# Influence of tree crown characteristics on the local $PM_{10}$ distribution inside an urban street canyon in Antwerp (Belgium) : a model and experimental approach

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# Influence of tree crown characteristics on the local $PM_{10}$ distribution inside an urban street canyon in Antwerp (Belgium): a model and experimental approach

**Keywords:**

Particulate matter (PM); Urban green; Light detection and ranging (LiDAR); Leaf deposition; Tree crown; Leaf area density (LAD); Particle size fraction; Air pollution; Atmospheric modelling

## Abstract

Apart from influencing the amount of leaf-deposited particles, tree crown morphology will influence the local distribution of atmospheric particles. Nevertheless, tree crowns are often represented very rudimentary in three-dimensional air quality models. Therefore, the influence of tree crown representation on the local ambient $PM_{10}$ concentration and resulting leaf-deposited $PM_{10}$ mass was evaluated, using the three-dimensional computational fluid dynamics (CFD) model ENVI-met® and ground-based LiDAR imaging. The modelled leaf-deposited $PM_{10}$ mass was compared to gravimetric results within three different particle size fractions (0.2 - 3, 3 - 10 and >10 µm), obtained at 20 locations within the tree crown. Modelling of the LiDAR-derived tree crown resulted in altered atmospheric $PM_{10}$ concentrations in the vicinity of the tree crown. Although this model study was limited to a single tree and model configuration, our results demonstrate that improving tree crown characteristics (shape, dimensions and LAD) affects the resulting local $PM_{10}$ distribution in ENVI-met. An accurate tree crown representation seems, therefore, of great importance when aiming at modelling the local PM distribution.

**Capsule**

An accurate tree crown representation seems of great importance when aiming at modelling the local PM distribution in urban environments.

# 1. Introduction

In contemporary cities, vegetation exerts many so-called ecosystem services. Apart from carbon sequestration, micro-climate regulation, noise reduction, rainwater drainage, psychological and recreational values (Bolund and Hunhammar, 1999; Jim and Chen, 2009; Li et al., 2010; Ulrich, 1984), a significant amount of research has focussed on the air pollution mitigation potential of urban vegetation (Beckett et al., 1998; Litschke and Kuttler, 2008; McPherson et al., 1997; Nowak et al., 2006; Vos et al., 2013). Because of its high surface area, relative to the ground it covers, vegetation (especially trees) can influence local atmospheric particulate matter (PM) concentrations through both direct and indirect pathways. While vegetation can lower ambient particle concentrations by stimulating deposition on its surfaces (direct pathway), it can also affect wind flow and, therefore, the dispersion of PM polluted air (indirect pathway) (Langner, 2008). Research indicated that this indirect effect is able to reduce, but also increase local atmospheric particle concentrations (Gromke and Ruck, 2007; Vos et al., 2013). The impact of urban vegetation on air pollution is frequently estimated using three-dimensional (3D) air quality models in which urban vegetation is often represented very rudimentary, resulting from a lack of species-specific information (e.g. leaf area density (LAD), crown dimensions, tree height, …). Especially in urban environments, where species-specific tree crown morphology will depend on local environmental conditions (light-, water-, nutrient- and space availability) and experienced pruning frequency. Therefore, experimental datasets, including a thorough description of the vegetation inside urban areas, are needed to improve existing dispersion models (Janhäll, 2015). Most dispersion models include urban vegetation as spherical shapes or rectangular blocks with theoretical leaf area densities (Buccolieri et al., 2011; Gromke and Ruck, 2007; Litschke and Kuttler, 2008; Tong et al., 2016; Vos et al., 2013; Wania et al., 2012).

Nevertheless, as previous studies already showed a clear influence of tree foliation (Hofman et al., 2013; Salmond et al., 2013) and spatial implantation of urban green on local pollutant dispersion (Buccolieri et al., 2011; Gromke and Ruck, 2012, 2007; Vos et al., 2013; Wania et al., 2012), an accurate representation of urban tree crowns is hypothesized vital for pollutant dispersion modelling. Therefore, this study evaluates the effect of a detailed tree crown representation on the ambient $PM_{10}$ concentration and the resulting leaf-deposited $PM_{10}$ mass, using the 3D computational fluid dynamics (CFD) model ENVI-met®. Moreover, modelled leaf-deposited $PM_{10}$ results were compared to gravimetric results obtained from leaf samples of a London plane tree (*Platanus x acerifolia* Willd.).

# 2. Material and Methods

## 2.1 Sampling site

A typical urban London plane tree (*Platanus x acerifolia* Willd.) was selected in the densely populated city center of Antwerp, Belgium (Figure 1). The solitary tree is located on a roundabout (51°11'47.72"N, 4°25'24.81"E) in line with the *De Villegasstraat* street canyon, described in a previous study (Hofman et al., 2014a). While the roundabout itself is relatively quiet in terms of traffic volume (50 vehicles $h^{-1}$ (SGS, 2010)), it is located in the vicinity (200 and 400m) of two busy thoroughfares of Antwerp (*Singel* and *R1*), as can be seen from Figure 1.

