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Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments

Matthew Tallis[a], Gail Taylor[a], Danielle Sinnett[b,1], Peter Freer-Smith[b,*]

[a] School of Biological Sciences, Life Sciences Building, University of Southampton, SO17 1BJ, UK
[b] Forest Research, Alice Holt Lodge, Farnham, Surrey GU10 4LH, UK

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ABSTRACT

Urban green space and particularly the tree canopy have been highlighted as offering a mitigation potential against atmospheric particulate pollution. In this paper current and future particulate (PM_{10}) deposition to the urban tree canopy of the Greater London Authority (GLA) was estimated. A modelling approach was used based on the Urban Forest Effects Model (UFORE) and a modified version. Here we give evidence showing that these deposition models can be adapted to run from annual mean meteorological and PM_{10} concentration data, thus providing a methodology to examine future scenarios.

Depending on the modelling approach, the urban canopy of the GLA is currently estimated to remove between 852 and 2121 tonnes of PM_{10} annually; representing between 0.7% and 1.4% of PM_{10} from the urban boundary layer. Estimates of PM_{10} removal which take into account a planned increased in tree cover, from the current 20% to 30% of the GLA land area, suggest deposition of 1109–2379 tonnes (1.1–2.6% removal) by the year 2050. The evidence provided here suggests that the targeting of tree planting in the most polluted areas of the GLA and particularly the use of street trees which have the greatest exposure to PM_{10}, would have the greatest benefit to future air quality. The increased deposition would be greatest if a larger proportion of coniferous to broadleaved trees were used at such sites.

1. Introduction

In the urban environment reductions in air quality resulting from emissions of particulate matter, primarily from road traffic, are a serious health issue globally (Gupta, Kumar, Maharaj Kumari, & Srivastava, 2004; Nowak, Crane, & Stevens, 2006; Yang, McBride, Zhou, & Sun, 2005). Estimates for the UK indicate that short-term exposure to the levels of particulate matter of less than 10×10^{-6} m in aerodynamic diameter (PM_{10}) led to an additional 6500 deaths and 6400 hospital admissions in 2002 (AQEG, 2005). The UK Department of Health also estimates that 1.9% of urban deaths can be attributed to PM_{10} pollution (COMEAP, 1998). Vegetation captures gases, particulates and aerosols from the atmosphere more effectively than other land surfaces (Fowler, Cape, & Unsworth, 1989; Smith, 1981). 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; Powe & Willis, 2004). For example, Fowler et al. (2004) found that woodlands in the West Midlands of England collect three times more PM_{10} than grassland. Brownian motion accounts for the flux of gases and fine particles along concentration gradients (diffusion) and this mechanism is important for pollutants that dissolve on wet leaf surfaces. Larger tree leaf areas will thus increase the uptake of fine particles by diffusion. However, turbulent air flow and associated impaction are the main mechanisms resulting in the greater deposition of particles to trees as compared to that to shorter vegetation. 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. Thus the canopy area and structure (i.e. tree species), concentration of particles in the airstream, particle size distribution, and windspeed are all important factors in determining particle uptake by vegetation (see a full discussion in Beckett, Freer-Smith, & Taylor, 2000c), and these factors are the main inputs required to model particle deposition (see Section 2.1). Two deposition models, the Urban Forest Effects Model (UFORE; Nowak & Crane, 1998) and FRAMES (Bealey et al., 2007), have been developed to evaluate PM_{10} uptake by trees in urban areas. Recently Tiwary et al. (2009) used a pollution/deposition flux approach and species-specific deposition velocities (Freer-Smith, Beckett, & Taylor, 2005; Freer-Smith,

* Corresponding author. Tel.: +44 01420 526211.
E-mail addresses: m.j.tallis@soton.ac.uk (M. Tallis), g.taylor@soton.ac.uk (G. Taylor), danielle.sinnett@uwe.ac.uk (D. Sinnett), peter.freer-smith@forestry.gsi.gov.uk (P. Freer-Smith).
[1] Current address: Centre for Sustainable Planning and Environments, Department of Planning and Architecture, University of the West of England, Frenchay Campus, Coldharbour Lane, Bristol BS16 1QY, UK.

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El-Khatib, & Taylor, 2004) to estimate PM_{10} capture in a case study area of London, UK.

There is a need for urban greenspace to be established strategically at a landscape scale in order to maximise the full range of potential benefits it can bring. These benefits include improving air quality, urban drainage, aesthetics, urban biodiversity, climate amelioration, enhancing recreation, conservation and health and well-being. The Read report suggests these services will help urban populations adapt to climate change (Read et al., 2009). Using a 10,000 ha study area within the Greater London Authority (GLA) (estimated as 6.4% of GLA land area) Tiwary et al. (2009) suggests that the implementation of the East London Green Grid with 25% tree cover could result in the aversion of two deaths and two hospital admissions per year through PM_{10} removal. While Powe and Willis (2004) suggest that current woodland cover in Great Britain mitigates between five and seven deaths and four and seven hospital admissions annually, through PM_{10} and SO_2 removal.

Dry deposition of PM_{10} to trees primarily results from sedimentation under gravity and impaction under the influence of wind (Nowak, 1994a) and is therefore less influenced by rapidly fluctuating meteorology, but is largely affected by leaved canopy duration and total canopy leaf area (Nowak et al., 2006). During the hot summers of 2003 and 2006 experienced in the UK urban PM_{10} concentrations, mostly the $<PM_{2.5}$ size fraction, increased through enhanced photochemical formation of secondary particles (Bower et al., 2008). Future temperatures are predicted to increase, particularly in urban areas, so understanding the role of trees is needed to maximise future benefits to urban air quality. The modelling approach used in this study has allowed an estimation of the role of urban trees in removing PM_{10} from urban air under current and future environments.

Here we describe a detailed analysis of PM_{10} uptake by tree from dry deposition in the c. 157K ha area covered by the Greater London Authority (GLA see Fig. 1); one of five European cities selected as case studies in the EU FP 7 Project "Sustaina**B**le u**R**ban plann**I**ng **D**ecision support accountin**G** for m**E**tabolism" (BRIDGE; www.bridge-fp7.eu). In order to determine the relationships between amount and type of tree cover and PM_{10} uptake we have used two modelling approaches: (i) the pollution/deposition flux method which has been used in a number of studies (e.g. Lovett, 1994; Nowak, 1994a; Nowak & Crane, 1998; Smith, 1981) and (ii) the approach used by Tiwary et al. (2009) where species specific deposition velocities were used with the pollution flux approach – referred to here as "the Tiwary method". We have used these methods to estimate the PM_{10} deposition to street trees, urban woodland, garden and other trees (remainder) for the whole GLA for current and future (2050) PM_{10} capture. We also set out the methodology which allows these estimates to be made from annual input data of PM_{10} concentrations and meteorology. This is an approach which can be taken for other cities where similar data are available.

