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Effectiveness of Green Infrastructure for Improvement of Air Quality in Urban Street Canyons

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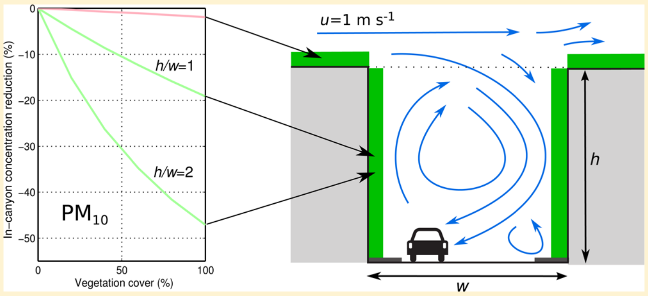
Ⓢ *Supporting Information*

ABSTRACT: Street-level concentrations of nitrogen dioxide (NO_2) and particulate matter (PM) exceed public health standards in many cities, causing increased mortality and morbidity. Concentrations can be reduced by controlling emissions, increasing dispersion, or increasing deposition rates, but little attention has been paid to the latter as a pollution control method. Both NO_2 and PM are deposited onto surfaces at rates that vary according to the nature of the surface; deposition rates to vegetation are much higher than those to hard, built surfaces. Previously, city-scale studies have suggested that deposition to vegetation can make a very modest improvement (<5%) to urban air quality. However, few studies take full account of the interplay between urban form and vegetation, specifically the enhanced residence time of air in street canyons. This study shows that increasing deposition by the planting of vegetation in street canyons can reduce street-level concentrations in those canyons by as much as 40% for NO_2 and 60% for PM. Substantial street-level air quality improvements can be gained through action at the scale of a single street canyon or across city-sized areas of canyons. Moreover, vegetation will continue to offer benefits in the reduction of pollution even if the traffic source is removed from city centers. Thus, judicious use of vegetation can create an efficient urban pollutant filter, yielding rapid and sustained improvements in street-level air quality in dense urban areas.



INTRODUCTION

Outdoor air pollution causes 35 000−50 000 premature deaths per year in the U.K.,[1] and more than 1 million worldwide,[2] in addition to increased morbidity.[3] The pollutants mostly harmful in cities in the developed world are nitrogen dioxide (NO_2), ozone, sulfur dioxide, and particulate matter with aerodynamic diameter less than 10 μm (PM_{10}), all of which cause or exacerbate pulmonary and cardiac diseases.[4,5] Attempts to reduce concentrations of these air pollutants have been ongoing for several decades, with much progress being made.[3] Methods usually center on the reduction of pollutant emissions, an increase in atmospheric dispersion, or the locating of high emitters away from existing pollution hotspots or areas of high population. Yet concentrations of air pollutants in many urban areas still consistently exceed public health standards, with annual mean concentration trends that are near-zero or even increasing.[6] Furthermore, there is a growing body of evidence that there is no safe threshold for exposure to air pollutants, especially PM,[7,8] so strategies are required to continue to drive concentrations down. Air quality management is particularly needed in poorly ventilated street canyons.[9] This study focuses on NO_2 and PM_{10}, which are the dominant pollutants in most urban areas, where they are largely derived from vehicle emissions (e.g., ~50% of NO_2 and ~80% of PM_{10} in central London, U.K.[10]). Although vehicular pollutants are reduced by dispersion, this is limited at the street-level by in-canyon air recirculation and low wind speeds. Pollutant concentrations can also be reduced by increasing dry deposition to surfaces. Compared to controlling emissions or enhancing dispersion, relatively little attention has been paid to deposition as a pollution control measure. An effective and accessible means of achieving an enhancement in pollutant deposition is to plant additional vegetation.

