Integrated dispersion-deposition modelling for air pollutant reduction via green infrastructure at an urban scale

Arvind Tiwari[a] and Prashant Kumar[a, b1]

[a]*Global Centre for Clean Air Research (GCARE), Department of Civil and Environmental Engineering, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford GU2 7XH, United Kingdom*

[b]*Department of Civil, Structural & Environmental Engineering, School of Engineering, Trinity College Dublin, Dublin, Ireland*

Abstract

Green infrastructure (GI) can reduce air pollutant concentrations via coupled effects of surface deposition and aerodynamic dispersion, yet their magnitudes and relative effectiveness in reducing pollutant concentration are less studied at the urban scale. Here, we develop and apply an integrated GI assessment approach to simulate the individual effects of GI along with their combined impact on pollutant concentration reduction under eight GI scenarios. These include current for year 2015 (2015-Base); business-as-usual for year 2039 (2039-BAU); three alternative future scenarios with maximum possible coniferous (2039-Max-Con), deciduous (2039-Max-Dec) trees, and grassland (2039-Max-Grl) over the available land; and another three alternative future scenarios by considering coniferous (2039-NR-Con), deciduous (2039-NR-Dec) trees, and grassland (2039-NR-Grl) around traffic lanes. A typical UK town, Guildford, is chosen as study area where we estimated current and future traffic emissions (NO_x, PM_{10} and $PM_{2.5}$), annual deposited amount and pollutants concentration reductions and

---

[1] Corresponding author. Address as above. Email: p.kumar@surrey.ac.uk; prashant.kumar@cantab.net

percentage shared by dispersion and deposition effect in concentration reduction under above scenarios. The annual pollutant deposition was found to vary from 0.27-2.77 t.yr^{-1}.km^{-2} for NO_x, 0.46-1.03 t.yr^{-1}.km^{-2} for PM_{10} and 0.08-0.23 t.yr^{-1}.km^{-2} for $PM_{2.5}$, depending on the percentage share of GI type and traffic emissions. The 2039-Max-Dec showed the aerodynamic effect of GI can reduce the annual pollutant concentration levels up to ~10% in NO_x, ~1% in PM_{10} and ~0.8% in $PM_{2.5}$. Furthermore, the total reductions can be achieved, via GI's coupled effects of surface deposition and aerodynamic dispersion, up to ~35% in NO_x, ~21% in PM_{10} and ~8% in $PM_{2.5}$ with ~75% GI cover in modelled domain under 2015-Base scenario. Coniferous trees (2039-Max-Con) were found to promote enhanced turbulence flow and offer more surface for deposition. Moreover, planting coniferous trees near traffic lanes (2039-NR-Con) was found to be a more effective solution to reduce annual pollutant concentration.

Keywords: Aerodynamic dispersion; traffic emission; Urban air quality; Deposition velocity; Air pollution mitigation; iSCAPE project

1 Introduction

Exposure to air pollution is linked to increased morbidity and mortality burden (Cohen et al., 2017; Lelieveld et al., 2018). Air pollution causes 0.4 million premature deaths per year in Europe alone despite reduced concentrations over the last decades (Guerreiro et al., 2018). The Lancet commission estimated 9 million premature deaths worldwide in the year 2015 (Landrigan et al., 2018). Infiltration of air pollutants such as nitrogen oxides (NO_x), particulate matter with aerodynamic diameter ≤10 μm (PM_{10}) and ≤2.5 μm ($PM_{2.5}$) into human body can cause several health effects including morbidity rates, respiratory symptoms, cardiovascular diseases and premature mortality (Boningari and Smirniotis, 2016; Kim et al., 2015). In urban areas, traffic emissions are one of the major sources of air pollution and the dominant source of air pollutants including PM_{10}, $PM_{2.5}$ and NO_x. For instance, vehicular emissions are responsible for up to 30% of PM in European cities; 32-85% of NO_X in Asian cities; and 55-97% of NO_X in Mexico City and São Paulo (UNEP, 2009; WHO, 2016). Despite relying on synthetic materials to remove air pollutants via adsorption or filtration such as selective catalytic, nanofiber air filter (Boningari and Smirniotis, 2016; Zhang et al., 2016), researchers also studied the nature-based solutions to mitigate the air pollution in urban areas (Gopalakrishnan et al., 2019). Increasing green infrastructure (GI) such as trees, hedges and grasslands in urban areas have been suggested as a passive method to reduce air pollutant concentration and exposure levels (Abhijith et al., 2017; Tallis et al., 2011; Ottosen and Kumar, 2020). However, most of the research is mainly focused on benefits of GI in microenvironment especially air pollutant exposure reduction. For instance, Abhijith and Kumar (2019) revealed that road-side hedges can reduce maximum of up to 63% for black carbon in open road condition. Further, Barwise and Kumar (Barwise and Kumar, 2020) highlighted the lack of published literature focused on plant species selection for improving air quality near traffic lanes. For near-road environment, Kumar et al. (2019b) published recommendation for plant species selection and their management to reduce the pollutant exposure.

In this work, we have focused on urban vegetation, also referred to as GI, in the form of trees and/or grass. Trees are divided into two categories; (i) coniferous (evergreen) that stays green all around the year and does not shed its leaves in the winter; and (ii) deciduous (broadleaf) that drops its leaves in the winter. The term ‘aerodynamic effect’ and ‘aerodynamic dispersion’ are used interchangeably to represent the process of the air pollutant dilution due to enhanced atmospheric turbulence cause by increased surface roughness. GI surface such as leaves, stems, barks, fruits and heads, serve as effective deposition sites for different air pollutants in different ways. For example, GI typically helps in biological degradation of gaseous air pollutants via leaf stomata; while deposited PM is either washed by rain or dropped with the leaf to the ground depending on prevalent environmental conditions and GI characteristic (Gourdji, 2018; Rowe, 2011). Apart from deposition, GI can also alter the air pollutant concentration levels by affecting the atmospheric turbulence e.g., by decreasing turbulence below tree canopy and high concentrations in street canyons (Salmond et al., 2013) or by increasing turbulence in open areas (Klingberg et al., 2017). Barnes et al. (2014) simulated the effect of spatially varying roughness on air pollutant ground concentration levels in operational dispersion model (ADMS-Urban; developed by the Cambridge Environmental Research Consultants, UK). They found that increasing surface roughness can reduce ground-level air pollutant concentrations via enhanced dilution. In addition to air pollutant reduction, GI also provides other ecosystem benefits such as reduce urban heat island effect (Loughner et al., 2012) and urban surface water runoff control (Grey et al., 2018).

Recently, Kumar et al. (2019a) evaluated the nexus between air pollution, GI and human health via summarising the limited evidence to establish links between pollution mitigation through GI and quantification of their health benefits. They highlighted the challenges to quantify health benefits that can be achieved from varying GI design, owing to the limited approaches to simulate the effect of GI at the macroscale. Table 1 shows a summary of previous studies that reported the GI benefits to mitigate the air pollution at the urban scale. For example, Jeanjean and co-workers have studied the effectiveness of trees to disperse traffic emissions by using a wind-tunnel validated CFD model to simulate a 4 km^2 area in Leicester city centre in the UK (Jeanjean et al., 2015, 2016). They reported that the concentrations of traffic-generated air pollutants reduced by 7 to 9% at the pedestrian height, owing to enhanced pollutant dilution due to increased air turbulence levels caused by trees. However, it is extremely challenging to conduct such studies at larger scales (such as city and regional scales) due to the considerable amount of resources required to build large-scale wind-tunnel or CFD models. Therefore, only a handful of such studies exist in the literature. In another study, Tiwary et al. (2009) proposed an integrated modelling approach to assess the effect of GI on PM_{10} concentration levels reduction and health benefits by using ADMS-Urban. Tallis et al. (2011) compared the Tiwary et al. (2009) approach with the UFORE (currently known as “i-Tree” developed by United States Forest Service) for estimating PM_{10} deposited amount and highlighted that deposition values used by Tiwary et al. (2009) are higher than i-Tree because of many assumptions such as (i) particle resuspension rate was not considered in average PM_{10} concentration; (ii) species-specific deposition velocity (V_d) values were used to estimate deposition; and (iii) constant surface resistance (R_c) is assumed through the season. However, i-Tree needs a high amount of data such as the species types, land use criteria, total tree height and crown size which needs to be collected by experience researchers to improve the model accuracy (Pace et al., 2018). In addition, i-Tree model does not include the dispersion effect of GI by assuming that air pollutant concentration is homogeneous over the domain (Cabaraban et al., 2013). These published literature show a need for modelling approaches that can quantify the aerodynamic dispersion and deposition effects of GI on pollutant concentration at urban scale based on the type of GI and its location.