2. Methodological strategy

Typically assessments of the capture of PM_{10} by the urban tree canopy are carried out as part of an assessment of the overall air pollution removal potential (e.g. Donovan, Stewart, Owen, MacKenzie, & Hewitt, 2005; Nowak et al., 2006; Yang et al., 2005). This consists of running uptake models using local hourly meteorological and pollution data (e.g. Nowak & Crane, 1998). Here we investigated the potential of using existing tree survey data and annual maps of PM_{10} distribution and observed/predicted meteorological conditions to estimate current and future PM_{10} removal by the whole urban canopy of the GLA.

2.1. The models

The downward PM_{10} flux (F; in $g\,m^{-2}\,s^{-1}$) to the urban tree canopy can be calculated as the product of the deposition velocity (V_d; in $m\,s^{-1}$) and pollutant concentration (C; in $g\,m^{-3}$) according to the methodology used in a number of studies (e.g. Lovett, 1994; Nowak, 1994b; Smith, 1981).

$$F = V_d \cdot C \qquad (1)$$

V_d is calculated as the inverse of the sum of the aerodynamic (R_a), quasi-laminar boundary layer (R_b) and canopy (R_c) resistances (Baldocchi, Hicks, & Camara, 1987).

$$V_d = (R_a + R_b + R_c)^{-1} \qquad (2)$$

To give PM_{10} flux (PM_{10} capture) the deposition value is multiplied by the area of the surface (e.g. canopy covered land area for the pollution flux method or canopy covered land area multiplied by the Leaf Area Index (LAI) for the Tiwary method) over time periods for which the pollutant concentration is known e.g. hourly or annually. Leaf Area Index is the ratio of total tree leaf area to the projected ground area occupied by the canopy ($m^2\,m^{-2}$). Local meteorological conditions are used to calculate the resistances R_a and R_b in $s\,m^{-1}$ as described in detail in Nowak, 1994b. Canopy resistance (R_c; $s\,m^{-1}$) values are derived from average R_a and R_b and deposition velocity (V_d; in $m\,s^{-1}$) as described by Nowak, 1994b and Tiwary et al. (2009). It is within the V_d parameter that the Tiwary method differs.

In the UFORE model a maximum value of V_d is set at $0.0064\,m\,s^{-1}$ based on the median deposition velocity from the literature (Lovett, 1994) and a 50% re-suspension rate (Zinke, 1967) as described by Nowak and Crane (1998). This V_d assumes a single sided LAI of $6\,m^2\,m^{-2}$, 6% coniferous cover and deposition to stems with a bark surface area of $1.7\,m^2\,m^{-2}$ of land area giving a total plant area index of $7.7\,m^2\,m^{-2}$. Here we assigned a V_d of $0.0064\,m\,s^{-1}$ (Summer), $0.0039\,m\,s^{-1}$ (Spring and Autumn) and $0.0014\,m\,s^{-1}$ (Winter) for broadleaved trees to represent a change in LAI from an urban peak of $6\,m^2\,m^{-2}$ to a Spring and Autumn mid value of $3\,m^2\,m^{-2}$ and also accounting for deposition to bark in Winter. We assigned the 4% coniferous component of the GLA an annual LAI of $6\,m^2\,m^{-2}$ and therefore an annual V_d of $0.0064\,m\,s^{-1}$; this is a likely under-estimate of true urban coniferous canopy LAI but allows for a comparison of the pollution flux model approach to be made with results from the UFORE model applied to multiple USA cities in which a LAI of $6\,m^2\,m^{-2}$ is assumed (Nowak et al., 2006). As V_d includes an LAI and bark area parameter the PM_{10} flux in Eq. (1) is multiplied by the land area to give total flux (F). Annual stem deposition was calculated as total broadleaf Winter deposition multiplied by four (Spring, Summer, Autumn and Winter) and deposition to foliage was calculated from the difference between total canopy deposition and deposition to the stems.

Tiwary et al. (2009) used species-specific V_d values to the foliage of *Acer pseudoplatanus* to represent the broadleaved canopy (this species being the most common large broadleaf in the survey of Britt and Johnson, 2009) and *Pinus menziesii* representing coniferous canopy (which has similar V_d values to Leyland cypress, the most common conifer in the Britt and Johnson survey). Depositions were calculated using the known relationships between wind speed (3–9 $m\,s^{-1}$) and V_d, which have been established for *A. pseudoplatanus* and *P. menziesii* but not Leyland cypress (Freer-Smith et al., 2004). Here we apply these same relationships as given in Tiwary et al. (2009) to represent deposition to foliage of broadleaved and coniferous canopies. The annual mean wind speeds were $3.6\,m\,s^{-1}$ and $3.8\,m\,s^{-1}$ for 2004 and 2006 respectively as calculated from the seasonal maps (Perry & Hollis, 2005). The mean wind speed used in the current study was therefore within the ranges of wind speed under which measured data