Dry deposition reduces pollutant concentration (C_i) through a first-order process,

$$\frac{\mathrm{d}C_\mathrm{i}}{\mathrm{d}t} = -\frac{V_\mathrm{d,i}}{z} \times C_\mathrm{i} \qquad (1)$$

where $V_\mathrm{d,i}$ is the deposition velocity and z is the height through which the pollutant is well-mixed. $V_\mathrm{d,i}$ depends on the pollutant species, i, and the nature of the surface and is generally higher to vegetation than to other urban surfaces because of metabolic uptake by the plant, the "stickiness" of the leaf surface, the large surface area of plants, and their aerodynamic properties.[11]

Previous estimates of the effect of dry deposition to urban vegetation suggest that it makes small reductions in NO_2 and PM_{10} concentrations on the city-scale.[12−19] For example, in Chicago, reductions of less than 1% are estimated based on current vegetation cover and less than 5% if the urban area is

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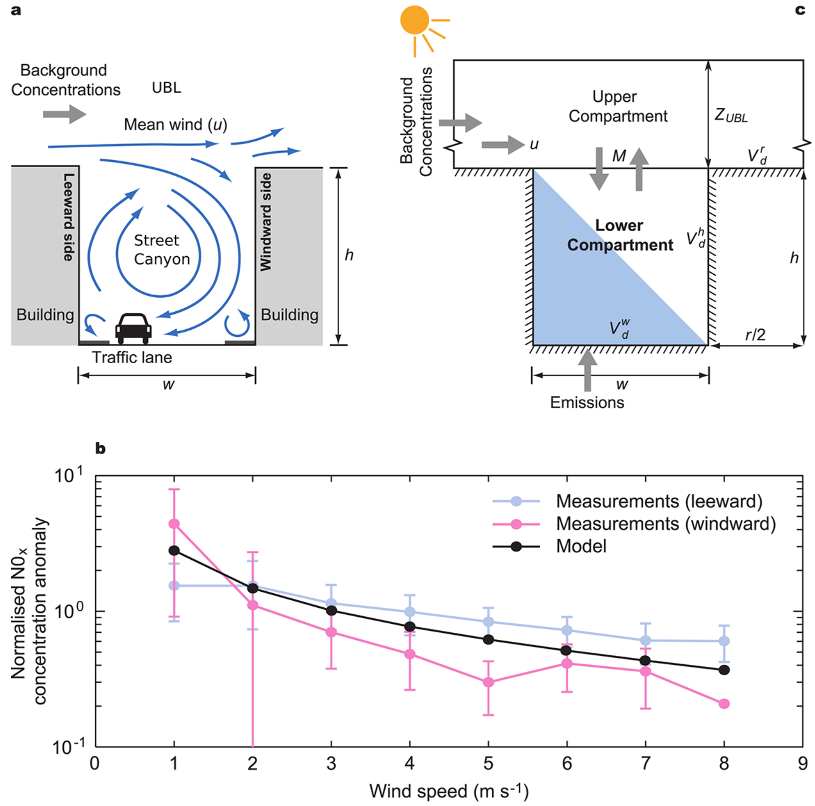

Figure 1. Interaction of street canyon and UBL air: (a) Conceptual view of circulation in street canyons redrawn from Vardoulakis et al.,[62] (b) comparison of mean modeled street canyon NO_x ($NO_x = NO + NO_2$) concentration anomaly with measurements at varying wind speeds, (c) CiTTy-Street model formulation. Measurements are a year of data from Göttinger Strasse, Hannover, which is an unvegetated canyon with $h/w \approx 1$ (http://www2.dmu.dk/atmosphericenvironment/Trapos/datadoc.htm). Anomalies are calculated by subtracting background concentrations from in-canyon concentrations for both model and measurements and normalizing against the mean concentration anomaly (see Supporting Information for details). Data are split according to whether the measurement is on the leeward or windward side of the canyon. Larger concentration anomalies are typically found at the leeward wall where pollutants tend to accumulate.[62] The error bars indicate plus/minus one standard deviation from the mean. The model results generally fall between those for the leeward and windward walls, consistent with that which would be expected for a street-canyon average value.