{Figure 1}

***Figure 1:*** *Left panel: Location of the street canyon, "Singel" and ring road (R1) in Antwerp (source: Google). Right panel: photographic image (upper left; source: Google) and LiDAR scan (upper right) of the considered tree crown, with a sideview (lower) of the tree LiDAR hits and a plot of the number of LiDAR hits (x-axis) as a function of height (y-axis in meters).*

## 2.2 Gravimetric analysis of leaf samples

Quantitative information on the amount of leaf-deposited atmospheric particles was obtained by means of a leaf sampling campaign, according to the protocol described in Hofman et al. (2014a). Since differences in leaf Saturation Isothermal Remanent Magnetisation (SIRM) become more pronounced as the growing season proceeds due to a prolonged exposure time (Hofman et al., 2014b; Kardel et al., 2011), leaf samples were collected at the end of the growing season, i.e. on September 11, 2012. The tree was sampled at the outer surface by means of a boom lift at three heights (3.5, 8.5 and 13.5 m) and four azimuthal directions (NE, NW, SE, SW) around the tree crown. Next to leaf samples of the outer tree crown surface, leaf samples were collected from within the tree crown as well, at half the distance between the trunk and the crown outer surface, at two heights (3.5 and 8.5 m) and four azimuthal directions (NE, NW, SE, SW), resulting in 20 leaf sampling locations. Three leaf samples were collected for each leaf sampling location, with each sample consisting of five fully developed and undamaged leaves. The leaf samples were separately collected in paper bags, labelled and transported to the laboratory for analysis.

In the laboratory, the leaf samples were processed according to the procedure described in Hofman et al. (2014a). Each leaf sample was hand-washed in ultrapure water (<0.1 µS $cm^{-1}$) (Eurowater, Belgium). The washed leaf area was determined using a Li-3100 area meter (LI-COR Environmental, US). The washing water was subsequently filtered over pre-weighed Nuclepore track-etched polycarbonate filter membranes (Whatman, UK) with pore sizes of in succession 10 µm, 3 µm and 0.2 µm. Doing so, we collected three particle size fractions on the filter membranes: large (>10 µm), coarse (3-10 µm) and fine (0.2-3 µm). Loaded filter membranes were consequently dried at ambient temperature, equilibrated for 24 h at 50% relative humidity and weighed using a 1 µg precision Mettler MT5 balance (Mettler-Toledo International Inc., Switzerland). To avoid electrostatic charges on the filters, they were passed through an ionizer antistatic system (Mettler-Toledo International Inc., Switzerland) before weighing. Blank filter weights were determined for every size fraction by completing the entire filtration procedure using only Ultrapure water. The blank filter weight was consequently subtracted from the loaded filter weight. The resulting weights were finally normalized for washed leaf area yielding the leaf-deposited particulate weight (mg $m^{-2}$ leaf area) in three different size fractions (>10 µm, 3-10 µm and 0.2-3 µm).

## 2.3 ENVI-met® model configuration

Two model studies were conducted in ENVI-met® to, respectively, (i) evaluate the effect of a detailed three-dimensional tree crown representation on the modelled atmospheric $PM_{10}$ concentration and resulting leaf-deposition, and (ii) quantify the amount of leaf-deposited $PM_{10}$ for the representative exposure period of the collected leaf samples (May to September 2012).

ENVI-met® is a 3D computational fluid dynamics (CFD) model developed by Bruse & Fleer (1998). It is Reynolds Averaged Navier-Stokes (RANS) equations based, non-hydrostatic micro scale obstacle-resolving with advanced parameterizations for the simulation of interactions between urban surfaces, vegetation and atmosphere (Bruse and Fleer, 1998). ENVI-met was selected because of its ability to simulate the influence of plants on the atmosphere in a built environment at micro scale. This is useful since plants will not only alter the distribution of particulates, but also intercept particles on their surfaces. In ENVI-met®, sedimentation of particles due to gravitational forces and particle deposition to different surfaces (roofs, walls, vegetation and soils) is simulated, taking into account the aerodynamic and sub-layer (quasi laminar) surface resistances (Bruse, 2007). The initial variables required as an input in ENVI-met® are meteorological data, pollutant emissions and domain characteristics (Nikolova et al., 2011).

### 2.3.1 Three-dimensional tree canopy structure

In ENVI-met®, each plant is represented as a one-dimensional permeable column that is subdivided into multiple LAD layers, expressed as $m^2\ m^{-3}$ (Wania et al., 2012). To account for the influence of vegetation on atmospheric processes, all prognostic equations in the model are extended into the vegetation layers using source/sink terms describing heat, humidity and momentum exchanges (Wania et al., 2012). The loss of wind speed due to vegetation friction is parameterized in airflow equations, while additional turbulence and dissipation due to vegetation are integrated in the turbulence equations. The sensible heat flux, evaporation flux and transpiration flux are calculated in the vegetation module.