As evident from the above discussion, GI can help to improve air quality via a combination of the dispersion and deposition effects on air pollutant. The maximum benefits can be achieved by strategical GI planting near the air pollution sources since air pollutant high concentration would lead to higher deposition. However, GI potential in air pollutant concentration reduction is rarely studied in term of strategical GI development at the city-scale. The objective of this work is to develop and demonstrate an integrated GI assessment approach to quantify the GI’s individual effects (deposition or aerodynamic dispersion) as well as their combined impact on pollutant concentration reduction under different GI scenarios for current (2015) and future (2039) years. We evaluated the potential of GI planning in controlling the concentration of different traffic-related air pollutants (NO_x, PM_{10}, $PM_{2.5}$), taking a typical UK town Guildford as a case study to demonstrate the modelling approach for developing GI-influenced air quality map and estimating the annual averaged reduction in air pollutant concentrations under 8 different GI scenarios (Section 2). We then quantified the aerodynamic and deposition effects of GI and compare the annual averaged air pollutant concentration reduction under different GI scenarios.

2 Methodology

2.1 Study region

Guildford (51.23° N, 0.57° W; 56 m above sea level) is a typical UK town, which is also one of the six case study cities of the iSCAPE project (https://www.iscapeproject.eu/). It has large urban green spaces as well as strong traffic sources inside. Guildford is one of the most populated areas in the Guildford Borough Council (GBC) under Surrey County, which is located southwest of central London (GBC, 2016). The study area can be categorised as urbanised region of Surrey County and dominated by heavy traffic. Consequently, four major roads, known as M25, A3, A31 and A331 (the first letter defines the type of road and numerical value represent the road number as per Department for Transport, UK; DfT, 2012), pass through Guildford. Further, the motorway M25 passes via Guildford at Wisley junction at its junction with the major road A3. The A3 road passes through the centre of town and runs north-south linking with the A31 and A331. The A3 road carries about 43746 to 96135 vehicles day^{-1} as traffic volume which is dominated by cars. The car consists of ~97% of the total traffic volume because 72% of residents prefer to commute between home and work using cars (Al-Dabbous and Kumar, 2014). Thus, traffic emission is one of the main sources of NO_x, PM_{10}, and $PM_{2.5}$ within the study area. The land use in Guildford is predominantly residential, and about half of the population (population estimated at around 130,000) lives within the urban area of Guildford town, located in the centre of GBC that has an area of 270.9 km^2 (GBC, 2016). We used a 19 km × 26 km domain area of Guildford for our assessment, as shown in Figure 1.

2.2 Modelling approach

We assessed the effect of change in traffic emission on air quality and benefits of new vegetation planting on the city-scale model with the help of integrated modelling approach that combines (i) GI's aerodynamic effect that reduce the air pollutant concentration levels via enhanced atmospheric turbulence owing to increased surface roughness in dispersion modelling by using Gaussian plume model (ADMS-Urban); and (ii) GI's deposition effect that reduce the air pollutant concentration levels via pollutant deposition over vegetation through deposition modelling (Figure 2). Further, the aerodynamic effect of GI was quantified by subtracting the levels of pollutant concentration simulated with GI surface roughness, according to GI type (Supplementary Information, SI Table S1), from those simulated by altering GI surface roughness to zero in ADMS-Urban models. To include deposition effect, the deposited amount over GI covers were modelled as area sources and its emission rates were assumed to be equal to deposition flux (F/t, in $gm^{-2}s^{-1}$; as per Eq. 1) in the ADMS-Urban model. The resulting pollutant concentrations, as an effect of deposition, at each grid were subtracted from pollutant concentrations simulated with an aerodynamic effect (Figure 2) to estimate the deposited amount of pollutants.

This approach can be used with readily available dispersion models. For instance, ADMS-Urban is used here to demonstrate the feasibility of an integrated approach for assessing GI impact on annual pollutant concentration reduction. The ADMS-Urban has a chemistry module to treat the chemical reactions into pollutant dispersion and the detailed information about these chemistry schemes are available in SI (Section S1). However, due to lack of monitoring station within study domain, it was unfeasible to include chemistry schemes that need concentrations of other pollutant such as Ozone and Sulphate. Further, the annual average pollutant concentration map was generated based on estimated hourly pollutant concentrations at 1.5 m height (human breath level). In addition, the grid resolution was chosen as a combination of

250m × 250m (1068 grid points) and 17 specified locations. Later, these pollutant concentrations were used to calculate the deposition amount and deposition effect of GI on pollutant concentration reduction. For model validation (Section 2.3) and pollutant concentration estimation (Section 3.3), the spatial average of pollutant concentration, after incorporating GI's deposition and aerodynamic effect, at 1 km^2 (267) grid points was compared with the Defra modelled annual mean hourly background concentration and specified location were compared with measured NO_x (via diffusion tube) by the GBC. The aerodynamic effect of GI was considered by altering the surface roughness (in metres) based on GI type (such as trees, grassland).

Road traffic is the major source of some of the air pollutants in Guildford (DEFRA, 2015a) which has ~1728 km roads (M roads, A roads, B roads, C roads, and U roads; DfT, 2012), Figure 1. For example, traffic had contributed around 34% in total NO_x emission in the year 2015 (GBC, 2016). In the modelled domain, there are 16.6 km of M roads (motorways) and 232.9 km of A roads; henceforth referred to as "major roads", 99.6 km of B roads and C roads (classified unnumbered); henceforth referred to as "minor roads", and 1379.0 km of U roads (unclassified unnumbered); henceforth referred to as "local roads". Most of the traffic volume passes through the major and minor roads; whereas local roads have relatively much lower traffic volumes. In order to estimate the pollutant emissions from the roads, the EFT v8.0.1 developed by DEFRA (2016) is used, which requires (i) vehicle counts, fleet composition, and traffic speed as inputs. We obtained the data for the traffic counts and fleet composition in Guildford for the year 2015 from the Department for Transport (DfT), the UK which operates ~130 traffic counters for "major roads", and ~30 traffic counters for "minor roads". In this study, the traffic speed on the roads was assumed to be constant, and taken to be the average traffic speed in the UK (SI Table S2). Furthermore, other local emissions (such as domestic, industry and rail) and secondary particulate contribution within study domain were modelled as area sources and were obtained from National Atmospheric Emissions Inventory, UK (NAEI, 2014). In addition, the effect of outside domain sources was modelled as background concentration (DEFRA, 2015a).

Meteorological variables such as wind velocity and direction, temperature, relative humidity, and cloud cover are required to solve the transport equations in the ADMS-Urban model. The hourly data for those variables were obtained (Meteorological Office, 2018) for the year 2015 from a weather station located in South Farnborough (51.28° N, 0.77° W; 65 m above sea level), which is a distance of 14.5 km from the centre of the modelled domain. The dominant wind direction was South-West as per wind rose diagram (SI Figure S1). The land-cover data for the modelled domain was obtained for the year 2015 as shown in Figure 1, which is produced by the Centre for Ecology and Hydrology, UK, based on satellite imagery and digital cartography at a resolution of 25 m (Rowland et al., 2017). The domain was divided into seven types of land cover including deciduous forest, coniferous forest, grassland, water surface, agriculture surface, rural surface and urban surface. Further description of land cover is presented in SI Table S3. The fraction of land cover for the year 2015 in Guildford mention in SI Table S1. The variable surface roughness value was used based on the type of land cover. It is assumed that the ground surface has negligible change over the year from 2015 to 2017 and effect of variation in the ground surface on dispersion was incorporated in the modelled domain by use terrain data for 2017, which is generated by the Ordnance Survey (OS) and available under Open Government Licence (https://www.ordnancesurvey.co.uk).