totally covered by trees.[12] These studies are based on domains of 12−3350 km^2 and use aggregate variables to describe the city or subregions of a city. Thus, these estimates fail to take account of how the complex geometry of the urban surface affects street-level concentrations, where people are primarily exposed, in particular through the occurrence of street canyons Street canyons are virtually ubiquitous in dense urban areas such as central London, Paris, Rome, or Manhattan. Within street canyons, overturning eddy circulations are largely isolated from the urban boundary layer (UBL) above, leading to greatly increased residence times of air within the canyon[20−24] (Figure 1a). Residence times increase substantially as the aspect ratio (height/width; h/w) of the canyon increases and as the above-roof wind speed decreases.[20,21] Where street canyons contain a pollutant source (e.g., traffic), the increased residence time within the canyon acts to increase street-level pollutant concentrations. Deposition in street canyons acts to reduce street-level pollutant concentrations and is more effective than deposition from the UBL, because of (i) the increased surface-to-volume ratio in the canyon as compared with the UBL, (ii) the decreased volume into which the pollutant is initially mixed, and (iii) the higher concentrations found within the street canyon, especially at low wind speeds (Figure 1b). All these effects could be exploited for pollution control by enhancing deposition velocities to in-canyon surfaces. “Green walls” and street trees offer two means to achieve this enhancement.

Here, a model of street-canyon chemistry and deposition was used to show that judicious use of enhanced-deposition surfaces in concert with the urban form can very substantially reduce pollutant concentrations in one of the parts of the atmosphere where people are most likely to be exposed, i.e., at street level in street canyons. The model results were evaluated against available measurements. They demonstrate that vegetation can be an important component of pollution control strategies in dense urban areas but only if it is applied with due regard to in-canyon air recirculation and the spatial distribution of emission sources. Urban greening initiatives whose focus is purely to increase urban tree coverage will fail to achieve their maximum air quality potential and may even worsen air quality in street canyons. By taking into account the particular characteristics of street canyons, the potential for air quality improvements could be greatly enhanced.

■ EXPERIMENTAL SECTION

Model Formulation. The tortuous flows in street canyons can be simulated using computational fluid dynamic (CFD) models[20,22−24] or deduced from measurement studies.[21] Although some of the modeling studies have used simple chemical schemes to study reacting pollutants, such simulations are very expensive computationally, limiting the scope for sensitivity studies. Therefore, the atmospheric chemistry model

Table 1. Modeled Vegetation Scenarios and Expected In-Canyon Concentration Reductions under Different Canyon Configurations and Meteorological Conditions.

			concentration change relative to control scenario (%)			
			U = 2 m s^{-1}			U = 0.5 m s^{-1}
	deposition velocities (cm s^{-1})		aspect ratio = 1		aspect ratio = 2	
scenario	NO_2	PM_{10}	numerous canyons	single canyon		
control (brick walls/roofs)	walls: 0.05	walls: 0.02				
	roof: 0.05	roof: 0.2				
green walls (100% coverage)	walls: 0.3	walls: 0.64	NO_2: −8.9	NO_2: −6.4	NO_2: −19.9	NO_2: −42.9
	roof: 0.05	roof: 0.2	PM_{10}: −13.1	PM_{10}: −10.8	PM_{10}: −32.0	PM_{10}: −61.9
green roof	walls: 0.05	walls: 0.02	NO_2: −0.9			
	roof: 0.3	roof: 0.64	PM^{10}: −1.1			

CiTTyCAT[25] has been enhanced to simulate mixing and dry deposition within street canyons.

Conceptually, the urban form consists of two compartments, the lower of which can represent either a single street canyon or every street canyon within a city. In this newly developed version of the CiTTyCAT model, called CiTTy-Street (Figure 1c), deposition velocities for roofs, canyon walls, and floors can be assigned separately. Emissions of NO_x, PM_{10}, and volatile organic compounds (VOCs), including, if necessary, biogenic VOCs, are input to the lower compartment. Mixing, M, between the two compartments is parametrized using dimensionless air exchange rates (E) for different canyon aspect ratios[20] for the case of a perpendicular wind and modified by h and above-roof wind speed, u:

$$M = E \times \frac{u}{h} \tag{2}$$

Concentrations in the upper compartment are refreshed using background concentrations at a rate dependent on u and the assumed horizontal length scale of the compartment (f). By varying f, CiTTy-Street can simulate either a single street canyon or a series of generic street canyons. When considering exposure to the population across a whole city, the appropriate model output is an average of the canyon and overlying box, weighted by the proportion of the urban population exposed within the urban canyons. Similarly, the effects of parkland and other land-use variations can be accommodated by a weighted average of emissions and deposition in the overlying box. By changing deposition velocities to surfaces in the lower and upper compartments, deposition to different surface types is simulated.