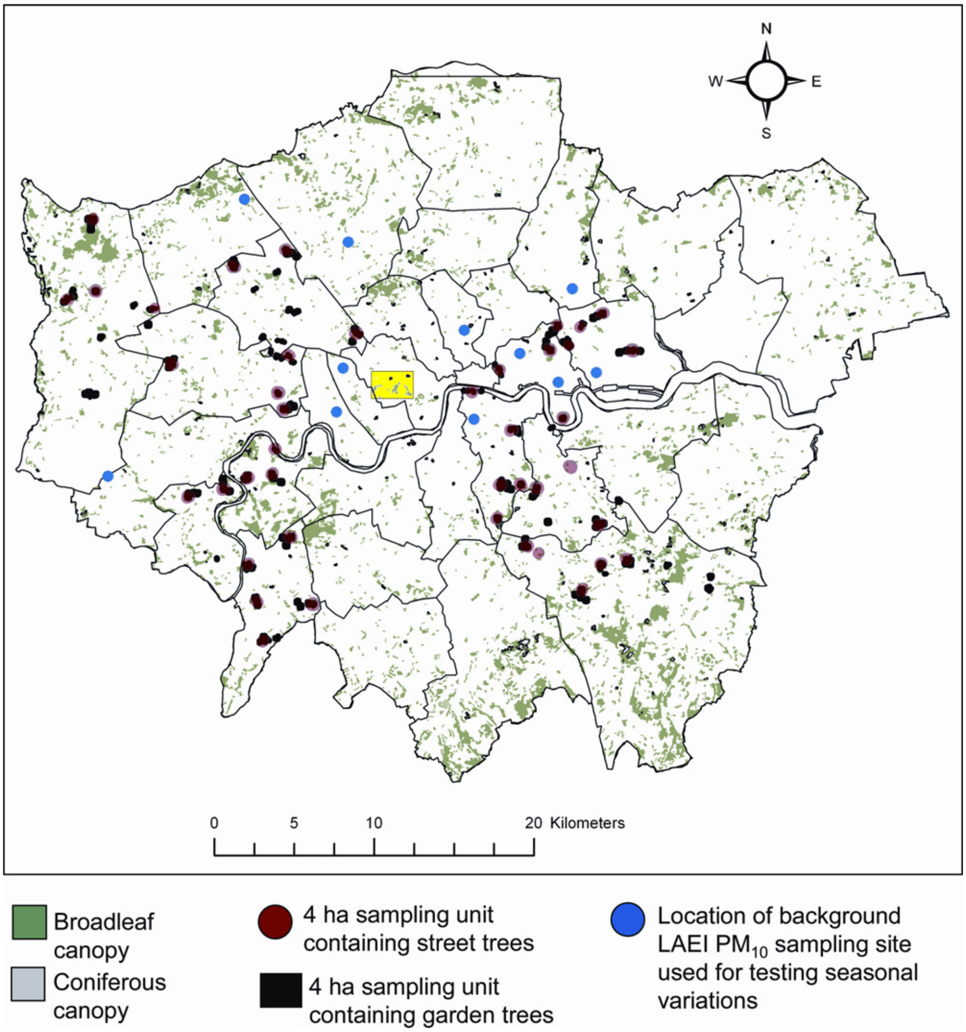

Fig. 1. The Greater London Authority (GLA) displaying the administrate boundaries of the 33 boroughs and the mapped broadleaf and coniferous woodland cover. Also mapped are the locations of the four hectare sampling units used by Britt and Johnston (2008) to survey (■) garden and street tree (●) the location of the 11 LAQN background PM_{10} monitoring sites (●) used for the background PM_{10} seasonal correction factor and the location of figure two (□).

were collected (Freer-Smith et al., 2004). Using the mean wind speed for 2006 resulted in a deposition velocity of 0.0021 m s^{-1} and 0.0109 m s^{-1} to broadleaf and coniferous foliage respectively. Although the V_d were modelled with mean wind speeds, it is noted that windspeed will fall as air travels through a canopy so that estimates could be improved by more detailed modelling of urban airflow. As V_d is calculated to foliage area, PM_{10} flux from Eq. (1) is multiplied by the land area and seasonal LAI to give total leaf flux. Similarly, stem deposition was modelled as a linear relationship with wind speed for *A. pseudoplatanus* and *P. menziesii* (Freer-Smith et al., 2004) and deposition velocities for the mean wind speed of 3.8 m s^{-1} were estimated. These relationships were $Y = 0.2 \times 10^{-3}X$ ($r^2 = 0.96$; $n = 3$) and $Y = 0.8 \times 10^{-5}X$ ($r^2 = 0.83$; $n = 3$), giving V_d values of 7.6×10^{-4} m s^{-1} and 27.2×10^{-6} m s^{-1} for stems of *A. Pseudoplatanus* and *P. menziesii* respectively. Given the surface area index for bark of 1.7 m^2 m^{-2} this results in a V_d term to the land surface under broadleaved trees of 0.0013 m s^{-1} and 0.000046 m s^{-1} under coniferous. As deposition velocity to broadleaf stems was very similar to the UFORE value of 0.0014 m s^{-1}, and deposition to coniferous stems was lower (combined with a low area, was assumed negligible) then the UFORE deposition to stems was added to the leaf deposition here to give total deposition for the Tiwary method. Particles deposited to tree canopies either remain on the leaf and bark surfaces, are resuspended to the atmosphere or are washed of by precipitation. Unlike UFORE, the Tiwary method assumes 0% re-suspension because there is now published experimental evidence that that resuspension is extremely small to tree canopies at wind speeds similar to those experienced in London (see Tiwary et al., 2009). In addition the V_d values used in the Tiwary method are based on measurements made in windtunnels and are calculated from net uptake; that is the final uptake after resuspension has occurred.

The percentage reduction in PM_{10} within the whole mixing layer of the GLA caused by the urban canopy was estimated assuming a well mixed boundary layer which is common during daytime, stable conditions (Colbeck & Hanison, 1985). The total amount of PM_{10} removed by the canopy over the year was expressed as a percentage of the total amount of PM_{10}. present in the mixing layer; the annual exposure where:

$$\text{Annual exposure} = PM_{10}\ \ (\mu g\ m^{-3}) \times MLH\ \ (m) \times 8760\ \ (\text{hours per year}) \times LA\ \ (m^2)$$

when PM_{10} = mean annual PM_{10} concentration, MLH = mean annual mixing layer height and LA = land area cover by urban canopy.

Annual PM_{10} removal and mixing layer height were estimated using the seasonal models for current and future scenarios, annual mean PM_{10} concentration were estimated from LAEI (2006) for the

Table 1
Current and future estimates of urban tree canopy cover for the Great London Authority (GLA) reported as total cover and cover of each of the four canopy types. For 2050 two scenarios are presented; in 1 tree cover is increased across all woodland types to give 30% tree cover of the GLA land area and in scenario 2 cover is increased in only one woodland type – a to d to achieve 30% tree cover. Changes from the current tree cover are shown in bold.

Scenario	Canopy type				
	Total	Woodland	Street	Garden	Remainder
Current tree cover					
As a % of the total GLA	20	8.64	1.1	4.73	5.40
Total hectares	31,265	13,503	1782	7394	8586
2050 scenario 1					
As a % of the total GLA	**30**	**12.9**	**1.8**	**7.2**	**8.1**
Total hectares	**46,898**	**20,166**	**2814**	**11,256**	**12,662**
2050 scenario S2a					
As a % of the total GLA	**30**	**18.6**	1.1	4.73	5.4
Total hectares	**46,898**	**29,135**	1782	7394	8586
2050 scenario S2b					
As a % of the total GLA	**30**	8.64	**11.1**	4.73	5.40
Total hectares	**46,898**	13,503	**17,415**	7394	8586
2050 scenario S2c					
As a % of the total GLA	**30**	8.64	1.1	**14.8**	5.4
Total hectares	**46,898**	13,503	1782	**23,027**	8586
2050 scenario S2d					
As a % of the total GLA	**30**	8.64	1.1	4.73	**15.5**
Total hectares	**46,898**	13,503	1782	7394	**24,219**

current scenario and from Williams (2007) for the future scenario. Mixing layer height (MLH) was determined as follows:

$$\text{MLH} = \frac{275 \cdot c \cdot u_z}{(\sin(\varphi) \cdot \log(z - d/z_o))}$$

where φ is latitude, c is a parameter related to stability classes using the stability classification scheme of Pasquill, u_z is the windspeed at canopy height (z), d is the displacement height ($d = 0.7z$) and z_o is the aerodynamic roughness length ($z_o = 0.1z$) and z = canopy height (10 m); see detail and references in Tiwary et al. (2009).