To test for the effect of a detailed tree crown representation on the ambient $PM_{10}$ concentration and the resulting leaf-deposited $PM_{10}$ mass, two model runs were performed. While the first run was conducted with a theoretical tree crown representation, the second run was performed with the actual tree crown representation assessed with ground-based Light Detection And Ranging (LiDAR).

Within ENVI-met®, vertical LAD profiles are normalized from z $h^{-1}$ = 0.1 (LAD1) to z $h^{-1}$ = 1 (LAD10), where z is the height of the LAD entry and h is the total plant height (m). Each vertical profile thus consisted of 10 different horizontal LAD layers. For the theoretical tree crown representation, we used 8 unique vertical LAD profiles (Table 1) to be able to adjust the tree crown dimensions in relation to the distance to the center of the crown. The applied LAD values (0.1-1.15 $m^2\ m^{-3}$) were based on standard deciduous LAD values provided in the local ENVI-met® database consisting of 27 different plant structures (Bruse, 2012). The resulting average Leaf Area Index (LAI) of the theoretical tree crown (5.12 $m^2\ m^{-2}$) falls within the limits of, although scarce, reported averages (0.3-7 $m^2\ m^{-2}$) for London Plane (*Platanus x acerifolia* Willd.) within urban environments (OCA, 2007; Wu et al., 2008).

***Table 1****: Vertical LAD profiles in ENVI-met® are normalized from z h-1 = 0.1 (LAD1) to z h-1 = 1 (LAD10), where z is the height of the LAD entry and h is the maximal height (m). Each vertical profile thus consisted of 10 different horizontal LAD layers (LAD1-LAD10). Overview of the applied vertical LAD profiles (P1-P8) to describe the theoretical tree crown structure with maximal height (m) of each vertical profile and LAD values ($m^2\ m^{-3}$) for the individual horizontal LAD layers (LAD1-LAD10). The sum of all LAD layers over the maximal height results in the LAI (m² m-2) of each LAD profile.*

{Table 1}

Ground-based Light Detection and Ranging (LiDAR) was applied to improve the three-dimensional tree crown representation inside the model. This is an active remote sensing technology which provides a novel tool for generating a comprehensive and detailed 3D mathematical description of tree and canopy structure in a non-destructive manner (Van Der Zande, 2008). These state of the art systems are mobile, robust and small and can be used for diverse applications e.g. airborne topographic mapping, surveying of buildings and plants, etc. (Van Der Zande, 2008). In this study we used the RIEGL VZ-400 ground-based scanner (RIEGL Laser Measurement Systems GmbH, Horn, Austria). This time-of-flight scanner has a range up to 350 m and a beam divergence of nominally 0.35 mrad and operates in the near infrared (wavelength 1550 nm). The RIEGL VZ-400 scanner records multiple returns (up to four returns per emitted pulse), with returns being derived from on-board waveform processing. Multiple returns will lead to an improved sampling at greater canopy heights, which is of interest for monitoring vegetation (Calders et al., 2015, 2014; Lovell et al., 2003). The angular resolution in both zenith and azimuth direction was set to 0.06 degrees.

LiDAR data were acquired prior to the leaf sampling campaign, on September 7, 2012, to avoid potential effects of structural tree crown damage during the leaf sampling campaign. Different scan locations were used with reflecting targets, distributed throughout the scene. These targets were used to register each individual scan location to a single registered pointcloud with the RiSCAN PRO software (provided by RIEGL). The points belonging to the individual tree were manually selected from the pointcloud. Next, this subset was filtered, by removing all individual points that had a distance of ≥ 10 cm to each other point were removed in order to reduce noise. Further, due to the setup of the different scan locations some parts of the trees may be oversampled (e.g due to overlapping scans and shorter distance to the scanner). Therefore, the pointclouds were converted to 5x5x5 cm, where a voxel is considered filled if it contains a return. The tree crown domain was applied to the model grid size resolution (1x1x1 m) and the number of filled voxels per grid cell was obtained. Theoretically, it is possible to derive the LAD from the number of filled voxels using the approach of Hosoi and Omasa (2006), but then additional information on the leaf inclination and the number of laser beams per voxel is required which is difficult to assess when multiple laser scans are combined. We therefore normalized the number of filled voxels to the LAD values of the theoretical tree crown by equating the maximal number of filled voxels per grid cell (10401) to the maximal LAD (1.15 $m^2\ m^{-3}$) used in the LAD profiles of the theoretical tree crown (Table 1). As a result, we obtained 206 unique LAD profiles. Because the number of unique vertical LAD profiles in ENVI-met is restricted to 150, we reduced the number of profiles by averaging LAD profiles in the center of the tree crown (Figure 2). In fact, the LiDAR-derived data reflects the Plant Area Index (PAD), as no distinction was made between woody (stem, branches and twigs) and leaf material. The use of PAD is justified as woody tree material will influence local air flows and has shown to act as accumulation surface for atmospheric particles (Catinon et al., 2011, 2009; Huhn et al., 1995; Sawidis et al., 2011).