On the basis of the available literature, it is currently not possible to draw a firm conclusion as to how E varies for above-roof wind directions that are not perpendicular to the canyon axis or indeed the effects of junctions (see Supporting Information). It was assumed here that for a large area of street canyons the air exchange rates from Liu et al.[20] are valid for all wind directions, although the exact value of E for a particular street or set of streets remains a significant uncertainty, and one that may be sensitive to small features of canyon geometry or downwind fetch. For the case of single street canyons under a nonperpendicular wind, horizontal ventilation is highly uncertain, but may be substantial (see Supporting Information). Thus the exchange rates applied in this study must be taken as a first approximation to the generic street canyon situation, and extrapolations to specific canyons must be carried out with caution. CiTTy-Street was evaluated against measurements made in and above street canyons in Hanover, Berlin, and Copenhagen.[26,27] It was able to simulate successfully the magnitude of in-canyon NO_2 concentrations in a nonvegetated canyon given information on NO_2 and O_3 concentrations in the UBL, traffic emission rates, photolytic flux, and above-roof wind speed (Figure S2 in Supporting Information). The simulated change in anomaly between canyon and UBL concentrations with above-roof wind speed fell between that measured at leeward and windward walls in these canyons (Figure 1b, and Figure S1 in Supporting Information). This indicates that the lower compartment represented the canyon-average anomaly well. Full details of the model formulation and evaluation are given in the Supporting Information.

CiTTy-Street was used to calculate the effects of urban vegetation on pollutant concentrations, taking central London, U.K., as a case study. One control and three green wall/green roof scenarios were considered (Table 1), and each was evaluated for both a single canyon (f = 40 m) and for a large area of street canyons (f = 10 000 m). Note that the latter study does not represent a true simulation of central London but rather a scaling-up of the single canyon run to represent a large area of generic street canyons. In the following, green walls are considered as a proxy for any in-canyon vegetation which minimally affects in-canyon residence time. Street trees are addressed later, as they have the potential to substantially lengthen canyon air residence times and so increase street-level pollution concentrations.[28,29] The model results and conclusions presented below are sensitive to h/w but not to canyon volume or cloud cover (see Supporting Information).

Deposition Velocities. In this study, green walls can refer to any type of wall greening, from *Hedera* spp. (ivy) to a complete vertical canopy of grass or broadleaved plant species. Coverings of ivy are commonly found on old buildings in the U.K. and U.S., whereas pilot studies using specially designed vertical canopies have been installed at several locations (e.g., O2 Arena, Greenwich, London; Grosvenor House, Luton). A reasonable value for the single-sided leaf area index (LAI) of a green wall is 1−2 m^2 leaf m^{-2} wall.[30] Green roofs can vary from a covering of grass to shrubs and small trees and thus may have LAI varying from 2 to >5.[31]

NO_2 and O_3 deposition velocities for brick and concrete surfaces are taken from Grøntoft and Raychaudhuri.[32] Literature values for NO_2 deposition velocities for grasses and broadleaf species, i.e., those species likely to be used for green walls and roofs, generally lie in the range 0.2−0.4 cm s^{-1},[15,33−39] although velocities as high as 1.3 cm s^{-1} have been calculated over tropical pasture.[40] Likewise, O_3 deposition velocities for the same species types vary from 0.06 to