2.2. Quantifying the urban tree canopy for London

A combination of published data from ground, airborne and satellite surveys were used to classify and quantify the tree canopy cover for London. The GLA borough boundaries and water features were visualised from the 1:20,000 scale vector boundary data maps (Great Britain boundary data, Collins Bartholomew, UK) using Geographic Information Systems (GIS) software (ERSI® ArcMap version 9.3, ESRI, Aylesbury, UK) with the OSGB_1936 coordinate system and the Transverse Mercator projection.

For each of the 33 London boroughs we were able to quantify canopy cover as (i) urban woodland, (ii) street trees, (iii) garden trees and, for the whole GLA area, data were also available for a fourth class (iv) remainder (Fig. 1). Urban woodland was mapped to the GLA boundary using the 25 m^2 resolution land classification map (Fuller, Smith, Sanderson, Hill, & Thompson, 2001). This provides the spatially referenced mapped woodland data as can be seen in Fig. 1. The 25 m raster data were extracted for land cover classes 1.1 (broadleaved woodland) and 2.1 (coniferous woodland). The broadleaved class comprised broadleaved woodlands of stands >5 m high with tree cover of >20%; scrub (<5 m) requires cover >30% for inclusion. The coniferous canopy represents only c. 4% of the urban tree cover of the GLA area and includes stands and plantations of >20% cover, more details can be found in Fuller et al. (2002). We took the borough land area and the estimated canopy cover of street trees for ten London boroughs from Britt and Johnston (2008) to estimate street tree area for each borough giving 1.1% cover of land area. Additionally, the area of land covered by street trees in each borough was estimated by multiplying the number of street trees in each borough (GLA, 2007) with the mean estimated ground area under street tree canopy (Britt & Johnston, 2008) giving 0.94% coverage of land area. The coverage of trees in residential gardens was also estimated from Britt and Johnston (2008) and the locations of the sample survey sites used by these authors to quantify the land area occupied by street and garden canopy cover are shown in Fig. 1. Table 1 shows the breakdown of canopy classes discussed. Urban woodland, street and garden trees represent 22,286 ha which is 72.5% of the total reported canopy area. The further 27.46% (8441 ha) was classed as 'remainder'. This class could includes individual trees in parks and other green spaces, woodland of less than 25 m^2, and street or garden trees missed due to the spatially limited sampling areas of these two canopy types.

For trees which are not spatially referenced canopy area can only be localised to the borough or whole GLA, and therefore model input data of PM_{10} concentrations and meteorology had to be obtained that represent the whole GLA. Spatially averaged PM_{10} concentrations and meteorology values for the whole GLA area were calculated from mapped PM_{10} dispersion data that exists as annual mean values and those for 2006 were used (LAEI, 2006) and monthly mean mapped meteorological data (Perry & Hollis, 2005). The ability to use such input data would also allow the potential benefits of future tree planting to be modelled using future predictions of climate and PM_{10} concentrations, which are typically estimated as annual means. In order to estimate the effects of using annual rather than hourly inputs we used both the pollution/deposition flux approach and the Tiwary method with hourly and seasonal input data and have compared the annual mean resistance parameters and canopy PM_{10} uptake values.

2.3. Future canopy cover

The GLA has announced the ambitious aim of increasing urban tree cover from the current area (2006–08) of 20% of the whole GLA land surface area to 30% by 2050 (GLA, 2009), which could be achieved through the planting of trees on land managed by the boroughs or through encouraging tree planting on private land. To determine the influence of this increase on PM_{10} removal from the atmosphere we ran models for five future scenarios of tree cover (Table 1). In the first (S1), the increase in tree cover was obtained by increasing each canopy type (i.e. urban woodland, street trees, garden trees and remainder) so they contributed the same proportional cover as they do currently. Secondly in scenarios S2a to S2d, the increase was achieved by increasing only one of each of the canopy types rather than all four. Thus under scenario S2a urban woodland was increased by increasing the areas of street trees, with the area of garden trees and remainder left unaltered. In S2b street tree cover was increased, in S2c garden trees and S2d the cover of remainder trees was increased. The current distribution of 96% broadleaf and 4% coniferous was used in all the scenarios examined and we have assumed that the newly planted areas will reach normal canopy size by 2050. This is a reasonable assumption given the time frame and the very common use of large containerized trees in urban plantings.

2.4. The seasonal adaptations

To estimate the current PM_{10} removal by the urban canopy the models were run using both hourly input and annual input values using both the pollution flux method and the Tiwary method. This allowed us to examine the difference in the outputs from these two approaches and to identify the extent to which seasonal values derived from annual means can be used where hourly data are not available. For the GLA annual mean data were available for future predictions of meteorology (UKCP09) and for PM_{10} concentrations (Williams, 2007). In order to take account of seasonal changes in canopy LAI we used different values for the LAI for winter, spring, summer and autumn. The LAI for broadleaf trees and coniferous trees was set as described earlier and season start and end dates are those used by UKCP09. Daily mean PM_{10} concentration data for 2006 were downloaded from 11 Local Air Quality Network monitoring sites (LAQN) in order to provide background PM_{10} concentrations (www.londonair.org.uk/). These 11 sites where those that remained after rejection of those where site-specific factors gave peak values. These monitoring data were used to calculate seasonal correction factors from the fraction of the annual mean which was represented by each seasonal mean. An identical approach was taken using monitoring stations designated as 'street' ($n = 21$ stations) and the same mean seasonal correction factor values resulted. Annual background and street PM_{10} concentrations were then converted to seasonal values using this factor.

2.5. Meteorological and PM_{10} concentration input data

2.5.1. Current

Hourly meteorological data for 2004 from Heathrow airport (−0°44.9′W, 51°47.9′N) was obtained from the Meteorological Office (Meteorological Office, 2006). These data were used in both the model runs using hourly inputs and to calculate the seasonal means for the seasonal inputs. The mapped seasonal data for the GLA were extracted from the UKCP09 gridded data sets of monthly values (www.metoffice.gov.uk; Perry & Hollis, 2005) for 2004 and 2006 at a 5 km resolution for the whole GLA area. Seasonal mean data were calculated using the mosaic function in ArcMap® and designated as 'seasonal' from mapped model inputs.