The deposited amount (F; in gm^{-2}) to green infrastructure is estimated based on the deposition velocity (V_d; in ms^{-1}), time of exposure ($t = 3.1\times10^7$; sec), pollutant concentration (C; in gm^{-3}), factor (f; assumed 0.5 of leaf-on period for deciduous trees or 1 for coniferous trees and grassland; Baraldi et al., 2019) and resuspension rate (r; 0.5 for particles only to incorporate the 50% of resuspension rate of particles back to the atmosphere) as per Eq.1 (Bottalico et al., 2016; Jeanjean et al., 2016; Tiwary et al., 2009).

$$F = V_d.C.t.f.r \tag{1}$$

The deposition velocity for different gases pollutant is calculated using Eq. (2) as an inverse sum of aerodynamic resistance (R_a; in sm^{-1}), quasi-laminar boundary layer resistance (R_b; in sm^{-1}) and surface resistance (R_s; in sm^{-1}) (Janhäll, 2015; Jayasooriya et al., 2017; Tallis et al., 2011; Tiwary et al., 2009; Wesely, 1989). To evaluate particle deposition velocity (Eq. 3), virtual resistance ($R_a.R_b.V_s$), aerodynamic resistance and quasi-laminar layer resistance should be considered in series and the whole term in inverse was calculated in parallel to settling velocity (V_s) without surface resistance (Seinfeld and Pandis, 2006; Wesely, 2000).

$$V_d = \frac{1}{R_a+R_b+R_c} \quad for\ gaseous\ pollutants \tag{2}$$

$$V_d = V_s + \frac{1}{R_a+R_b+R_aR_bV_s} \quad for\ particulate\ matter \tag{3}$$

The hourly meteorological data obtained from South Farnborough meteorological station were used to estimate R_a and R_b (Tiwary et al., 2009) and; R_c (for gases) was calculated depending upon the land cover and seasonal category as per Wesely (1989). V_s (only for particles) was evaluated for particles diameter up to 50 μm according to the Stokes law (Eq. 4)

$$V_s = \frac{d_p^2 g(\rho_p - \rho_a)C_c}{18\mu_a} \tag{4}$$

ρ_p is the density of the particles (1500 kg m^{-3}), ρ_a is the density of the ambient air, d_p is particle diameter and g is the gravitational acceleration. LCM2015 map has 21 classes (see Table S2) based on the UK's terrestrial Broad Habitats (Jackson, 2000) and out of them, only 9 classes are available in the modelled domain that has been divided into 7 types of land cover.

2.3 Model validation

The levels of annual air pollutant concentration were simulated by a combination of aerodynamic effects of GI and deposition over GI surface. The model validation was performed by comparing the model results for the annual mean hourly NO_2 concentration with the corresponding concentrations at 17 different sites in Guildford, as measured (via diffusion tube) by the GBC (GBC, 2016) and modelled annual mean hourly background concentration for air pollutants NO_x, PM_{10} and $PM_{2.5}$ provided by DEFRA (DEFRA, 2015a) at 267 points for the year 2015 (SI Figure S2). Those measurements by GBC include roadside, urban background, and rural background concentrations of NO_2. However, similar classification for their modelled points is not readily available by DEFRA. The coefficient of determination (R^2) for modelled annual mean hourly concentration with GBC measured NO_x concentration was 0.74 (after removing red dots because these are near to traffic lanes; pollutant concentration on these points could be simulated through micro-scale model) and with DEFRA modelled annual mean hourly concentration for NO_x, PM_{10} and $PM_{2.5}$ were 0.82, 0.81, and 0.75, respectively (SI Figure S3). SI Table S4 shows the statistical analysis for DEFRA annual mean hourly concentration and modelled annual mean hourly concentration have been conducted using openair package in R (Carslaw and Ropkins, 2012).

2.4 Modelled scenarios for "what if" analysis

To evaluate the benefits of planting vegetation in Guildford vis-à-vis a combination of aerodynamic effect and deposition over GI surface (Section 2.2). We investigated different scenarios with GI for the years 2015 and 2039 as described below. The year 2015 was chosen to represent the current situation in Guildford since data for the model inputs are freely available for this year. The year 2039 has been chosen since 2040 is the year when the strategic road network (SRN) of UK aspires to have zero breaches of road-side air quality (DfT, 2015) and the UK government will end the sale of new conventional petrol and diesel cars and vans (DEFRA, 2017). This implied that the end of the year 2039 would mark a radical shift towards zero-emission vehicles, and therefore year 2039 is an ideal year for evaluating the impact of planting road-side vegetation as an intervention to comply with air quality standards.

2015-Base: This is the baseline case for the year 2015 with the currently estimated vegetation cover (sum of coniferous, deciduous tree and grassland land that is around 66% of the total study area) within Guildford. The pollutants sources from GBC are modelled using ADMS-Urban to estimate the annual average concentrations at 1.5 m height. This process used traffic emission data, meteorological data, deposition estimation (Section 2.2). The GI-influent air quality maps are estimated by a combination of the aerodynamic effect of GI and deposition of air pollutant via integrated approach in ADMS-Urban. It is worth noting that surface roughness and deposition of land covered by GI were considered as zero to estimate the air pollutant concentration levels under without GI scenario (SI Section S2).

2039-BAU: This is the business as usual scenario for the year 2039, which assumes that the traffic and fleet composition have changed based on government policies, while the type of green infrastructure, meteorological condition, surface roughness and other modelling parameters remain at the same as a 2015-BASE scenario. These government policies are related to the new air quality plan for NO_2, a number of initiatives have been taken to bring NO_2 level down, including (i) new real driving emissions standards (NRDS), (ii) adopting retrofit technology in old vehicles' engine to reduce NOx emissions, (iii) promoting low emission vehicles and alternative fuel, (iv) clean air zones for road traffic emissions, and (v) new measures to tackle NO_2 emissions for non-traffic sources. Under the NRDS (DfT, 2016), vehicle manufacturers will have to comply to ensure that on-road emissions of NO_x, PM_{10} and $PM_{2.5}$ for new vehicles will meet the laboratory testing limits. Further, the traffic pollutant emissions for the year 2039 are estimated based on projected traffic counts and fleet composition up to the year 2039 (SI Section S3). The comparison of this scenario with the 2015-Base will allow estimating the air quality benefits provided by the existing GI in GBC for the year 2039 with changed traffic emissions based on the government policies.

2039-Max-Con; 2039-Max-Dec; 2039-Max-Grl: These are three alternative scenarios for the year 2039 with the aim of maximum possible coniferous (2039-Max-Con) or deciduous (2039-Max-Dec) trees or grassland (2039-Max-Grl) cover on available GI areas. In each scenario, the total land covered by coniferous, deciduous tree and grassland, which is in total around 66% of the modelled study area, are assumed to be an either coniferous, deciduous or grassland. Therefore, the deposition velocities for area around 326 km^2 are modified corresponding to the coniferous tree, deciduous tree and grassland for 2039-Max-Con, 2039-Max-Dec, 2039-Max-Grl, respectively. In addition, the surface roughness is also altered to adjust changes according to GI types (SI Table S3). Further, the emissions, meteorological condition and other modelling parameters are assumed to be same as 2039-BAU. Comparison of the air pollutant concentration levels with 2039-BAU will give maximum air quality benefits achieved by planting coniferous/deciduous trees or grassland.

2039-NR-Con; 2039-NR-Dec; 2039-NR-Grl: These are three alternative scenarios for the year 2039 where the coniferous (2039-NR-Con), deciduous (2039-NR-Dec) trees and grassland (2039-NR-Grl) are assumed to around traffic lanes (total area is 135 km^2 in the modelled domain) that is covered by the leased GI space in the 2039-BAU. To reflect this assumption, the deposition velocities and surface roughness are altered according to coniferous tree, deciduous tree and grassland for 2039-NR-Con, 2039-NR-Dec, 2039-NR-Grl, respectively, around traffic lanes. Further, the GI cover on other areas, emissions, meteorological condition and other modelling parameters are remained to be same as 2039-BAU. Comparison of the air pollutant concentration levels with 2039-BAU will give maximum air quality benefits achieved by planting coniferous, deciduous trees and grassland near traffic lanes.

Through a systematic evaluation of the eight scenarios outlined above, we estimated the pollutants deposition benefits of planting trees or grassland at maximum potential or along major roads and estimate the potential for reductions in the NO_x, PM_{10} and $PM_{2.5}$ concentration levels in the year 2039.