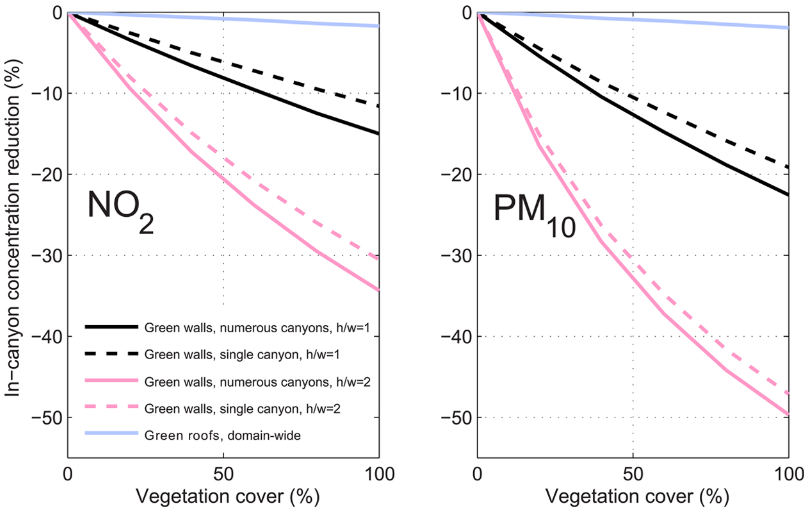

Figure 2. Modeled daytime average (0600−1800) in-canyon concentration reduction (relative to no vegetation cover) as a function of wall or roof vegetation coverage, when the above-roof wind speed is 1 m s^{-1}.

1.8 cm s^{-1}.[15,39,41−44] Given the wide range of candidate species for green walls/roofs, and the substantial overlap in measured deposition velocities for NO_2 and O_3 for different plant types and LAI, it was chosen not to identify a particular species for consideration. Rather, the study was kept general by using deposition velocities in the middle of the most commonly reported values in the literature: 0.3 cm s^{-1} for NO_2, 1.0 cm s^{-1} for O_3 (simulations are carried out during daytime when leaf stomata are likely to be open).

Reported deposition velocities for PM_{10} to vegetation vary by about 3 orders of magnitude, i.e., from ∼0.01 to ∼10 cm s^{-1}.[30] In addition, Freer-Smith et al.[45] have reported deposition velocities exceeding 30 cm s^{-1} for particles less than 1 μm in diameter, although to the knowledge of the authors these measurements have not yet been replicated elsewhere. Particle deposition rates are strongly dependent on the surface properties and orientation of the surface, and the wind speed, with higher wind speeds producing greater impaction rates and hence yielding higher deposition velocities. As leaves typically present favorable surfaces for particle capture, but wind speeds in canyons and immediately above roofs are likely to be low relative to the above-roof mean wind speed, the relatively conservative value of 0.64 cm s^{-1} used by Nowak[12,13] is adopted. Use of this commonly used deposition velocity aids comparison of the results herein with those of previous studies. Moreover, this V_d of 0.64 cm s^{-1} is considered suitable for this study because it is comparable with that predicted by the process-based model of Petroff and Zhang[46] for deposition to grass (LAI 1−2; the same as the assumed LAI for a green wall) for PM_{10} mass distributions measured in polluted street canyons (mass distribution peaking at 3−10 μm)[47,48] and broadly comparable with (although smaller than) the ∼1 cm s^{-1} measured for particles of comparable size over moorland by Nemitz et al.[49] The considerable uncertainty in this deposition velocity should be emphasized, and the deposition velocity may need to be reevaluated if a different mass size distribution is assumed (see Supporting Information for further discussion). Secondary processes such as resuspension and possible deposition limitation due to PM_{10} loading on leaves are not explicitly modeled. Both these processes would act to decrease overall deposition rates, but the uncertainties are much less than those in the initial choice of $V_{d,PM10}$. Modeled PM_{10} deposition fluxes are compared to measurements below.

RESULTS

Simulating adoption of green walls across large areas of street canyons in CiTTy-Street reduced in-canyon concentrations of NO_2 and PM_{10} by as much as 15% and 23%, respectively, at u = 1 m s^{-1} and h/w = 1 (Figure 2; for results in terms of absolute concentrations, please refer to Supporting Information). These reductions were strongly dependent on residence time (i.e., wind speed and canyon geometry) and fraction of canyon wall greening (Table 1) but not on the initial pollutant concentration (see Supporting Information). The net pollutant flux out of the canyon was itself reduced by 2−11% for NO_x (Figure S6 in Supporting Information, left) and became inward for PM_{10}, leading to small concentration reductions in the UBL above the canyon. As cities are a major regional source of air pollutants, for cities with large areal coverage of street canyons (e.g., London, New York City, Paris), this is expected to make an important difference to pollutant transport and regional-scale photochemistry, but this aspect is not pursued further here. Release of VOCs from urban trees can influence regional-scale photochemistry[15] but did not significantly alter the NO_2 and PM_{10} budgets in the canyon in this study.