To represent the mean hourly GLA background concentrations, hourly background PM_{10} concentrations were obtained from the Islington 1 LAQN site (the mean daily data at this site closely represent the mean daily background concentrations of the 11 sites selected for the background correction factor). A seasonal average PM_{10} concentration was also calculated from this data (seasonal from hourly means). Seasonal PM_{10} concentration data were also calculated from PM_{10} distribution maps for the GLA (LAEI, 2006) for 2006 (seasonal from maps). Seasonal street level PM_{10} concentrations were obtained from a 20 m buffer applied to the GLA road network using ArcMap® (Fig. 2). The mean 20 m street buffer PM_{10} concentration for the whole GLA was 23.5 $\mu g\,m^{-3}$ (mean borough range: Bromley 21.7 $\mu g\,m^{-3}$ to City 26.8 $\mu g\,m^{-3}$) and the remaining background was 21.7 $\mu g\,m^{-3}$ (range: Bromley 20.5 $\mu g\,m^{-3}$ to City 24.7 $\mu g\,m^{-3}$). A large spatial concentration range within the street tree buffer was evident (as exemplified by Fig. 2) ranging from 19.9 $\mu g\,m^{-3}$ to a GLA maximum of 83.4 $\mu g\,m^{-3}$ from the 20 m street buffer for 2006. To estimate the current capture of PM_{10} by the urban woodland canopy, models were run using the hourly input data and the seasonal data (calculated as described above). This allowed for an analysis of the effect of using hourly and seasonal input data for meteorology and PM_{10} exposure, the results are given in Tables 2 and 3.

2.5.2. Future estimates

Input data to describe the future climate in the GLA were extracted from UKCP09 (http://ukclimateprojections-ui.defra.gov.uk). The absolute values (for a 50% probability) were extracted from the 'UK probabilistic projections of climate change over land' based on the medium emissions scenario (SRES A1B) for London in the 2050s. Seasonal change in wind speed for the London area was estimated from the UKCP02 maps for the mean of the medium emissions scenarios for 2080 (the only data available at the time of analysis). These estimates for wind speed are increases of 6%, 1.5% and 1.5% for winter, spring and summer respectively and a decrease of 4% for the autumn. The annual mean PM_{10} concentrations in London for the year 2050 were taken from Williams (2007) who estimated as 17.5 and 21 $\mu g\,m^{-3}$ for background and roadside respectively. In calculating PM_{10} concentrations the same seasonal adjustment factors were used for 2006 and 2050.

3. Results

3.1. Current and future urban canopy cover

The current and future scenarios (S1 and S2a-d) of urban canopy cover for the GLA are given in Table 1 (urban woodland, garden trees, street trees and remainder). Both the available estimates of street tree canopy area are close at 1.1% (estimated from Britt & Johnston, 2008 area survey) and 0.94% (estimated from Britt & Johnston, 2008 canopy spread class survey and borough tree inventories, GLA, 2007). By neglecting the remainder class (which cannot be resolved at borough level), canopy cover per borough ranged from 5.9% (City) to 23.7% (Bromley). Fig. 1 clearly demonstrates the lack of urban forest included in the survey of Britt and Johnston (2008) which estimated the GLA to have only 8.2% tree canopy cover.

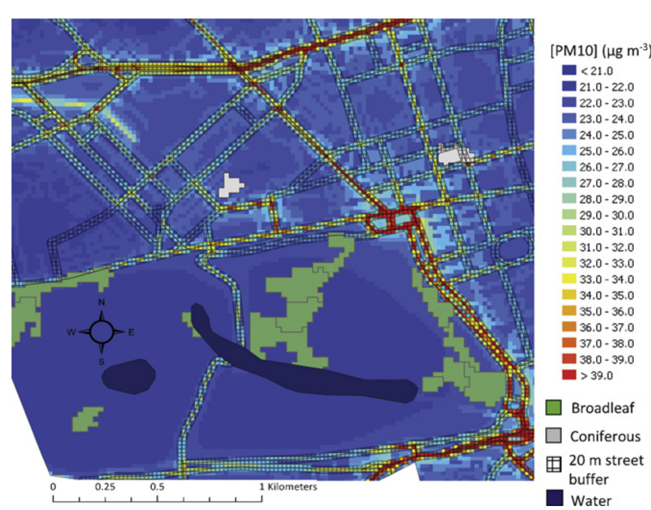

Fig. 2. An example area of the PM_{10} concentration map (LAEI, 2006) showing distribution of PM_{10} within the 20 m road buffer used to extract the street level PM_{10} concentrations.

Table 2
The effect of changing input data from hourly to seasonal on the estimated values of mixing layer height, frictional velocity and the resistance parameter (R_a, R_b and R_c) for both the pollution/deposition and Tiwary approaches. Seasonal R_c values are given for the pollution flux method as the model estimates deposition to a canopy covered land surface with seasonal LAI. The Tiwary method estimates deposition to foliage therefore R_c remains a single value through the season but LAI changes.

Model inputs [PM_{10}] and meteorological data	Mixing height (m)	Frictional velocity ($m\,s^{-1}$)	R_a ($s\,m^{-1}$)	R_b ($s\,m^{-1}$)	R_c ($s\,m^{-1}$)				
					Poll./Dep. method assuming a 10% coniferous canopy			Tiwary approach	
					Winter	Spring + Autumn	Summer	Broadleaf On leaf	Coniferous On leaf
Hourly	319.8	4.36	0.31	0.13	713.85	255.00	155.81	471.6	103.7
Seasonal calculated from hourly	388.4[a]	4.45	0.22	0.04	714.03	256.15	156.00	447.5	82.4
Seasonal calculated from hourly and map	409.0	3.82	0.25	0.05	713.98	256.11	155.95	484.2	98.4
Seasonal from Map	409.0	3.82	0.25	0.05	713.98	256.11	155.95	484.2	98.4

[a] The mean of seasonal day and night estimates.

Table 3
The effect of changing input data from hourly to seasonal on the estimated PM_{10} capture of the urban woodland component (foliage and stems, model outputs) of the total GLA urban canopy using the flux/deposition model approach.