{Figure 2}

***Figure 2***: *Top view of the applied vertical LAD profiles for the theoretical tree crown (left), based on eight unique vertical LAD profiles (P1-P8), and the LIDAR-derived tree crown (right), based on 150 unique vertical PAD profiles (A1-W9), in the ENVI-met® Area Input file Editor.*

### 2.3.2 Model domain

Within this chapter, two separate model studies were evaluated. In a sensitivity study, we considered the effect of tree crown structure within a theoretical three-dimensional model domain of 100x100x50 m and a 1x1x1 m equidistant grid cell resolution. One model run was performed with the theoretical spherical tree crown consisting of 8 unique LAD profiles while a second run was conducted with the improved tree crown representation based on 150 unique LiDAR-derived LAD profiles (Figure 2). While the theoretical tree crown had an average Leaf Area Index (LAI) of 5.12 $m^2\ m^{-2}$, a LAI of 7.79 $m^2\ m^{-2}$ was obtained for the LiDAR-derived tree crown (Figure 3). This results from the applied procedure to transform the filled voxel numbers to LAD values using the maxima equation, and the inclusion of the woody tree material using the LiDAR procedure.

{Figure 3}

***Figure 3***: *Model domain of the sensitivity study in which the effect of tree crown structure on the ambient $PM_{10}$ concentration and $PM_{10}$ leaf deposition was tested. A theoretical spherical shaped tree crown (left) was compared to a detailed LiDAR-derived tree crown (right).*

In the second model study (real-life study), the leaf-deposited $PM_{10}$ mass was simulated throughout the entire in-leaf season using a model domain that represented the actual situation. As the size of the model domain is directly related to its computational time, we first evaluated the need to incorporate two busy thoroughfares of Antwerp *R1* and *Singel* inside the real-life model domain. To do so, we considered a slim three-dimensional model domain of 750x250x50 m with an equidistant grid cell resolution of 50 $m^3$ (5x5x2 m). To simulate the maximal potential influence, we modelled maximal (rush hour) traffic intensities at 90% of the maximal hourly wind speed obtained during the growing season (3.04 m $s^{-1}$), perpendicular on the *R1* and *Singel* in the direction of the considered tree crown. As can be seen from Figure 4, the emission plume of the *R1* and *Singel* only resulted in a limited (<0.30 µg $m^{-3}$) local increase of the atmospheric $PM_{10}$ concentration without any vertical stratification at the considered tree crown location. Considering the recessed nature of the *R1* road below ground level, the actual influence of the emission plume will even be overestimated in this model scenario. We, therefore, assumed that both roads do not influence the spatial leaf-deposited $PM_{10}$ variation within the considered tree crown, and can be excluded from the final model domain.

{Figure 4}

***Figure 4***: *Model results to evaluate the influence of the nearby two busy thoroughfares of Antwerp, i.e. ring road and Singel, on the atmospheric $PM_{10}$ concentration in the vicinity of the considered tree crown.*

After evaluating the effect of tree crown structure (sensitivity study) and vicinity of *R1* and *Singel*, we constructed the model domain for the real-time study. We, therefore, made use of the detailed LiDAR-derived tree crown in a three-dimensional model domain of 239x239x30 m with a 1x1x1 m grid cell resolution (Figure 5). The equidistant mesh consisted of grid cells with identical heights (H = 1 m), except for the lowest five grid cells (near soil/pavement simulation) which had a smaller vertical extension (0.2 x H = 0.2 m). The building height inside the model domain was obtained from the LiDAR based Digital Height Model (DHM) of Flanders (Flemish Environment Agency). To avoid edge effects, 5 nesting grids were considered at each border of the model domain, which contained a total of 1.71 million grid cells.

{Figure 5}

***Figure 5****: Model domain of the final model study with the detailed LiDAR derived tree crown and the urban morphology of the surrounding buildings.*