Area-for-area, and for surfaces with comparable LAI and, hence, comparable deposition velocities, the model results showed that greening of in-canyon surfaces is more effective than greening of roofs at reducing street-level pollutant concentrations because it acts directly upon the relatively small volume of air in the canyon, rather than indirectly via the UBL (Figure 2 and Figure S6, right). Further, the model calculations indicated that canyon greening can actually increase the pollutant sink, area-for-area, relative to a rural vegetated surface (by 15−70% for NO_2 for 100% green wall coverage at h/w = 1; see Figure S7 in Supporting Information).

Modeled PM_{10} deposition rates were evaluated by comparing the modeled deposition flux per unit leaf area, $F_{L,i}$, with measurements, where $F_{L,i}$ was calculated from the deposition velocity and the modeled concentration:

$$F_{L,i} = \frac{V_{d,i}}{LAI} \times C_i \tag{3}$$

Assuming a single-sided LAI of 2, the modeled $F_{L,PM10}$ varied from 6 to 9 mg m^{-2} (leaf area) day^{-1} for wind speeds from 0.5 to 5 m s^{-1}. This is well within the range of available measurements. For roadside trees, $F_{L,PM10}$ = 11−119 mg m^{-2} (leaf area) day^{-1} has recently been measured.[50] Another study measured mean $F_{L,PM}$ for particles with aerodynamic diameter greater than 0.45 μm as 25 mg m^{-2} (leaf area) day^{-1} to trees alongside a major road over a 14-day period in summer; similar deposition rates were observed to leaves in central London.[51]

Pollutant concentration reductions are strongly dependent upon canyon residence time and hence wind speed. To evaluate urban greening effects over a realistic wind climatology, a year (2008) of daily average wind speeds from Kew Gardens, London, was used.[52] The concentration change indicated by CiTTy-Street for each wind speed was multiplied by the probability of that wind speed occurring. In an idealized city of uniform street canyons with h/w = 1, annual average concentrations of in-canyon NO_2 and PM_{10} were reduced by 9% and 13% by greening of canyon walls across large areas of street canyons. Despite implementation of considerable pollution control measures, U.K. roadside NO_2 concentrations have changed little over the period 1997−2010,[53] an effect attributed to an increased proportion of NO_x being emitted directly as NO_2.[6] In-canyon greening could be an effective tool to reduce street-level concentrations of NO_2 and other pollutants throughout dense urban areas.

Currently it is believed that large-scale tree planting across the city is required for vegetation to make discernible improvements to street-level air quality. Contrary to this, the results presented herein show that, because the air within a street canyon is, to a degree, isolated from the air in the UBL and all the other street canyons,[20−24] greening in one canyon may have a profound effect on air quality in that canyon and will have a small effect elsewhere through reductions in UBL concentrations (Table 1 and Figure 2). The street-level reductions were slightly smaller than for greening of large areas of street canyons, because actions in a single street canyon did not significantly reduce UBL pollutant concentrations. Using the 2008 Kew Gardens wind speed climatology produced reductions over a year for action in a single canyon (h/w = 1) of 7% and 11% for NO_2 and PM_{10} concentrations respectively. This increased to 20% and 31%, respectively, when h/w = 2. Note that when considering single canyons, along-street ventilation may also be important when the above-roof wind is not near-perpendicular to the along-canyon axis (see Supporting Information). Counter-intuitively, increasing h/w for green street canyons reduced absolute concentrations at low wind speeds (Figure S4), as the increased overall deposition rate more than compensated for the greater pollution-trapping effect at high h/w. This implies that there may be a case for artificially increasing the aspect ratio of some streets in conjunction with greening activities, perhaps by the addition of living vegetation (green) "billboards" on top of existing buildings.