3 Results and discussion

3.1 Current and future exhaust emissions

The trend in emissions of NO_x, PM_{10} and $PM_{2.5}$ within Guildford was projected from 2015 to 2039 (Figure 3). These total emissions are estimated, from on-road vehicle activities over the road length within Guildford, based on on-road vehicle population and future emission factor projection (SI Section S1). Between the year 2015 and 2039, the falling emission trend in NO_x, PM_{10} and $PM_{2.5}$ are projected from 1883 Mg, 122 Mg and 72 Mg to 371 Mg, 95 Mg and 57 Mg, respectively. A significant reduction in NO_x emission has been observed between 2015 and 2039 because of the new air quality plan for NO_2 has been adopted by the UK government (DEFRA, 2015b). Till the year 2039, the major NO_x emissions reduction is expected from cars, light goods vehicles (LGVs) and heavy goods vehicles (HGVs) that will be 73% (648 Mg), 80% (490 Mg) and 97% (278 Mg), respectively compared with the year 2015. These NO_x emission reduction is due to NRDS and new tax treatment for diesel vehicles which will shift the fleet composition towards petrol and electrical vehicles rather than diesel (DfT, 2019). In addition, other government incentives (DEFRA, 2017), such as retrofitting on old buses, green bus fund and clean bus technology fund, further reduced NO_x emission from buses by 98% (90 Mg) in the year 2039 with compared to the year 2015. Overall NO_x emission reductions from all traffic sources are targeted to be 80% (1512 Mg) between the years 2015 to 2039 for improving the air quality in the UK.

Reduction in PM_{10} and $PM_{2.5}$ emissions from traffic, including an exhaust and non-exhaust emissions, are also noted over the same period (during 2015-2039). These reductions are anticipated mainly due to the use of diesel particulate filters and implementation of NRDS in the UK (DfT, 2018). As a result of these policies, the PM_{10} emissions will be reduced by 53%

(14 Mg) and 12% (10 Mg) from LGVs and cars, respectively, whereas $PM_{2.5}$ emission reduce by 50% (8 Mg) and 5% (3 Mg) from LGVs and cars, respectively, between the years 2015 to 2039. Similarly, total PM_{10} and $PM_{2.5}$ emissions, from buses and HGVs, will also decline by 20% (4 Mg) and 37% (3 Mg), respectively, because of retrofitting of old buses and other government policies towards zero traffic emissions. PM_{10} and $PM_{2.5}$ emissions will have less reduction than NO_x emission because most of the government strategies are towards traffic emission control from exhaust pipe but many researchers (Lawrence et al., 2016; Timmers and Achten, 2016) showed that non-exhaust PM emissions are nearly 60-80% of the total emission from road traffic. Although the UK government has promised to reduce the non-exhaust emissions of PM by launching a call for evidence on these emissions (DfT, 2018). The overall PM_{10} and $PM_{2.5}$ emissions are expected to reduce by 23% (28 Mg) and 21% (15 Mg), respectively, between the years 2015 and 2039 because these PM reductions are a combined effect of an increase in traffic count and reduction in traffic exhaust PM emissions. In summary, the UK government's Clean Air Strategy (DfT, 2018) will have a much higher positive impact on the reduction of NO_x emissions compared with PM emissions, mainly because these actions are to control exhaust emissions such as NO_x and non-exhaust emissions of PM will require specific attention of policies.

3.2 Deposition amount over GI under current and future scenarios

The spatial distribution of NO_x, PM_{10} and $PM_{2.5}$ depositions are shown in Figures 4, 5 and S6, respectively, and spatial statistical analysis results are shown in SI Table S5. The vegetation was found to remove 0.028 t ha^{-1} yr^{-1} NO_x, 0.010 t ha^{-1} yr^{-1} PM_{10} and 0.002 t ha^{-1} yr^{-1} $PM_{2.5}$ from the atmosphere under the 2015-Base scenario. Cavanagh and Clemons (2006) simulated the NO_x deposition rate equal to 0.06 t ha^{-1} yr^{-1} over tree cover which is 8% of the study area (431 km^2) in Auckland, New Zealand. They had reported the annual average NO_x concentration 20 $\mu g\ m^{-3}$ which reveal the reason for a higher removal rate than our 2015-Base scenario where annual average NO_x concentration is 11.04 µg m^{-3} (Section 3.3). Conversely, the removal rate of PM_{10} is higher than those reported by Nowak (1994) for Chicago in which they estimated that trees cover could remove PM_{10} at a rate of 0.004 t ha^{-1} yr^{-1}. Nowak (1994) simulated removal rate based on the trees cover at 11% in 3350 km^2 which support the lower removal rate as compared to 2015-Base scenario where the tree covers 66%. Similarly, Yang et al. (2004) estimated PM_{10} removal rate 0.026 t ha^{-1} yr^{-1} via 16.4% of trees cover over 300 km^2 area, using the UFORE model, in Beijing. This higher PM_{10} removal rate is expected due to higher PM_{10} concentration range between 40 and 120 µg m^{-3} compared to 10.19 µg m^{-3} under 2015-Base scenario. Furthermore, the removal rate of $PM_{2.5}$ is lesser than PM_{10} due to lower settling velocity for small particles. However, the net $PM_{2.5}$ removal rate is 0.002 t ha^{-1} yr^{-1} which is in the same range to Nyelele et al. (2019) assessment for Bronx, USA. Nyelele et al. (2019) estimated, using i-Tree model, the $PM_{2.5}$ removal rate of 0.002 t ha^{-1} yr^{-1} equivalent to human health benefits valued at $6.9 million yr^{-1}. Most of the studies used the i-Tree model that has a number of assumptions to address the more complex deposition process. The i-Tree model only estimates dry deposition over GI and does not consider the effect of surface roughness that reduces the air pollutant concentration over GI due to the increase in atmospheric turbulence. Moreover, the results indicate that maximum air pollutants concentration reduction is near the traffic source because the deposition amount is proportional to pollutant concentration. In conclusion, the net deposition amount offered by vegetation is dependent on the pollutant concentration level, percentage GI percentage cover and their location.

The comparison between 2039-BAU and 2015-Base scenario shows the total pollutant deposition projected to decline in future especially NO_x deposition that is expected to decrease from 2957 tonnes to 581 tonnes (~80% less than 2015-Base scenario) because of a significant reduction in NO_x emissions in the year 2039 (Section 3.1). Furthermore, in the year 2039, PM_{10}

and $PM_{2.5}$ will also reduce by ~3% and ~2%, respectively, compared to 2015-Base scenario due to a minor change in PM emission. Under the 2039-MAX-Con, about ~16%, ~17% and ~24% of the increase in NO_x, PM_{10} and $PM_{2.5}$ depositions, respectively, are simulated as compared to 2039-BAU scenario. This may be associated with the availability of leaves throughout a year in case of coniferous trees for deposition. The opposite trends have been observed under the 2039-MAX-Dec where NO_x, PM_{10} and $PM_{2.5}$ depositions are decreased by ~13%, ~10% and ~31%, respectively, due to half vegetation period for deciduous trees compared to coniferous trees (Baraldi et al., 2019). The trend of lower pollutant deposition amount in 2039-Max-Dec scenario compared to 2039-Max-Con scenario are similar to those found by Tallis et al. (2011) for Greater London Authority who estimated that 100% coniferous trees (tree cover ~30%) within the study area (~47 Kha) has 1.6 times higher PM_{10} deposition amount than 100% deciduous trees. Under the 2039-Max-Grl scenario, significant reductions in deposition amount of all the pollutant are estimated as compared to 2039-BAU scenario, such as ~50% in NO_x, ~58% in PM_{10} and ~57% in $PM_{2.5}$. Such reductions are foreseen due to pollutants' lower deposition velocities over grassland because of high R_a value, which increases with a decrease in surface roughness (Tiwari et al., 2019), compared to trees.

When the more realistic scenarios were simulated to study the potential use of GI near to traffic lanes with the motive to confine the concentration near the sources. The pollutant depositions are increased by ~2% in NO_x, ~6% in PM_{10} and ~5% in $PM_{2.5}$, respectively, under the 2039-NR-Con scenario compared to 2039-BAU scenario. This increase in pollutant deposition amount has been observed under 2039-NR-Con scenario as a result of more deposition surface available near to source throughout a year and increase in coniferous tree cover from ~8% to ~50% compared to 2039-BAU scenario. However, under the 2039-NR-Dec scenario, about ~ 21%, ~16% and ~38% of the decrease in overall NO_x, PM_{10} and $PM_{2.5}$ deposition amounts, respectively, are simulated as compared to 2039-BAU scenario. This is so because of half vegetation period in a year for deciduous trees whose area is assumed to increase from ~20% to ~45% compared to 2039-BAU scenario. Lastly, under the 2039-NR-Grl scenario, there is a further reduction in overall deposition amount from ~24% in NO_x, ~22% in PM_{10} and ~44% in $PM_{2.5}$ as compared to 2039-BAU. A relatively high decrease in deposition amounts has been simulated under this scenario owing to pollutants' lower deposition velocities over grassland and an increase in grassland cover from ~37% to ~63% compared to 2039-BAU. Similar outcomes have also been reported by Tiwary et al (2009), who simulated the PM_{10} deposition amounts under the GI scenarios within East London Green Grid area in London using ADMS-Urban. They reported the 100% grassland cover has minimum PM_{10} annual deposited amount 17.99 ton compared to deciduous species (*A. pseudoplatanus*; 60.49 ton) and coniferous species (*P. menziesii*; 1277.13 ton). In conclusion, the above findings reinforce the fact that planting coniferous trees near the traffic lanes has the highest pollutants deposition amount compared to deciduous trees or grassland.