#### 2.3.3 Meteorology

The in-leaf period (May 1st to September 11, 2012) was characterised by a mean air temperature of 16 °C, relative air humidity of 73%, vector averaged wind direction and speed of 277° and 1.40 m $s^{-1}$ and a total cumulative precipitation of 370 mm. As dry deposition of atmospheric particles on leaf surfaces has been shown to occur throughout the entire in-leaf season, ENVI-met® simulations should ideally cover all environmental variation that is experienced during this period. Meteorological data were, therefore, obtained from the closest measuring station of the Flemish Environment Agency (VMM), located at 7 km from the considered tree crown, for the period from May 1st to September 11, 2012. Model simulations of an entire in-leaf season are, however, not feasible due to calculation time restrictions. We therefore, simulated the entire in-leaf season with average atmospheric temperature (°C) and relative atmospheric humidity (%) at the hour of model initialisation (8am), while average wind direction and speed were considered for different wind sectors. As it is widely established by now that wind is the most important meteorological factor determining local particle dispersion in urban environments (Hofman et al., 2016, 2013; Janhäll, 2015; Kozawa et al., 2012; Kumar et al., 2011), we conducted model runs for eight wind sectors (N, NE, E, SE, S, SW, W, NW) with averaged wind speed within each wind sector (see Table 2). Wind speed measurements were obtained at a height of 30 m while ENVI-met requires wind speed at 10 m. Therefore, wind speed at 10 m was derived from the measured wind speed using the logarithmic wind velocity profile originally described by Priestley (1959) and adapted for flow over a disturbed surface (equation 1):

$$\frac{u}{u*} = \frac{1}{k}\ln\left(\frac{z-z_d}{z_0}\right) \quad (1)$$

where u is the wind speed (m $s^{-1}$), u* is the friction velocity, k is the von Karman constant (≈ 0.41), z is the considered height (m), $z_d$ zero displacement height (m) and $z_0$ is the roughness length (m). The roughness length was considered to be 0.1 m following the parameterization of Britter and Hanna (2003) for a moderately open urban surface. The displacement height is set to be equal to 0.5 times the nearest building height (6 m) to the considered tree, following Grimmond and Oke (1999).

***Table 2**: Wind flow characteristics for each of the eight considered wind sectors (N, NE, E, SE, S, SW, W, NW). Sector range (°), considered wind direction inside the model (°), average wind speed (m $s^{-1}$) during the in-leaf season and time (h) that wind blew in this sector throughout the in-leaf season.*

{Table 2}

Average measured meteorological data are only used in the initialization phase of the model during which meteorological parameters are calculated up to a height of 2500 m (1D model). Thereafter, initial 3D model parameters are calculated based on surface solar exposition and inclination (sky-view factor) of the 3D terrain resulting in thermal stratification, surface temperature and disturbed wind flow field.

After the model runs were performed for each wind sector, the modelled hourly leaf-deposited $PM_{10}$ loads for the 20 leaf sampling locations were summed up over the entire in-leaf season using the number of hours within each wind sector (Table 2).

### 2.3.4 Emissions

Pollution sources in ENVI-met® are defined in the model domain and can be line, point or area sources with hourly emission rates. Traffic emissions are calculated by multiplying an emission factor (g $km^{-1}$) with the prevailing traffic intensity (vehicle $s^{-1}$) (Ketzel et al., 2007). Emissions were calculated separately for every street inside the model domain using vehicle type-specific traffic intensities and emission factors. The traffic intensity was obtained from a traffic model (SGS, 2010) specifically developed for the city of Antwerp and previously applied in a study of Lefebvre et al. (2011). The model generates street-specific traffic intensity, expressed as vehicles $hour^{-1}$, for light, medium and heavy traffic. Emission factors were obtained from the most recent Environmental Impact Report (LNE, 2012) of the Flemish Environment, Nature and Energy department. In this report, emission factors for $PM_{10}$ (g $km^{-1}$) are provided for each vehicle type (light, medium and heavy), taking into account driving speed. The resulting hourly averaged line source emissions (µg $s^{-1}$ $m^{-1}$) were then calculated for every street in the model domain (Table 3) and appended in the source database. As described in 2.2.3, the traffic-intensive *R1* and *Singel* roads were not included in the final domain since they showed a limited influence on the local atmospheric- and leaf-deposited $PM_{10}$ concentrations at the considered tree crown location.

***Table 3****: The applied $PM_{10}$ emission factors for light/medium/heavy traffic (Emission factor in g $km^{-1}$), kind of traffic intensity (Traffic), sum of light, medium and heavy traffic intensity (Total Traffic intensity in veh $h^{-1}$), and the resulting $PM_{10}$ emission strength ($PM_{10}$ emission in µg $s^{-1}$ $m^{-1}$) of the considered streets in the model domains.*

{Table 3}

## 3. Results and Discussion

Two model studies were conducted in ENVI-met® to, respectively, (i) a sensitivity study to evaluate the effect of a detailed tree crown representation on the modelled atmospheric $PM_{10}$ concentration and resulting leaf-deposition, and (ii) a real-life study to quantify the amount of leaf-deposited $PM_{10}$ for the representative exposure period of the collected leaf samples (May to September 2012).