Model inputs	Annual PM_{10} deposition to urban woodland (tonnes)			Annual PM_{10} deposition to urban woodland ($kg\,ha^{-1}\,y^{-1}$)	
[PM_{10}] and meteorological data	Broadleaf (sum of all seasons)	Coniferous	Total	Broadleaf	Coniferous
Hourly	327.7	22.1	348.8	25.3	41.8
Seasonal calculated from hourly	337.4	22.9	360.3	26.0	43.4
Seasonal from hourly and map	337.4	22.9	360.3	26.0	43.4
Seasonal from Map	344.8	23.1	367.9	26.6	43.8

3.2. Testing the seasonal model

The mixing height, frictional velocity and resistance parameters R_a, R_b and R_c (aerodynamic, quasilaminar boundary layer and canopy resistance terms respectively) are given in Table 2. The values given are for the pollution/deposition and Tiwary models using hourly or seasonal input data. All terms showed small changes as a result of scaling from hourly to seasonal inputs and the canopy terms (R_c) are expressed differently because of adaptations made by Tiwary et al. (2009). The total PM_{10} capture in 2004 by the urban woodland component of the GLA's canopy cover are shown in Table 3 for the pollution flux approach and in Table 4 for the Tiwary method. Estimates of PM_{10} capture are given based on hourly and seasonal input parameters. For the pollution/deposition flux method the total annual PM_{10} deposition ranged from 348.8 tonnes per year ($t\,y^{-1}$) using hourly data to 367.9 $t\,y^{-1}$ using seasonal inputs; a difference of 19 $t\,y^{-1}$ (only 4%) (Table 3). Using this approach deposition was 27 $kg\,ha^{-1}\,y^{-1}$ and 44 $kg\,ha^{-1}\,y^{-1}$ to broadleaved and coniferous canopies respectively with seasonal input data and was very similar when hourly data were used (25 $kg\,ha^{-1}\,y^{-1}$ for broadleaves and 42 $kg\,ha^{-1}\,y^{-1}$ for conifers). With the Tiwary method deposition values are greater ranging from 985 $t\,y^{-1}$ when based on hourly data to 756 $t\,y^{-1}$ with seasonal inputs; a difference of 229 $t\,y^{-1}$ (30%) (Table 4). Deposition to conifers (between 422 $kg\,ha^{-1}\,y^{-1}$ and 709 $kg\,ha^{-1}\,y^{-1}$) was considerably greater than to broadleaves (41 $kg\,ha^{-1}\,y^{-1}$ to 47 $kg\,ha^{-1}\,y^{-1}$). Estimates of mean annual mixing layer height were 320 m using hourly input data and 410 m using seasonal inputs, Nowak and Crane (1998) estimate a minimum urban boundary layer height of 150 m and 250 m for night and day respectively.

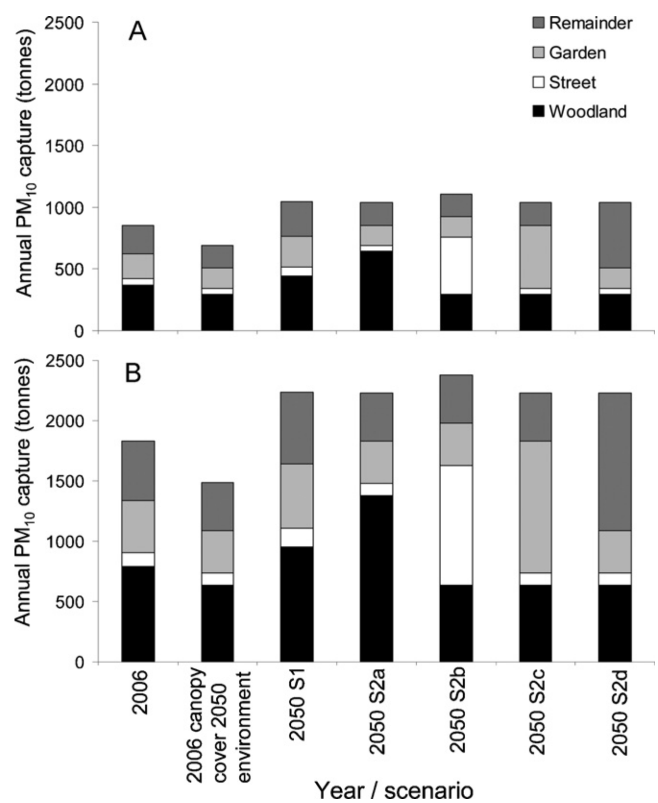

Fig. 3. The estimates of annual PM_{10} capture by the urban canopy of the GLA using (a) the pollution/deposition and (b) Tiwary models. Values are given for direct model outputs; therefore values are for deposition to foliage and stems for the deposition approach and foliage alone for the Tiwary method. Current canopy cover in 2006 meteorology and PM_{10} environment, current cover in 2050 meteorology and PM_{10} environment and four different future scenarios of canopy cover in 2050 meteorology and PM_{10} environment are given.

3.3. PM_{10} removal by the current and future (2050) GLA tree cover

Total annual estimates of PM_{10} removal by dry deposition to the urban canopy (assuming a 96% broadleaf and 4% coniferous distribution) are given in Fig. 3. Across all scenarios and for 2006 and 2050 the Tiwary method gives an approximate 2.5 fold increase

Table 4
The effect of changing input data from hourly to seasonal input data on the estimated PM_{10} capture of the urban woodland component (foliage only, model outputs) of the total urban canopy using the Tiwary approach.

Model inputs	Annual PM_{10} deposition to urban woodland foliage (tonnes)			Annual PM_{10} deposition to urban woodland foliage (kg ha^{-1} y^{-1})	
[PM_{10}] and meteorological data	Broadleaf	Coniferous	Total	Broadleaf	Coniferous
Hourly	609.6	375.1	984.7	47.0	709.8
Seasonal calculated from hourly	569.6	263.5	833.1	43.9	498.6
Seasonal from hourly and map	518.1	222.9	741.0	39.9	421.8
Seasonal from map	532.9	223.2	756.1	41.1	422.4

Table 5
The deposition of PM_{10} to the urban canopy (kg ha^{-1} y^{-1}) estimated using both modelling approaches and with current canopy cover and 2006 meteorology and [PM_{10}] taken from spatial maps of the GLA.