3.3 Pollutant concentration levels under current and future scenarios

Figures 6, 7 and S7 show the spatial distribution of NO_x, PM_{10} and $PM_{2.5}$ concentration levels at 1.5 m height, respectively, within study domain under different GI scenarios (Section 2.4) and the corresponding statistical analyses are provided in SI Table S6. In addition, the hourly average pollutant concentration levels and percentage concentration change under different GI scenarios are shown in SI Figure S8. Under the 2015-Base scenario, the average hourly pollutants concentration levels over a year (hereafter pollutants concentration levels) are 11.04 $\mu g\ m^{-3}$, 10.19 $\mu g\ m^{-3}$ and 7.95 $\mu g\ m^{-3}$ for NO_x, PM_{10} and $PM_{2.5}$, respectively, for the year 2015. These average hourly concentrations are agreed with DEFRA modelled NO_x, PM_{10} and $PM_{2.5}$ concentration and GBC measured NO_x concentration for the year 2015 (Section 2.3). The comparison between 2015–Base and 2039-BAU scenarios reveals that pollutant concentration levels are decreased by 11.77% in NO_x, 1.47% in PM_{10} and 0.13% in $PM_{2.5}$ as a result of UK government’s plan project “Clean Air Strategy” to reduce the vehicle emissions over next decades (DEFRA, 2019). This is because of the new air quality plan adopted by the Department of Transport in the UK (Section 3.1). The pollutants concentration levels are expected to reduce further by 0.24 μg m^{-3}, 0.28 μg m^{-3} and 0.05 μg m^{-3} in NO_x, PM_{10} and $PM_{2.5}$ levels under the 2039-Max-Con scenario compare to 2039-BAU scenario. The main reasons for these decreases are higher pollutants deposition over GI surfaces that are offered throughout a year by coniferous trees (Section 3.2) and increased atmospheric turbulence owing to the higher surface roughness of trees compared to grassland (Section 3.4). Although surface roughness of deciduous and coniferous trees is assumed same while simulating 100% deciduous trees within the study area, the pollutants concentration levels are increased by 0.1 μg m^{-3} in NO_x, 0.36 μg m^{-3} in PM_{10} and 0.18 μg m^{-3} in $PM_{2.5}$ under the 2039-Max-Dec compared to 2039-BAU. The reason for these concentration increases is the unavailability of deciduous leaves during the leaf-off season for pollutant deposition. Under the 2039-Max-Grl scenario, the NO_x, PM_{10} and $PM_{2.5}$ concentration levels are increased by 0.78 μg m^{-3}, 1.41 μg m^{-3} and 0.3 μg m^{-3}, respectively, compared to 2039-BAU scenario. These increases are results of pollutants’ low deposition velocity and laminar flow (low atmospheric turbulence) over grassland (Jeanjean et al., 2016). The above comparisons of different scenarios are showing that the pollutant concentration reductions are the combination of the aerodynamic effect of GI and deposition over GI (Section 3.4). Therefore, the lower pollutant concentration levels have been observed in 100% trees scenarios than 100% grassland scenario, similar results are found in the literature. For instance, Jeanjean et al (2016) studied the impact of tree aerodynamics on concentration reduction and comparison of depositions on trees, grass and building using the CFD model. They observed depositions were higher for trees than for grassland and the aerodynamic dispersive effect of trees can further reduce pollutant concentration levels in the downwind side.

The further scenarios have been developed to identify the locations, to harvest their maximum potential, for new GI which is an important aspect for urban planners and cities' authorities. Under the 2039-NR-Con scenario, 0.08 µg m^{-3}, 0.11 µg m^{-3} and 0.02 µg m^{-3} reductions in the NO_x, PM_{10} and $PM_{2.5}$ concentration levels, respectively, were observed as compared to 2039-BAU scenario. This may be linked to the confinement of the pollutants near traffic lanes which could increase the local pollutant concentration but reduce the downwind concentration. However, the NO_x, PM_{10} and $PM_{2.5}$ concentration levels are increased by 0.24 µg m^{-3}, 0.45 µg m^{-3} and 0.20 µg m^{-3}, respectively, under the 2039-NR-Dec scenario compared to 2039-BAU. Such concentration increase was anticipated by planting deciduous trees near traffic lanes as a result of pollutants' low deposition amount (Section 3.2). Finally, under the 2039-NR-Grl scenario, there is a further increase in pollutant concentration levels, such as 0.33 µg m^{-3} in NO_x, 0.61 µg m^{-3} in PM_{10} and 0.23 µg m^{-3} in $PM_{2.5}$, as compared to 2039-BAU. A significantly high increase in pollutant concentration levels has been observed under this scenario as a result of lower reduction from the deposition over grass. These results are comparable to those reported by Chen et al. (2016), where owing to greater elevation from land, trees promote air turbulence that increases the probability of pollutant deposition considerably higher than low-height GI such as shrubs or grass. Overall results have good agreement with the previous studies such as Tiwary et al. (2009), Tallis et al. (2011) and Jeanjean et al. (2016), where trees have been reported as a more efficient GI to remove pollutant and reduce pollutant concentration compare to others GI such as grass, shrubs and lianas.

3.4 Deposition and aerodynamic effect of GI on reduced pollutant concentrations

The aerodynamic effect induced by GI also reduces pollutant concentration levels, apart from pollutant deposition over GI surface. The ratios of deposition and aerodynamic effect (hereafter ratios) in the reduction of pollutant concentration levels are shown in Figure 8. The percentage of deposition in overall pollutant concentration reductions is higher in particles than gases because gravitational force on particles (settling velocity), which is a function of particle size and density, compared to gases dry deposition velocity (Tiwari et al., 2019). The pollutant concentrations reductions are lower in 2039-BAU as compared to the 2015-Base scenario, but the ratios are similar in both scenarios. This is a result of reductions in pollutant emission owing to the new air quality plan which has been adopted by the government (Section 3.1). Hence, pollutant concentration levels are lower in 2039-BAU scenario compared to 2015-Base (Section 3.3). However, the main reason for similar ratios is the percentage of GI cover and meteorological conditions that were assumed to be same in both scenarios. Under the 2039-Max-Con scenario, pollutant concentration reductions are increased by 0.24 (aerodynamic effect; deposition = 0.12; 0.12) µg m^{-3} in NO_x, 0.28 (0.03; 0.25) µg m^{-3} in PM_{10} and 0.09 (0.01; 0.08) µg m^{-3} in $PM_{2.5}$, as compared to 2039-BAU. The predominant reason for such reductions is pollutant deposition offered along with aerodynamic dispersion induced by coniferous trees. In contrast, pollutant concentration reductions are decreased by 0.11 (–0.12; 0.23) µg m^{-3} in NO_x, 0.36 (–0.03; 0.39) µg m^{-3} in PM_{10} and 0.18 (–0.01; 0.15) µg m^{-3} in $PM_{2.5}$ under the 2039–Max-Dec compared to 2039-BAU. It can be noted that the aerodynamic effects are similar under maximum trees scenarios but owing to the longer vegetation period over a year offers more deposition over coniferous trees compared to deciduous trees. Under the 2039-Max-Grl scenario, there is a further decrease in the pollutant concentration reduction offered by GI for NO_x, PM_{10} and $PM_{2.5}$ concentrations by 0.78 (0.24;0.54) µg m^{-3}, 1.41 (0.07; 1.34) µg m^{-3} and 0.26 (0.04; 0.22) µg m^{-3}, respectively, compared to 2039-BAU scenario. The substantially lower efficiency of pollutant concentration removal is observed via grassland under this scenario. This is owing to negligible surface roughness, which leads to no turbulent dispersion under laminar flow and lowers pollutant removal via deposition over grass.