### 3.1 Sensitivity study

The sensitivity study consisted of an evaluation of the effect of considering a detailed LiDAR-derived tree crown (150 unique LIDAR profiles) on the resulting modelled atmospheric and leaf-deposited $PM_{10}$ concentrations in ENVI-met. As can be seen form Figure 6, the LiDAR-derived tree crown resulted in an altered local atmospheric $PM_{10}$ concentration when compared to the theoretical tree crown. Applying the LiDAR-derived tree crown, local $PM_{10}$ concentrations are increased up to 34% at a height of 3.5 m (and 62% at a height of 0.1 m) relative to the theoretical tree crown structure. As can be seen from the relative flow differences (vectors) in Figure 6, the increased $PM_{10}$ concentration was due to a wind field alteration at the downwind side of the tree crown. By using the LiDAR based methodology, not only the total LAI of the tree crown increased (from 5.12 to 7.79 $m^2\ m^{-2}$), making it less permeable to wind flow, but also the roughness of the crown surface increased giving rise to disturbance of the flow field (turbulence) along the edges of the canopy, especially at the leeward side of the tree crown.

{Figure 6}

***Figure 6****: Relative difference (%) in atmospheric $PM_{10}$ concentration and wind flow between the LiDAR-derived tree crown and the theoretical tree crown (reference) at a height of 3.5 m. The wind rose depicts the north azimuth (black arrow) and simulated wind direction (red arrow).*

The capacity of urban green to alter local pollutant concentrations was previously demonstrated in several modelling and wind tunnel studies (Buccolieri et al., 2011, 2009; Gromke and Ruck, 2012, 2007; Janhäll, 2015; Ries and Eichhorn, 2001; Vos et al., 2013; Wania et al., 2012). Trees in urban street canyons have shown to obstruct the wind flow, thereby reducing pollutant dilution (ventilation), resulting in higher pollutant concentrations. Vos et al. (2013) modelled the effect of 17 different urban vegetation scenarios, including trees, hedges and green barriers, on the resulting atmospheric $PM_{10}$, $PM_{0.2}$ and $NO_2$ concentrations in ENVI-met. They predominantly observed a deteriorating air quality due to the considered vegetation scenarios, mainly determined by the type, height and permeability (=LAD) of the vegetation. Besides inhibition of the street canyon ventilation, vegetation was also found to reduce wind speed at crown-height and to disrupt the flow field in close vicinity to the canopy in an ENVI-met model study by Wania et al. (2012). Previous wind tunnel experiments and numerical simulations (FLUENT) by Gromke and Ruck (Gromke and Ruck, 2012, 2009, 2007) and Buccollieri et al. (Buccolieri et al., 2011, 2009) confirmed the aerodynamic effect of vegetation on in-canyon pollutant concentrations, with denser tree crowns leading to lower wind speeds and higher resulting pollutant concentrations. Increased foliage density (LAD) typically results in higher pollutant concentrations, obtained at the leeward side of the street canyon, which is in agreement to our results.

It is now commonly believed that the aerodynamic effect exerted by urban vegetation outweighs its pollutant removal capacity, which pleads for thoughtful consideration during the spatial planning of urban green. Nevertheless, observed air quality outcomes due to vegetation are still less pronounced than outcomes due to street canyon geometry (e.g. height-width ratio) or wind fields.

Looking at the resulting leaf-deposited $PM_{10}$ load, the elevated atmospheric $PM_{10}$ concentration results in elevated deposition loads of up to 18% at a height of 3.5 m (0.44 µg $m^{-2}$ after 6 hours) on the leaves at the downwind side of the tree crown (Figure 7).

{Figure 7}

***Figure 7**: Relative difference (%) in leaf-deposited $PM_{10}$ load and wind flow between the LiDAR-derived tree crown and the theoretical tree crown (reference) at a height of 3.5 m. The dark blue color (-100%) is due to the microscale difference in tree crown dimensions. The wind rose depicts the north azimuth (black arrow) and simulated wind direction (red arrow).*

As can be seen from Figure 8, a clear relation ($R^2 \approx 1$) exists between the atmospheric $PM_{10}$ concentration and the leaf-deposited $PM_{10}$ mass when model results are extracted for the tree crown grid cells at eight heights (n=1075). This relation was previously described in Hofman & Samson (2014) and is clearly demonstrated by the relative tree crown differences in Figure 6 and 7. We must, however, note that no resuspension of leaf-deposited particles, nor saturation of the particle loading capacity of the leaf surface is simulated by ENVI-met. The deposited $PM_{10}$ mass might, therefore, be overestimated in the model simulations.

{Figure 8}

***Figure 8***: *Relation between the modelled atmospheric $PM_{10}$ concentration (µg $m^{-3}$) and the amount of leaf-deposited $PM_{10}$ (µg $m^{-2}$) after six hours of simulation time with associated regression line (full line). Modelled results (n=1075) were extracted for the tree crown grid cells at heights of 0.5, 1.5, 2.5, 3.5, 6.5, 8.5, 10.5 and 13.5 m.*

Although this model study was limited to a single tree and model configuration, our results show that improving tree crown characteristics (shape, dimensions and LAD) affects the local distribution and resulting leaf-deposition of $PM_{10}$ in ENVI-met. An accurate tree crown representation seems, therefore, of great importance when aiming at modelling local PM distributions.