At low wind speeds, when the effect of in-canyon vegetation was enhanced, the greening of canyon walls offered considerable potential for reductions in the frequency of exceedence of air quality limit values. In these circumstances, reductions in NO_2 and PM_{10} concentration of as much as ∼40% and ∼60%, respectively, were predicted by the model (Table 1 and Figure S4). This indicates that street canyon vegetation not only results in a substantial overall reduction of in-canyon pollutant concentrations, but it also forms a natural buffer against high-pollution episodes (which are often associated with low wind speeds) and associated acute impacts on human health.[4]

Like green walls, street trees increase deposition, but in addition they reduce mixing, M, between street canyon air and the UBL.[28,29] Because of this potential to alter M, it remains difficult to quantify the effect of street trees on in-canyon pollutant concentration. In order to assess whether trees have a beneficial or negative effect on in-canyon pollutant concentrations, the sensitivity of CiTTy-Street to deposition velocity and to canyon residence time was explored using a bivariate sensitivity study (Figure 3 and Figure S5). In-canyon pollutant concentrations increased with residence time when deposition velocity was low. As deposition velocity increased, a compensation deposition velocity, $V_{d,i}(P)$, was reached for each pollutant species, i. Above $V_{d,i}(P)$, in-canyon concentrations decreased as residence times increased at a given deposition velocity. Therefore, if trees increase in-canyon deposition velocity sufficiently, they will improve, rather than worsen, in-canyon air pollution. The position of $V_{d,i}(P)$ for each pollutant depends on the in-canyon emission rate of that pollutant. Higher emission rates require a higher canyon-average deposition velocity to prevent concentration build-up. This could be achieved through using different or greater amounts of street tree vegetation. For the high emission scenario used here (central London), $V_{d,PM10}(P)$ corresponded to a LAI of 1.3 averaged across the canyon width, whereas $V_{d,NO2}(P)$ was beyond the maximum of the sensitivity study.

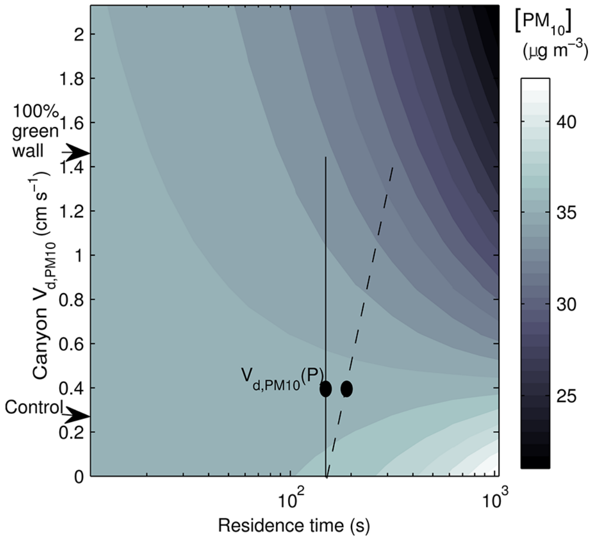

Figure 3. Effect of canyon residence time and canyon deposition velocity on modeled concentrations of PM_{10} for a single street in central London. Residence time is defined as the e-folding time for a pollutant initialized with a positive concentration in the lower compartment and a zero concentration in the upper compartment with no emissions. Total canyon $V_{d,PM10}$ is expressed relative to the width of the canyon to aid comparison of these results to future studies. The solid black line indicates the trajectory that may be followed as green walls are added, for a fixed canyon geometry and wind speed whereas the dashed black line shows how this trajectory may be altered by the addition of trees, which act to increase residence time as well as deposition velocity. Note that these lines are illustrative only. The compensation deposition velocity, $V_{d,PM10}(P)$, is that above which an increase in residence time yields a reduction in concentration.