Under the 2039-NR-Con scenario, the pollutant concentration reductions are slightly higher than 2039-BAU scenario, i.e., 0.08 (0.05; 0.03) µg m^{-3}, 0.11 (0.01; 0.1) µg m^{-3} and 0.02 (0;

0.02) µg m^{-3} in the NO_x, PM_{10} and $PM_{2.5}$ concentration levels, respectively. Such an increase in pollutant concentration reductions is anticipated by planting coniferous trees along the traffic lanes through more deposition surfaces as well as the increased turbulent near the source. Under the 2039-NR-Dec scenario, the overall pollutant concentration reduction efficiency is decreased by 0.24 (–0.05; 0.29) µg m^{-3}, 0.45 (–0.01; 0.46) µg m^{-3} and 0.20 (0; 0.20) µg m^{-3} in the NO_x, PM_{10} and $PM_{2.5}$ concentration levels, respectively, compared to 2039-BAU scenario. Although the aerodynamic dispersive effect of deciduous trees has a positive impact on pollutant concentration reduction due to lower deposition compared to 2039-BAU (Section 3.2), the overall pollutant concentration levels are higher than 2039-BAU scenarios (Section 3.3). Finally, under the 2039-NR-Grl scenario, the NO_x, PM_{10} and $PM_{2.5}$ concentration reduction offered by new GI configuration are further decreased by 0.34 (0.01; 0.33) µg m^{-3}, 0.62 (0.01; 0.60) µg m^{-3} and 0.23 (0; 0.23) µg m^{-3}, respectively. These decreases are owing to negligible surface roughness and lower deposition amount over grass near to traffic lanes. These results are similar to the conclusion drawn by Jeanjean et al. (2016), where they reported that trees are more efficient to reduce $PM_{2.5}$ concentration by aerodynamic dispersion induced by trees and higher depositions for trees compared to grass over the same area. Tiwary et al. (2009) have also found coniferous trees are more efficient to reduce PM_{10} concentration levels than deciduous and grass.

3.5 Consideration of GI in an operational dispersion model

To demonstrate an integrated approach that can be applied to currently available operational models, we simulated pollutant concentration levels within Guildford (Section 3.3) using this approach in ADMS-Urban model. The approach combines the aerodynamic dispersion as well as deposition capabilities of different GI's to evaluate their impact in terms of pollutant concentration reduction (Section 3.4). Tiwari et al. (2019) highlighted the modelling limitations in terms of consideration of GI in currently available operational models, which are originally not developed to study the impact of GI in air quality simulations. Therefore, this approach has been developed to simulate the aerodynamic dispersion component in addition to the deposition process induced by different GI in simulations that can help the urban planner to assess their impacts on pollutant concentration reduction. In addition, the engineered GI should be designed to cover several objectives such as improvement of air quality by pollutant removal, pollutant concentration reduction by dilution and pollutant exposure reduction by aerodynamic dispersion. In order to determine the additional feature offered by this approach, we compared it with two of previously applied approaches – (i) i-Tree (Nowak et al., 2018), and (ii) Tiwary et al. (2009) – to evaluate the impact of GI on pollutant concentration reduction. The i-Tree (www.itreetools.org) has been used in most studies to estimate the pollutants removal over various GI surfaces via deposition i.e. PM_{10} (Nowak et al., 2006; Tallis et al., 2011), $PM_{2.5}$ (Nowak et al., 2013; Nyelele et al., 2019) and gaseous pollutants (Nowak et al., 2014, 2006). In the i-Tree model, nearest air quality measurement stations are located to obtain the pollutant concentration data which are assumed to be uniform over the studied area (Nowak et al., 2014). Hence i-Tree do not consider the evaluation of the aerodynamic dispersion effect of GI on air pollutant concentration reduction (Tiwari et al., 2019). Apart from GI capabilities to reduce pollutant concentrations, there are many benefits such as carbon sequestration, stormwater runoff reduction and air temperature reduction that can be estimated by i-Tree model but have not been considered in our approach. Another approach used by Tiwary et al. (2009), where pollutant emissions reduction in each grid were used to estimate GI associated health benefits under different GI scenarios. The East London Green Grid within GLA was selected to demonstrate the approach and found that the PM_{10} removal rate could be achieved between 0.03-2.33 t ha yr^{-1} depending upon different GI species scenarios. In Tiwary et al. (2009), the model estimates PM_{10} removal in each cell based on emission within a cell and species-specific deposition velocities without resuspension of particles. In our approach, the pollutant removal in each cell depends upon pollutant emission within the study model and assumes 50% resuspension rate as suggested by Selmi et al. (2016). Hence, Tiwary et al. (2009) approach may overestimate the pollutant reduction. In summary, the estimated pollutant concentration levels based on the demonstrated approach has shown acceptable confidence, following model validation (Section 2.3) and results from the previous studies (Section 3.3).

4 Summary, Conclusions and Future Work

This research demonstrates the modelling approach that could be used to evaluate the impact of different GI on air pollutant concentration reductions at the city scale. Furthermore, we evaluated eight different GI scenarios (Section 2.4) to assess their effectiveness in terms of pollutant deposition and pollutant concentration reduction. In addition, the exhaust emissions for future years were estimated based on the new air quality plan adopted by the Department of Transport in the UK. This study also presents the percentage shared by aerodynamic dispersion and deposition capabilities of GI under different planting schemes in urban areas to harvest their maximum potential in air pollution mitigation.

The key conclusions drawn from this study are as follows:

- The future emission estimations show that Clean Air Strategy adopted by the government will have a significant reduction on exhaust emissions such as NO_x and PM by promoting electrical vehicles, but non-exhaust PM emissions will also be required to control by introducing new emission standards for electrical vehicles.
- The deposition estimations under different GI scenarios reveals that the amount of pollutant deposited over GI surface changes with pollutant emissions, the distance between source and GI, and percentage of area covered by GI and their type. Overall, the depositions are greater for trees (among trees, coniferous trees > deciduous trees) compared with than for grass owing to enhanced air turbulence promoted by trees that

increase the probability of pollutant interaction with trees than grass. According to planting scenarios, coniferous trees could be planted near traffic lanes (or around pollutant sources) to harvest their maximum potential in terms of pollutant removal.

- When comparing the pollutant concentration levels among GI types, it is found that depositions were higher for trees than for grassland and the aerodynamic dispersive effect of trees can further reduce pollutant concentration levels in the downwind side. Further, among GI scenarios, the results show coniferous trees around the highway appears to be an optimum and realistic solution to reduce pollutant concentration levels. Although 100% coniferous trees over existing GI land shows a higher reduction in pollutant concentration levels, this solution may have an adverse effect on the urban ecosystem.
- The aerodynamic dispersion is also an important factor that needs to be considered in simulating air pollutant concentration levels and it depends upon the GI's geometry and their density (Leaf area density). Moreover, the high leaf area dense GI species not only promote high aerodynamic dispersion but also offers more area for pollutant deposition. Therefore, opting coniferous trees will help to create turbulent flow for pollutant dilution and higher pollutant removal via deposition over their surface.
- The demonstrated approach shows how GI planting schemes in urban areas can best be used for pollutant concentration levels reduction via combining both their deposition and aerodynamic effects.

Furthermore, urban GI planning has attracted attention from the researcher, urban planner and governmental authorities as a passive method for air pollution abatement in recent years. The GI cover in the urban area could result in a reduction in pollutant concentration from a few percentages to ~35%, depending on the GI types. On the contrary, they may increase local pollutant concentration levels by confining pollutant under GI canopy. Apart from their capability to reduce pollutant concentration levels, there are other benefits such as carbon sequestration, stormwater runoff reduction and air temperature reduction that have not been incorporated in this approach. In addition, future research could consider the secondary pollutants (such as ozone) and their detailed atmospheric chemistry including the impact of GI emitted biogenic volatile organic compounds on pollutant transformation and secondary aerosol formation (Barwise and Kumar, 2020) to simulate pollutants' concentrations change in an urban area. These concentrations changes may be integrated with air pollution health risk assessment model to estimate the GI-related health benefits such as a reduction in mortality and morbidity and their associated monetary value.

5 Acknowledgements

This work is supported by the iSCAPE (Improving Smart Control of Air Pollution in Europe) project, which is funded by the European Community's H2020 Programme (H2020-SC5-04-2015) under the Grant Agreement No. 689954. The authors also thank Dr David Carruthers from the Cambridge Environmental Research Consultants (CERC) for support with the ADMS-Urban model, and the University of Surrey and its Department of Civil & Environment Engineering for an ORS Award and a PhD studentship to support AT's PhD research.

6 References

Abhijith, K. V., Kumar, P., Gallagher, J., McNabola, A., Baldauf, R., Pilla, F., Broderick, B., Di Sabatino, S., Pulvirenti, B., 2017. Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments – A review. Atmos. Environ. 162, 71–86.

Abhijith, K.V. V., Kumar, P., 2019. Field investigations for evaluating green infrastructure effects on air quality in open-road conditions. Atmos. Environ. 201, 132–147.