## 3.1 Real-life study

For the real-life simulations, the atmospheric $PM_{10}$ concentration in the vicinity of the LIDAR-derived tree crown differed considerably between the different wind sectors (Figure 9). This is not surprising as atmospheric $PM_{10}$ emissions, originating from the considered roads (with differing emission strengths) inside the model domain, will contribute differently under varying wind directions.

{Figure 9}

***Figure 9***: *Modelled atmospheric $PM_{10}$ concentration (µg $m^{-3}$) and wind vectors in the vicinity of the detailed LiDAR-derived tree crown for the considered wind sectors (N, NE, E, SE, S, SW, W, NW). Grey areas in the model domain represent buildings.*

Modelled hourly $PM_{10}$ depositions (µg $m^{-2}$ h) at every leaf sampling location were integrated over the entire in-leaf season using the number of hours within each wind sector (see Table 2). The resulting modelled in-leaf season leaf-deposited $PM_{10}$ load varied from 113.57 to 547.36 µg $m^{-2}$. The modelled amount of leaf-deposited particles decreased with 74% between a height of 3.5 and 13.5 m (Figure 10) and leaves at the inner crown locations accumulated less particles (on average 94%) compared to leaves at the outer canopy.

{Figure 10}

***Figure 10**: Azimuthal (SE, SW, NW and NE) variation of modelled (black) and average gravimetric (grey) leaf-deposited $PM_{10}$ (mg $m^{-2}$) for the outer bottom (b), middle (m) and top (t) locations in the tree crown. Standard deviations of gravimetric averages are denoted by the error bars. Note the different y-axis limits.*

The obtained model results of the real-time simulation (§3.2) were compared to the gravimetric results of the filter membranes obtained from the leaf sampling campaign (§2.1). The average gravimetrically-determined mass of leaf-deposited particles for the 20 leaf sampling locations was 626.13, 28.72 and 33.69 mg $m^{-2}$ for respectively the >10 µm, 3-10 µm and 0.2-3 µm size fraction. While the average total leaf-deposited mass was 687.93 mg $m^{-2}$, the average mass within the $PM_{10}$ size fraction (0.2-10 µm) amounted 62.41 mg $m^{-2}$. These results are comparable to other studies that quantified the amount of leaf surface-deposited particles (Dzierzanowski et al., 2011; Hofman et al., 2014a; Sæbø et al., 2012; Terzaghi et al., 2013). Apart from the leaf surface-deposited particles, previous studies found that part of the leaf-deposited particle load will be encapsulated inside epicuticular wax layers (Hofman et al., 2014a; Terzaghi et al., 2013). In Hofman et al. (2014b), it was shown that the biomagnetic signal of this fraction accounted for 33% of the total leaf *Saturation Isothermal Remnant Magnetisation* (SIRM). Our results yielded a similar 34% representation of the leaf-encapsulated fraction (washed leaves), compared to the total leaf biomagnetic (SIRM) signal. Moreover, due to aggregation of smaller (<10 µm) particles, part of the smaller size fractions will be retained on the largest (10 µm) filter membrane. This hypothesis was confirmed by scanning electron microphotographs of the PM loaded filter membranes (Figure 11). We can, therefore, assume that the amount of leaf-deposited <10 µm particles is still underestimated with the methodology used in our study.

{Figure 11}

***Figure 11****: Scanning electron microphotographs (back-scattered electron images) of the PM loaded 10 µm (left) and 0.2 µm (right) filter membranes. Note the clear 10 µm-sized filter pore (left).*

Comparing the gravimetric results for $PM_{10}$ (sum 3-10 and 0.2-3 µm) and $PM_{total}$ (sum >10, 3-10 and 0.2-3 µm) with the modelled seasonal $PM_{10}$ deposition for all 20 leaf sampling locations in the tree crown, an overall weak agreement ($R^2$ = 0.0004-0.14) is observed (Figure 12). Spearman Rank tests show no significant correlations between the modelled leaf-deposited $PM_{10}$ mass and the gravimetric $PM_{10}$ (r=-0.18, p=0.43) and $PM_{total}$ (r=0.31, p=0.18) results.

{Figure 12}

***Figure 12****: Relation between the modelled leaf-deposited $PM_{10}$ mass (mg $m^{-2}$) and the gravimetric results for the mass of the $PM_{10}$ (sum 0.2-3 and 3-10 µm) and $PM_{total}$ (sum 0.2-3, 3-10 and >10 µm) size fractions. Every point represents a sampling location in the tree crown (n=20). Regression lines with associated functions and $R^2$-values are denoted by the full lines.*