Hence, it is expected that street trees will act to reduce street-level PM_{10} but increase NO_2 concentrations in highly polluted canyons in most circumstances. However, for streets with moderate or low emissions, trees will have an unambiguously beneficial effect. In this case the situation is analogous to air in the center of a large wooded stand, where measurements have shown substantial concentration reductions as a result of deposition to the vegetation.[54]

Note that the effect of trees on deposition rates and residence time is unlikely to be constant. Residence time in street canyons will instead vary according to wind direction and speed. Deposition velocities will vary with aerodynamic factors, tree species/size and health, and season. No sufficiently detailed data set on urban tree health and net primary productivity exists to enable time-varying deposition velocities to be built into CiTTy-Street.

DISCUSSION

These results show that in-canyon vegetation offers a method to improve urban air quality substantially. Urban greening can be effectively enacted on the local scale, providing a complement to top-down policy and regulation that encourages local ownership of pollution mitigation strategy, and helping to focus intervention on problem areas. Even if in-canyon pollutant sources are removed, in-canyon vegetation continues to offer substantial pollutant removal benefits (very close to the single canyon values in Table 1 and Figure 2), with lower concentrations in the canyon than in the UBL above, in effect creating "filtered avenues". This effect is particularly important for pollutants with atmospheric lifetimes long enough to be transported long distances, such as PM_{10} and ozone. Hence, greened urban canyons may ultimately experience better air quality than in surrounding rural areas. The use of street trees must be considered on a case-by-case basis. In streets with low street-level emissions (i.e., light traffic), the filtered avenue effect will apply. Where street-level emissions are high, however, tree planting must be used with the utmost caution. The specific combination of tree species, canopy volume, canyon geometry, and wind speed and direction must be modeled on a case-by-case basis.

Unlike tailpipe-based emission reduction strategies, greening also offers wider benefits, including reduced surface temperature and noise pollution, and increased biodiversity and amenity value.[55] But it also offers challenges in ensuring vegetation health and minimizing damage to nongreen infrastructure (e.g., underground water infrastructure). There are potential feedbacks between urban climate and tree health which cannot as yet be captured by the model. In reality, the existence of suitable plant species and the ongoing costs of maintenance will determine the viability of green infrastructure. The results presented here must be considered as part of the wide-ranging interdisciplinary discussion on the merits and implementation of urban greening.[56,57] In particular, we expect there to be strong interdependencies between urban vegetation cover and urban water resources. It is not yet possible to treat such interdependencies in CiTTy-Street or, to the knowledge of the authors, in any other urban land−atmosphere model.

Many key uncertainties remain, which should be addressed as a matter of urgency. These are the residence times of pollutants under different canyon geometries and vegetation type/coverage (especially trees), the relationship between residence time and wind speed, deposition velocities of air pollutants to canyon walls and vegetation which take account of life-cycle and seasonality, and the behavior of vegetation in the street canyon environment. An alternative to green infrastructure for air quality benefits would be to increase deposition using, for example, titanium oxide or activated carbon surface coatings,[58,59] although research suggests that these should also be applied with care, as studies have indicated the revolatization of adsorbed NO_x as nitrous acid.[60,61]

Of the green infrastructure options available in a densely populated urban area, in-canyon vegetation offers by far the biggest benefits for street-level air quality, much greater than, for example, green roofs. The results of this analysis show that street-level reductions of as much as 40% for NO_2 and 60% for PM_{10} are achievable using green walls. This suggests that the potential benefits of green infrastructure for air quality have been substantially undervalued.[12−19] These results are consistent with field measurements of deposition to vegetation and point to the utility of innovative urban greening, e.g., increasing canyon aspect ratios with green billboards, for air quality control. Such changes may be retrofitted to existing developments or designed into new ones, with potential implications for how urban areas are structured. Green infrastructure in street canyons maximizes the ability of vegetation to remove pollutants, and offers the potential for large and sustained improvements in urban air quality in both single canyons and across large areas of street canyons. It is therefore essential that the potential pollution mitigation effects of in-canyon greening inform the future development of urban areas. By not considering the adverse effects of tree planting on canyon ventilation, urban greening initiatives that concentrate on increasing the number of urban trees, without consideration of location, risk actively worsening street-level air quality while missing a considerable opportunity for air quality amelioration.

ASSOCIATED CONTENT

Ⓢ Supporting Information

Model description and further detail of results. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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