Al-Dabbous, A.N., Kumar, P., 2014. The influence of roadside vegetation barriers on airborne nanoparticles and pedestrians exposure under varying wind conditions. Atmos. Environ. 90, 113–124.

Baraldi, R., Chieco, C., Neri, L., Facini, O., Rapparini, F., Morrone, L., Rotondi, A., Carriero, G., 2019. An integrated study on air mitigation potential of urban vegetation: From a multi-trait approach to modeling. Urban For. Urban Green. 41, 127–138.

Barnes, M.J., Brade, T.K., MacKenzie, A.R., Whyatt, J.D., Carruthers, D.J., Stocker, J., Cai, X., Hewitt, C.N., 2014. Spatially-varying surface roughness and ground-level air quality in an operational dispersion model. Environ. Pollut. 185, 44–51.

Barwise, Y., Kumar, P., 2020. Designing vegetation barriers for urban air pollution abatement: a practical review for appropriate plant species selection. *npj Climate and Atmospheric Science*. Available here: https://doi.org/10.1038/s41612-020-0115-3

Boningari, T., Smirniotis, P.G., 2016. Impact of nitrogen oxides on the environment and human health: Mn-based materials for the NOx abatement. Curr. Opin. Chem. Eng. 13, 133–141.

Bottalico, F., Chirici, G., Giannetti, F., De Marco, A., Nocentini, S., Paoletti, E., Salbitano, F., Sanesi, G., Serenelli, C., Travaglini, D., 2016. Air pollution removal by green infrastructures and urban forests in the city of Florence. Agric. Agric. Sci. Procedia 8, 243–251.

Cabaraban, M.T.I., Kroll, C.N., Hirabayashi, S., Nowak, D.J., 2013. Modeling of air pollutant removal by dry deposition to urban trees using a WRF/CMAQ/i-Tree Eco coupled system. Environ. Pollut. 176, 123–133.

Cavanagh, J.-A.E., Clemons, J., 2006. Do Urban Forests Enhance Air Quality? Australas. J. Environ. Manag. 13, 120–130.

Chen, L., Liu, C., Zou, R., Yang, M., Zhang, Z., 2016. Experimental examination of effectiveness of vegetation as bio-filter of particulate matters in the urban environment. Environ. Pollut. 208, 198–208.

Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R., Feigin, V., Freedman, G., Hubbell, B., Jobling, A., Kan, H., Knibbs, L., Liu, Y., Martin, R., Morawska, L., Pope, C.A., Shin, H., Straif, K., Shaddick, G., Thomas, M., van Dingenen, R., van Donkelaar, A., Vos, T., Murray, C.J.L., Forouzanfar, M.H., 2017. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. Lancet 389, 1907–1918.

DEFRA, 2019. CLEAN AIR STRATEGY 2019 [WWW Document]. URL https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/770715/clean-air-strategy-2019.pdf (accessed 4.4.19).

DEFRA, 2017. Improving air quality in the UK: tackling nitrogen dioxide in our towns and cities Draft UK Air Quality Plan for tackling nitrogen dioxide [WWW Document]. URL www.nationalarchives.gov.uk/doc/open-government-licence/version/3/oremailPSI@nationalarchives.gsi.gov.ukwww.gov.uk/defra (accessed 7.3.19).

DEFRA, 2016. Emissions Factors Toolkit v7.0 User Guide [WWW Document]. URL https://laqm.defra.gov.uk/documents/EFTv7.0-user-guide-v1.pdf (accessed 3.22.18).

DEFRA, 2015a. Background Mapping data for local authorities - 2015- Defra, UK [WWW Document]. URL https://uk-air.defra.gov.uk/data/laqm-background-maps?year=2015 (accessed 2.17.19).

DEFRA, 2015b. Improving air quality in the UK Tackling nitrogen dioxide in our towns and cities UK overview document.

DfT, 2019. Vehicle Licensing Statistics: Annual 2018 [WWW Document]. URL https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/800502/vehicle-licensing-statistics-2018.pdf (accessed 6.24.19).

DfT, 2018. The Road to Zero Next steps towards cleaner road transport and delivering our Industrial Strategy [WWW Document]. URL www.gov.uk/dft (accessed 7.4.19).

DfT, 2016. Vehicle emissions testing programme [WWW Document]. URL https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/548148/vehicle-emissions-testing-programme-web.pdf (accessed 6.24.19).

DfT, 2015. Road Traffic Forecasts 2015 [WWW Document]. URL https://www.gov.uk/government/publications/road-traffic-forecasts-2015

DfT, 2012. Guidance on Road Classification and the Primary Route Network [WWW Document]. URL https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/315783/road-classification-guidance.pdf (accessed 11.15.19).

GBC, 2016. Air quality annual status report (ASR) [WWW Document]. URL https://www.guildford.gov.uk/article/19807/Air-quality-monitoring (accessed 3.22.18).

Gopalakrishnan, V., Ziv, G., Hirabayashi, S., Bakshi, B.R., 2019. Nature-Based Solutions Can Compete with Technology for Mitigating Air Emissions Across the United States. Environ. Sci. Technol. acs.est.9b01445.

Gourdji, S., 2018. Review of plants to mitigate particulate matter, ozone as well as nitrogen dioxide air pollutants and applicable recommendations for green roofs in Montreal, Quebec. Environ. Pollut. 241, 378–387.

Grey, V., Livesley, S.J., Fletcher, T.D., Szota, C., 2018. Tree pits to help mitigate runoff in dense urban areas. J. Hydrol. 565, 400–410.

Guerreiro, C., Ortiz, A.G., Leeuw, F. de, Viana, M., Colette, A., 2018. Air quality in Europe — 2018 report, Europe.

Jackson, D.L., 2000. Guidance on the interpretation of the Biodiversity Broad Habitat Classification (terrestrial and freshwater types): Definitions and the relationship with other habitat classifications. Habitat.

Janhäll, S., 2015. Review on urban vegetation and particle air pollution – Deposition and dispersion. Atmos. Environ. 105, 130–137.

Jayasooriya, V.M.M., Ng, A.W.. W.M., Muthukumaran, S., Perera, B.J.C.J.C., 2017. Green infrastructure practices for improvement of urban air quality. Urban For. Urban Green. 21, 34–47.

Jeanjean, A.P.R., Hinchliffe, G., McMullan, W.A., Monks, P.S., Leigh, R.J., 2015. A CFD study on the effectiveness of trees to disperse road traffic emissions at a city scale. Atmos. Environ. 120, 1–14.

Jeanjean, A.P.R.P.R., Monks, P.S.S., Leigh, R.J.J., 2016. Modelling the effectiveness of urban trees and grass on PM 2.5 reduction via dispersion and deposition at a city scale. Atmos. Environ. 147, 1–10.

Kim, K.-H., Kabir, E., Kabir, S., 2015. A review on the human health impact of airborne particulate matter. Environ. Int. 74, 136–143.

Klingberg, J., Broberg, M., Strandberg, B., Thorsson, P., Pleijel, H., 2017. Influence of urban vegetation on air pollution and noise exposure – A case study in Gothenburg, Sweden. Sci. Total Environ. 599–600, 1728–1739.

Kumar, P., Druckman, A., Gallagher, J., Gatersleben, B., Allison, S., Eisenman, T.S., Hoang, U., Hama, S., Tiwari, A., Sharma, A., Abhijith, K.V., Adlakha, D., McNabola, A., Astell-Burt, T., Feng, X., Skeldon, A.C., de Lusignan, S., Morawska, L., 2019a. The nexus between air pollution, green infrastructure and human health. Environ. Int. 133, 105181.

Kumar, P., Valappil, A.K., Barwise, Y., 2019b. Implementing Green Infrastructure for Air Pollution Abatement: General Recommendations for Management and Plant Species Selection.

Landrigan, P.J., Fuller, R., Acosta, N.J.R., Adeyi, O., Arnold, R., Basu, N. (Nil), Baldé, A.B., Bertollini, R., Bose-O'Reilly, S., Boufford, J.I., Breysse, P.N., Chiles, T., Mahidol, C., Coll-Seck, A.M., Cropper, M.L., Fobil, J., Fuster, V., Greenstone, M., Haines, A., Hanrahan, D., Hunter, D., Khare, M., Krupnick, A., Lanphear, B., Lohani, B., Martin, K., Mathiasen, K. V, McTeer, M.A., Murray, C.J.L., Ndahimananjara, J.D., Perera, F., Potočnik, J., Preker, A.S., Ramesh, J., Rockström, J., Salinas, C., Samson, L.D., Sandilya, K., Sly, P.D., Smith, K.R., Steiner, A., Stewart, R.B., Suk, W.A., van Schayck, O.C.P., Yadama, G.N., Yumkella, K., Zhong, M., 2018. The Lancet Commission on pollution and health. Lancet 391, 462–512.