Canopy type	Flux/deposition model estimates of PM_{10} capture (kg ha^{-1} y^{-1})			Tiwary approach estimates of PM_{10} capture (kg ha^{-1} y^{-1})		
	GLA configuration (96%:4% broadleaf:coniferous)	100% broadleaf	100% coniferous	GLA configuration (96%:4% broadleaf:coniferous)	100% broadleaf	100% coniferous
Woodland, Garden and Remainder	27.3	26.6	43.8	58.5	42.2	448.2
Street trees	29.6	28.8	47.5	63.4	45.8	486.2

over the values derived from the original pollution flux method. This reflects the larger V_d values used in the Tiwary method, particularly for conifers at high wind speeds and also the 50% re-suspension rate included in the pollution flux method is not in the Tiwary approach. Total capture for 2006 is estimated at 852 tonnes, from the model output (559 tonnes to foliage) and 2121 tonnes (1828 tonnes to foliage) for the pollution flux and Tiwary approaches respectively. Table 5 gives the uptake of PM_{10} for both these models in kg ha^{-1} y^{-1}. In both approaches uptake to street trees was slightly larger than to other canopy types and the Tiwary method gave a 10-fold increase of deposition to the coniferous canopy when compared to the pollution flux method. In the absence of *in situ* validation data, we compared our modelled estimates of PM_{10} deposition to foliage with measured data of PM_{10} deposition to urban foliage within the UK. The mean street level PM_{10} concentration for the GLA was 23 μg m^{-3} and the flux/deposition model estimates a PM_{10} deposition of 638 mg m^{-2} to foliage and the Tiwary approach 1533 mg m^{-2}. Deposition of PM_{10} to urban street tree foliage has been measured as 205 mg m^{-2} (±145 mg m^{-2}) and 361 mg m^{-2} (±318 mg m^{-2}) (Broadmeadow, Beckett, Jackson, Freer-Smith, & Taylor, G., 1998; Beckett, Freer-Smith, & Taylor, 2000a, 2000b). Broadmeadow et al. (1998) also reports a maximum of 1400 mg m^{-2} of PM_{10} deposited to foliage of an urban woodland situated 25 m from a major UK highway (the M6). These were separate studies and issues with data comparisons are given in Section 4.

With no additional expansion to the urban canopy, by 2050 the PM_{10} removal is reduced to a total annual capture of between 693 tonnes (454 tonnes to foliage) and 1723 tonnes (1485 tonnes to foliage) for each respective model equating to a 19% reduction. This reflects the predicted decline in PM_{10} exposure by 2050. Implementing a 30% canopy cover under scenario 1 (S1) would result in an increased annual capture of 18% above 2006 levels for both models. Under scenario 2 planting dedicated to increasing the street tree canopy (S2b) offers a slight advantage in terms of increased deposition over the other canopy types: 1109 tonnes (728 tonnes to foliage) for the pollution flux model and 2760 tonnes (2379 tonnes to foliage) for the Tiwary method. This reflects the position of street trees on roadsides where PM_{10} ambient concentrations are greater. The pollution flux model estimates percentage reductions of PM_{10} concentrations in the turbulent boundary layer over the whole GLA of 0.7% currently and of up to 1.1% for scenario S2b and the Tiwary method estimates a 1.4% currently and up to 2.6% for scenario S2b.

Taking into account the heterogeneous nature of PM_{10} distribution and the greater concentrations around highways (Fig. 2) a relationship between PM_{10} concentration and canopy uptake was calculated (Fig. 4). The PM_{10} concentrations used (10–80 μg m^{-3}) are typical for the GLA which has a current mean street exposure of 23.5 μg m^{-3} and the current maximum street tree exposure concentration was 83.4 μg m^{-3} (LAEI, 2006). For a 96:4 broadleaf to coniferous mix and at a maximum PM_{10} concentration (80 μg m^{-3}), the deposition estimate from the Tiwary method (215.7 kg ha^{-1} y^{-1}) is double the estimate made by the pollution flux model (100.6 kg ha^{-1} y^{-1}). For both models a coniferous canopy sited in the most polluted areas resulted in the greatest capture of PM_{10} ranging from 161.5 to 1653.8 kg ha^{-1} y^{-1} (Fig. 4b). Based on the pollution flux model the percentage reduction of PM_{10} in the turbulent boundary layer over one hectare of canopy was 3.3% and 5.4% for broadleaved and coniferous canopies respectively and the Tiwary method estimates 5.2–54.9% reductions for broadleaved and coniferous canopies.

4. Discussion

The quantification of urban canopy cover reported here (Table 1) was in agreement with those reported from other studies. The calculated average canopy cover of a garden within the GLA is within the range of cover estimated for five other UK cities (0–30%) (Loram, Warren, & Gaston, 2008).

Both the modelling approaches used here for estimation of dry deposition of PM_{10} to the urban tree canopy estimate deposition as the inverse of three resistance parameters (R_a, R_b and R_c) (Baldocchi et al., 1987). When data were converted from hourly to seasonal input data those parameters computed using hourly wind speed were the most affected, for example R_b (s m^{-1}; quasi-laminar boundary layer) for both models and the deposition velocity term (V_d; m s^{-1}) and R_c (canopy resistance) for the Tiwary method (Table 2). The change from using hourly to annually derived inputs had little effect on the estimates made using the pollution flux model. This suggests that the R_b parameter has little influence and that seasonally corrected annual input data can be used to estimate dry deposition of PM_{10} to the urban canopy using the pollution flux model and that future predictions can be made from this approach. However, the estimated deposition by the Tiwary method was reduced by 30% when seasonal inputs were used. The V_d term in this approach was modelled as a near linear function with wind speed (Tiwary et al., 2009) from data collected in wind tunnels (Freer-Smith et al., 2004). This function results in very high deposition during wind gusts, for example the peak hourly wind speed in 2004 was 16.5 m s^{-1} giving V_d values of 0.0147 m s^{-1}