While the leaf-deposited $PM_{10}$ mass differs by two orders of magnitude between the modelled and gravimetric results, the spatial variation between modelled and measured results seems to differ as well. A 6% decrease of the gravimetric leaf-deposited mass is obtained between a height of 3.5 and 13.5 m and on average 44% higher leaf-deposits are found at the inner crown locations compared to the crown's outer edge locations. Considering the azimuthal variation between the sampling locations at the different heights (Figure 10), the gravimetric results appear to differ from the modelled results as well. Significant higher gravimetric results at the SE side at the bottom and middle of the tree crown might suggest an influence of the *Singel* and ring road (two busy thoroughfares of Antwerp in the neighbourhood of the tree), as was also suggested by Hofman et al. (2014a), while the modelled results suggest the *Statiestraat* as the main particle source at the NW side of the bottom sampling locations (Figure 10). Although the model analysis in §2.2.2 estimated a limited influence of the ring road and *Singel* (<0.30 µg $m^{-3}$), the low traffic intensity of the local streets seems to lead to rather low PM concentrations (<0.40 µg $m^{-3}$) in the vicinity of the tree crown as well, as can be seen in Figure 9.

The lack of agreement between the modelled and gravimetric results can be explained by the modelled sources and applied model parameters. Our model studies namely only included local traffic sources, to simulate spatial PM variation within the considered tree crown. This explains the generally low atmospheric $PM_{10}$ concentrations (<1.31 µg $m^{-3}$) obtained in Figure 9. Considering an average seasonal (from May to September) atmospheric $PM_{10}$ concentration of 25 µg $m^{-3}$, measured at an urban background monitoring station of the Flemish Environment Agency (VMM) at 1.5 km from the considered tree crown, the local modelled $PM_{10}$ concentration at a height of 3.5 m (<1.31 µg $m^{-3}$) would account for only 5% of the average atmospheric $PM_{10}$. Previous studies already demonstrated that local traffic emissions account for less than 20% of the urban $PM_{10}$ concentration in Antwerp (Deutsch et al., 2006; TML, 2012; VMM, 2014, 2011). Taking a homogeneous $PM_{10}$ background of 25 µg $m^{-3}$ into account, the modelled $PM_{10}$ concentration reduction with increasing height decreases to 4.44%, which is comparable to the 6% reduction with height obtained from the gravimetric results.

The lack of urban background concentration inside the model also explains the obtained smaller leaf-deposited PM mass, when compared to the gravimetric results. Nevertheless, when we take the urban background into account, the modelled leaf-deposited $PM_{10}$ weight amounts to an average 6.14 mg $m^{-2}$, which is still 15% of the averaged gravimetric results. Apart from the missing urban background concentration, road dust resuspension is not simulated in the ENVI-met model, due to a lack of traffic-induced turbulence. As $PM_{10}$ emissions due to road dust resuspension are approximately of the same order of magnitude as tailpipe emissions (Amato et al., 2009; de la Paz et al., 2015; Gehrig et al., 2004), depending on the considered environment, it might account for part of the observed discrepancy as well. Additional uncertainty in the model outcome might be due to various assumptions in our model setup, e.g. a potential underestimation of the deposition velocity, lack of local measurements of the input parameters (meteorology, traffic counts, ambient PM concentration, …) or oversimplification of the simulation period (May to September). Nevertheless, such assumptions are all frequently applied in contemporary air quality models.

Our findings emphasize the need for continuous validation efforts of modelled results against experimental data. Moreover, an integrated modelling approach should be envisaged, where pollutant sources at different spatial scales are integrated inside the model domain. As for many countries, more than 50% of the atmospheric PM concentration is due to cross-boundary pollution (EEA, 2015), and as the size of the model domain is directly related to the computational time, integration of sources over different monitoring scales is often achieved by defining boundary conditions inside the model domain. This is, however, not possible in the current ENVI-met® v4 version.

## 4. Conclusion

Overall, the application of ground-based LiDAR has shown to be very useful in generating a fast, detailed 3D model description of tree crown morphology in a non-destructive manner. The altered 3D shape and canopy density, improved by the LiDAR methodology, have shown to influence the modelled pollutant dispersion and resulting leaf-deposition of particulates by changing local wind flow characteristics in urban environments. With regard to the effect of urban green on local air flows, it might be more appropriate to use tree PAD instead of LAD. Moreover, our study confirmed the effect of urban vegetation on the natural ventilation in urban environments. An accurate tree crown representation seems, therefore, of great importance when aiming at modelling local PM distributions.

Gravimetrical determination of particle loaded filter membranes resulting from washed leaf samples, showed a leaf area normalised particle loading of 626.13, 28.72 and 33.69 mg $m^{-2}$, for respectively the >10 µm, 3-10 µm and 0.2-3 µm particle size fractions. The averaged total leaf-deposited mass was 687.93 mg $m^{-2}$, of which the $PM_{10}$ fraction (0.2-10 µm) amounted 62.41 mg $m^{-2}$. An overall bad agreement was obtained between the gravimetric and modelled leaf-deposited particulate mass. Apart from the need for an accurate tree crown representation in atmospheric models, our findings, therefore, emphasize the importance of continuous validation of modelled results against experimental data in order to guarantee reliable air quality model outcomes.

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