Lawrence, S., Sokhi, R., Ravindra, K., 2016. Quantification of vehicle fleet PM10 particulate matter emission factors from exhaust and non-exhaust sources using tunnel measurement techniques. Environ. Pollut. 210, 419–428.

Lelieveld, J., Haines, A., Pozzer, A., 2018. Age-dependent health risk from ambient air pollution: a modelling and data analysis of childhood mortality in middle-income and low-income countries. Lancet Planet. Heal. 2, e292–e300.

Loughner, C.P., Allen, D.J., Zhang, D.L., Pickering, K.E., Dickerson, R.R., Landry, L., 2012. Roles of urban tree canopy and buildings in urban heat island effects: Parameterization and preliminary results. J. Appl. Meteorol. Climatol. 51, 1775–1793.

McDonald, A.G., Bealey, W.J., Fowler, D., Dragosits, U., Skiba, U., Smith, R.I., Donovan, R.G., Brett, H.E., Hewitt, C.N., Nemitz, E., 2007. Quantifying the effect of urban tree planting on concentrations and depositions of PM10 in two UK conurbations. Atmos. Environ. 41, 8455–8467.

Meteorological Office, 2018. Farnborough climate information - Met Office [WWW

Document]. URL https://www.metoffice.gov.uk/public/weather/climate/gcp7ybkh7 (accessed 6.15.18).

NAEI, 2014. the UK’s National Atmospheric Emissions Inventory (NAEI) [WWW Document]. URL https://naei.beis.gov.uk/data/map-uk-das?pollutant_id=6&emiss_maps_submit=naei-20200219184938 (accessed 4.15.19).

Nowak, D.J., 1994. Air Pollution Removal by Chicago’s Urban Forest, in: Chicago’s Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project. PA, pp. 63–81.

Nowak, D.J., Crane, D.E., Stevens, J.C., 2006. Air pollution removal by urban trees and shrubs in the United States. Urban For. Urban Green. 4, 5–123.

Nowak, D.J., Hirabayashi, S., Bodine, A., Greenfield, E., 2014. Tree and forest effects on air quality and human health in the United States. Env. Pollut 193, 119–129.

Nowak, D.J., Hirabayashi, S., Bodine, A., Hoehn, R., 2013. Modeled PM2.5 removal by trees in ten U.S. cities and associated health effects. Environ. Pollut. 178, 395–402.

Nowak, D.J., Hirabayashi, S., Doyle, M., McGovern, M., Pasher, J., 2018. Air pollution removal by urban forests in Canada and its effect on air quality and human health. Urban For. Urban Green. 29, 40–48.

Nyelele, C., Kroll, C.N., Nowak, D.J., 2019. Present and future ecosystem services of trees in the Bronx, NY. Urban For. Urban Green. 42, 10–20.

Pace, R., Biber, P., Pretzsch, H., Grote, R., 2018. Modeling ecosystem services for park trees: Sensitivity of i-tree eco simulations to light exposure and tree species classification. Forests 9, 1–18.

Rowe, D.B., 2011. Green roofs as a means of pollution abatement. Environ. Pollut. 159, 2100–2110.

Rowland, C.S., Morton, R.D., Carrasco, L., McShane, G., O’Neil, A.W., Wood, C.M., 2017. Digimap [WWW Document]. URL http://digimap.edina.ac.uk/ (accessed 12.5.17).

Salmond, J.A., Williams, D.E., Laing, G., Kingham, S., Dirks, K., Longley, I., Henshaw, G.S., 2013. The influence of vegetation on the horizontal and vertical distribution of pollutants in a street canyon. Sci. Total Environ. 443, 287–298.

Seinfeld, J.H., Pandis, S.N., 2006. Atmospheric Chemistry and Physics: From Air Pollution to Climate Change, JOHN WILEY & SONS, INC. John Wiley & Sons, Inc., Hoboken.

Selmi, W., Weber, C., Rivière, E., Blond, N., Mehdi, L., Nowak, D., 2016. Air pollution removal by trees in public green spaces in Strasbourg city, France. Urban For. Urban Green. 17, 192–201.

Tallis, M., Taylor, G., Sinnett, D., Freer-Smith, P., 2011. Estimating the removal of atmospheric particulate pollution by the urban tree canopy of London, under current and future environments. Landsc. Urban Plan. 103, 129–138.

Timmers, V.R.J.H., Achten, P.A.J., 2016. Non-exhaust PM emissions from electric vehicles. Atmos. Environ. 134, 10–17.

Tiwari, A., Kumar, P., Baldauf, R., Zhang, K.M., Pilla, F., Di Sabatino, S., Brattich, E., Pulvirenti, B., 2019. Considerations for evaluating green infrastructure impacts in microscale and macroscale air pollution dispersion models. Sci. Total Environ. 672, 410–426.

Tiwary, A., Sinnett, D., Peachey, C., Chalabi, Z., Vardoulakis, S., Fletcher, T., Leonardi, G., Grundy, C., Azapagic, A., Hutchings, T.R., 2009. An integrated tool to assess the role of new planting in PM10 capture and the human health benefits: A case study in London. Environ. Pollut. 157, 2645–2653.

UNEP, 2009. Health and Environment Linkages Policy Series Healthy Transport in Developing Cities.

Wesely, M.., 2000. A review of the current status of knowledge on dry deposition. Atmos. Environ. 34, 2261–2282.

Wesely, M.L., 1989. Parameterization of surface resistances to gaseous dry deposition in regional-scale numerical models. Atmos. Environ. 23, 1293–1304.

WHO, 2016. WHO | Air pollution [WWW Document]. WHO. URL http://www.who.int/sustainable-development/transport/health-risks/air-pollution/en/ (accessed 9.20.18).

Yang, J., McBride, J., Zhou, J., Sun, Z., 2004. The urban forest in Beijing and its role in air pollution reduction. Urban For. Urban Green. 3, 65–78.

Zhang, R., Liu, C., Hsu, P.C., Zhang, C., Liu, N., Zhang, J., Lee, H.R., Lu, Y., Qiu, Y., Chu, S., Cui, Y., 2016. Nanofiber air filters with high-temperature stability for efficient PM2.5 removal from the pollution sources. Nano Lett. 16, 3642–3649.

List of Tables

Table 1. Summary of past relevant studies reported air pollutant deposition over GI.

City/ Country	Domain (% GI Cover)	Model type	Type of pollutant	Removal rate (t ha^{-1} yr^{-1})	Modelling approach	Author (year)
London, UK	10K ha (5.47)	ADMS-Urban	PM_{10}	0.03 – 2.33	Dis. + Depo.	Tiwary et al. (2009)
London, UK	157K ha (20)	i-Tree	PM_{10}	0.06	Depo.	Tallis et al. (2011)
New York, US	12000K ha (65)	i-Tree	Mix[a]	0.034[b]	Depo.	Nowak et al. (2014)
Beijing, China	30K ha (16.4)	UFORE	PM_{10} SO_2 NO_x	0.02 0.03 0.01	Dis.+ Depo.	Yang et al. (2004)
Glasgow, UK	21k ha (29.1)	FRAME	PM_{10}	0.004	Depo	McDonald et al., (2007)
Bronx, US	14.7K ha (22.7)	i-Tree	$PM_{2.5}$	0.002	Depo.	Nyelele et al. (2019)
Leicester, UK	0.4K ha (100)	CFD	$PM_{2.5}$	0.03 (trees) 0.006 (grass)	Dis. + Depo.	Jeanjean et al. (2016)
Strasbourg, France	7.83K ha (27.8)	i-Tree	CO NO_2 O_3 PM_{10} $PM_{2.5}$	0.0001 0.002 0.007 0.002 0.001	Depo	Selmi et al. (2016)
Auckland, New Zealand	43.1K ha (8.1)	Flux method	O_3 NO_x PM_{10}	0.046 0.064 0.031	Depo	Cavanagh and Clemons (2006)
West Midlands, UK	90K ha (29.2)	FRAME	PM_{10}	0.008	Dis. + Depo	McDonald et al., (2007)

[a] = NO_2, O_3, $PM_{2.5}$, SO_2; [b]= Average removal rate; Dis. = Dispersion; Depo. = Deposition