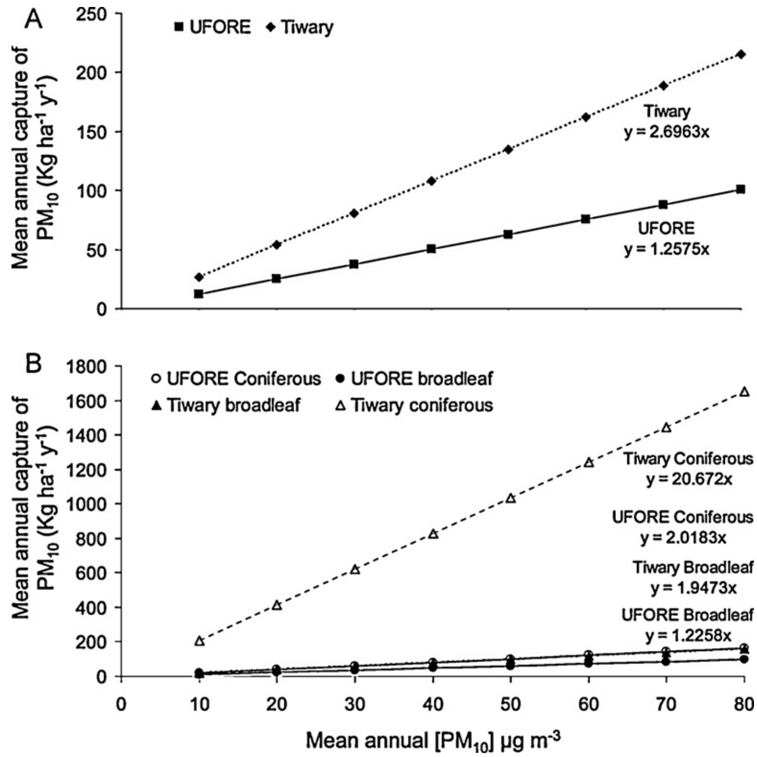

Fig. 4. The relationship between atmospheric PM_{10} concentrations and deposition of PM_{10} to (a) one hectare of urban canopy consisting of 96% broadleaf and 4% coniferous cover as estimated by both modelling approaches and (b) one hectare of either 100% deciduous or 100% coniferous canopies as estimated by both the pollution/deposition and Tiwary approaches. Values are given for direct model outputs; therefore values are for deposition to foliage and stems for the pollution flux and foliage alone for the Tiwary approach.

and 1.156 m s^{-1} and deposition to the whole GLA woodland of 591 kg h^{-1} and 3800 kg h^{-1} to deciduous and coniferous canopies respectively. Using the hourly input data this modelled function has been extrapolated outside of its range and the results are therefore uncertain. It has been suggested that deposition is reduced in high wind speed as leaves align themselves with wind to reduce drag, and particle bounce off becomes more common, and data from Freer-Smith et al. (2004) suggest that this near linear relationship does not exist in wind speeds greater than 9 m s^{-1}. Thus these high deposition rates estimated above the maximum wind speed from which the relationships were generated may be unrealistic. The mean seasonal wind speed for 2006 (3.8 m s^{-1}) was in the measured range used by Freer-Smith et al. (2004) at 4.1, 4.0, 3.3 and 3.9 m s^{-1} for winter, spring, summer and autumn respectively.

The pollution flux method gives an uptake of 27.3 kg ha^{-1} y^{-1} to the urban canopy for the mean background PM_{10} concentrations of the GLA (21.68 μg m^{-3} in 2006) (Table 5). This compares well with the uptake for Chicago's canopy estimated using UFORE and sub-sampling and hourly input data. Deposition to Chicago was 30.7 kg ha^{-1} y^{-1} at annual mean PM_{10} concentrations of 34 μg m^{-3} (Nowak et al., 2006). The Tiwary method estimates 58.5 kg ha^{-1} y^{-1} an uptake of approximately double the pollution flux model (Table 5). Both these values are within the range (11–80 kg ha^{-1}) given for annual PM_{10} removal by trees and shrubs for 55 USA cities (Nowak et al., 2006). The most recent estimates of canopy cover and the annual map of PM_{10} concentrations for 2006 gives the total deposition of PM_{10} as 852 tonnes for the pollution flux model (Fig. 4) similar to the 855 tonnes estimated by Powe and Willis (2002). Unsurprisingly, the estimated future reductions in atmospheric PM_{10} pollution (Williams, 2007) results in a reduced capture rate by the urban canopy.

For both models increasing the proportion of street trees offers the greatest potential for atmospheric PM_{10} mitigation due to the more concentrated pollutant exposure at roadsides. However, Litschke and Kuttler (2008) caution that a dense street tree canopy may not allow street derived emissions to mix with the surrounding atmosphere and therefore creating localised high PM_{10} concentrations at street level. Nevertheless, the data reported here suggest that extending the urban canopy in areas of high PM_{10} pollution offers the greatest potential for removal of PM_{10} from the atmosphere. Planting design may allow the possible decrease of dispersion ('canyon') effect to be minimized by avoiding long unbroken lines of trees or preventing the crown from closing over the top of roads. At exposures of 80 μg m^{-3} of PM_{10} the various planting scenarios reported in Fig. 4 offer annual reductions in the range 3.3–55% in PM_{10} concentrations within a well mixed boundary layer. Bealey et al. (2007) estimate that removal rates for PM_{10} of between 1% and 30% can be achieved in Glasgow depending on planting density and location but these authors also acknowledge the existence of land area constraints to planting at the most polluted sites.

Currently, in the absence of *in situ* validation for this study an attempt has been made to compare these modelled results of dry deposition with measured data of PM_{10} load to urban leaves in the UK environment. However, modelled data estimate the annual dry deposition assuming no rainfall (maximum potential dry deposition) while these measured data will have been subjected to prior rain events. and Beckett (2000a, 2000b) suggests that there is the potential for some wash off of PM_{10} by rainfall. Broadmeadow et al. (1998) supports this measuring deposition (on a leaf area basis) to an urban woodland later in the season to be less than early season values, suggesting that deposited mass was lost as the season progressed. Thus estimates of PM_{10} deposition based on leaf washing are likely to be a useful approach to the validation of model estimates although the leaf washing potential should be considered. There is clearly a wide range in measured values of PM_{10} deposition to urban trees. This wide range is accounted for by factors such as species differences, duration and intensity of rainfall, other meteorological factors such as wind speed, local PM_{10} concentration, re-suspension rate and techniques for measuring PM_{10} load and LAI.

5. Conclusion

Converting from hourly to seasonal input data had little impact on estimates of annual dry deposition of PM_{10} to the urban canopy suggesting annual estimates of future predictions can be used as input data. The modelling approaches used here gave a range of annual PM_{10} deposition to the urban canopy of London, depending on approach used and on whether trees are coniferous or broadleaved. This range is within those estimates derived for other cities using the UFORE model and the same V_d value which we used here in the pollution flux model but not in the Tiwary method (Nowak, 1994a; Nowak et al., 2006). The values derived from both the approaches described here are also very similar to those reported by Powe and Willis (2002) for London (852 tonnes and 855 tonnes respectively). Data reported here suggest that expanding the urban canopy will have a positive impact on the urban atmosphere through reduction of PM_{10} and that coniferous tree planting in areas of higher pollution offers the greatest PM_{10} mitigation potential. There are maintenance and opportunity costs associated with urban greenspace and when considering beneficial effects on air quality the, very species specific, potential of plants to produce biogenic volatile organic compounds (BVOCs) and their role in photochemical ozone formation also needs to be considered (see Donovan et al., 2005). There is a clear need for *in situ* validation of these modelled estimates to better parameterise the models, particularly the deposition velocity term, and improve the accuracy of modelled estimates. Sensitivity of selected species to atmospheric pollution and climate change, aesthetic appeal, biodiversity, soil factors, maintenance costs and the land availability for planting will also determine species choice and the use of trees in urban areas in future.

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