costs of the monitoring stations, biomagnetic monitoring seems to be a valuable alternative (Kardel et al., 2012b). Moreover, biomonitoring is seen as a valuable measure for long-term pollution loadings (Moreno et al., 2003; Szönyi et al., 2008; Kardel et al., 2011), since a proxy for the particulate load cumulated over the entire growth season is obtained (Kardel et al., 2011). The long exposure time of this technique has two advantages. Firstly, it integrates the exposed particulate concentrations over the entire season and secondly, due to its integrating nature it might be indicative for health impacts which are also due to a long-term exposure (Pope et al., 2002; WHO, 2006).

This paper reports on small-scale variations of PM depositions within an urban tree crown, a street canyon and the possible effect of trees on the dispersion of atmospheric particulates. Within this objective, we specifically focus on four hypotheses. We firstly hypothesize that within individual tree crowns, SIRM values will decrease with increasing height. This height effect is already described by former research (Mitchell and Maher, 2009), but has never been shown within individual tree crowns. Secondly, we expect azimuthal variation within individual tree crowns, depending on the street architecture and wind flow fields which influences atmospheric particulate dispersion. Thirdly, we will examine the PM variation throughout the street canyon by concentrating on the position of the trees in the street canyon (edge – canyon) to identify potential edge effects of street canyons and the formerly described reduced ventilation hypothesis. Finally, the effect of distance from the expected main pollution source will be tested. A reduction of the SIRM signal with increasing distance from the pollution source may therefore be expected. By reporting on the abovementioned hypotheses we will present the first biomagnetic monitoring data of leaf deposited particles of different trees within a single street canyon. Leaf material of London plane (*Platanus* × *acerifolia* Willd.) trees is hereby used as a bio-indicator for the ambient PM concentration.

2. Materials and methods

2.1. Study area

The Kunstlaan (51°2′26.22″ N, 3°43′27.11″ E) in Ghent, Belgium, was chosen as the study area. This street is located in the densely populated city center and consists of two opposing traffic lanes separated by two rows of London plane (*Platanus* × *acerifolia*) trees (Fig. 1). Underneath the trees, and thus in between the two traffic lanes, a bicycle path is located (Fig. 2). The Kunstlaan connects the inner city ring road (R40), which is considered as the beginning of the Kunstlaan, with the Overpoortstraat, which is considered as the end of the Kunstlaan (Fig. 2). The ring road has an average traffic intensity of 2460 vehicles (passenger cars + heavy duty traffic) per hour while the Kunstlaan has an average traffic intensity of 397 vehicles per hour, as indicated by most recent counting campaigns (October 2007 and March 2009) by the city of Ghent during the morning and evening rush hour. The R40 can be considered as a traffic intensive thoroughfare in the city center of Ghent and therefore the main local pollution source.

The Kunstlaan has a typical street canyon geometry with a width (W) of 24 m, a height (H) of 10 m and a length (L) of 200 m (Fig. 2). According to the geometry rules described by Vardoulakis et al. (2003), the street can thus be described as a long ($L/H > 7$) avenue street canyon (aspect ratio (H/W) < 0.5). The street canyon is continuous, except for a crossing street (Kattenberg) in the middle of the street canyon (Fig. 1).

2.2. Leaf sampling

Since previous research suggests that differences in leaf SIRM become more pronounced as the growing season proceeds due to a prolonged exposure time (Kardel et al., 2011), leaf samples were collected towards the end of the growth season, i.e. on August 29th, 2011. No rain events occurred during the sampling campaign. It did, however, rain on days prior to the sampling campaign (Fig. 3), but these events were only small (<17 mm).

The tree crowns of the *Platanus* × *acerifolia* trees were densely foliated and reached from a height of about 4 m (onset of the crown) to 13 m (top of the crown). Eight trees (see Fig. 1) with similar crown dimensions were sampled throughout the street canyon by means of a boom lift. From the 8 sampled trees, T1, T4, T5 and T8 were regarded as edge trees (e) since they were positioned at the edges of the street canyon, while T2, T3, T6 and T7 were regarded as canyon trees (c) since they were positioned inside the street canyon and completely surrounded by other tree crowns and street walls (Fig. 1). For each tree crown, leaf sampling occurred at the outer surface of the crown at three heights (5, 8 and 12 m) and four different wind directions parallel and perpendicular to the street axis (NE, SE, SW and NW with respect to the tree trunk). Doing so, four sampling locations were obtained at every height and twelve sampling locations for each of the eight considered tree crowns. At each sampling location, four samples were collected, with each sample consisting of three fully developed and undamaged leaves for SIRM determination.

2.3. Specific leaf area determination

For each tree, 10 additional leaves were collected for SLA (Specific Leaf Area) determination, calculated by dividing leaf surface (cm^2) area by its dry weight (g). Leaf area of the fresh leaves was determined by means of a leaf area meter (Li-3000 leaf area meter, Li-COR, Lincoln, Nebraska) with an accuracy of 0.01 cm^2. Subsequently, leaves were oven-dried at 45 °C for 5–6 days and the dry weight was determined with an electronic balance (ALS 220-4N, KERN & Sohn GmbH, Balingen, Germany) with an accuracy of 0.1 mg.