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Planning Post Carbon Cities

Improving Hyperlocal Air Quality in Cities

Impact of vegetation on pollutants concentration at pedestrian level

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ABSTRACT: Recent estimates published by WHO report that in 2016 outdoor air pollution caused 4.2 million premature deaths worldwide and urged urban planners, policymakers, and environmentalist to make health and wellbeing their number one priority when designing cities. In view of this, the current paper explores the effectiveness of trees and vegetation in dispersing air pollutants at pedestrian level by administering detailed fieldwork and spot measurement of both pollutants and microclimatic parameters close to one of the most polluted roads in London (Euston Road); followed by modelling a variety of real-life scenarios by using computational simulation application for validation and prediction. Whilst many studies agree in general on the mitigation of urban air pollutants by vegetation, the result of the current study contradicts this common understanding and demonstrates drastic increases in the concentration of particulate matters in the vicinity of trees. The results highlight that trees reduce wind velocity and air movement, causing pollutants to trap inside urban canyons. Therefore, planting more trees does not necessarily mean less pollution, at least locally. Instead, to alleviate air quality problems, more attention should be given to vegetation configuration, type, scale and most importantly, their locations and distributions within active urban pockets.

KEYWORDS: Air pollution, Vegetation, Urban form, ENVI-met, Particulate matters

1. INTRODUCTION

The recent Lancet report (2018) highlighted air pollution as the major cause of cardiovascular and respiratory illnesses and premature death in the world today. For instance, in 2015 pollutants such as Nitrogen Dioxide (NO_2) and Particulate Matter (PM_{10}, $PM_{2.5}$) have caused 64,000 premature deaths in the UK, out of which, 9000 belongs to a developed city like London. The health impacts of outdoor and indoor air pollution are well researched and established by a substantial body of research worldwide. In contrast, relatively little research has investigated the role that the built environment can potentially have on the concentration and dispersion of air pollutants [1].

Whilst the best way to tackle air pollution is to reduce and stop the pollutants at their sources, which must always be the primary focus of air quality policies, a secondary method, and one which has been increasingly perceived as effectively removing pollutants and improving urban life, is urban greenery [2]. There is a large body of studies referring to trees and their air purifying power and the fact that planting more trees is a cost-effective way to tackle urban air pollution [3]. In view of this assumption, the current paper explores the effectiveness of trees and vegetation in dispersing air pollutants at pedestrian level by administering detailed fieldwork and spot measurement of both pollutants and microclimatic parameters; followed by modelling a variety of real-life scenarios by using computational simulation software for validation and prediction.

2. METHODOLOGY

As an empirical basis for this investigation, this paper intentionally conducted its research far from the roadside and within an open courtyard (plaza) which was identified as a high-quality active pocket [4] which encourages the users to stay for longer periods of time, therefore increasing the risk of being exposed to pollutants. Accordingly, the Regent's Place pedestrian plaza which is located adjacent to one of the most polluted roads in London (Euston Road), was chosen as the fieldwork site for this paper. The fieldwork was conducted during a time when the Square was expected to be much busier than other times. In that respect, the on-site spot measurements were only carried out on the locations with the highest activities and a greater number of people density.

The Regent's Place characterised by street canyon configuration with an aspect ratio (height over width) of 1.81 and Sky View Factor of 0.35 and the built-up areas are 15 times greater than the green spaces (including trees, hedges, green roofs). Based on previous studies done by other researchers, the high aspect ratio and low SVF have a direct impact on the microclimate of a particular urban location (at a hyperlocal scale) [5]; specifically, on wind speed and its direction and accordingly influence the rate of dilution and dispersion of pollutants. Based on a scheme (Local Climate Zone) developed by Stewart and Oke in 2012, the study site classified as 'compact high-rise' where tall buildings are tightly packed beside each other with little green spaces and a few trees between them.

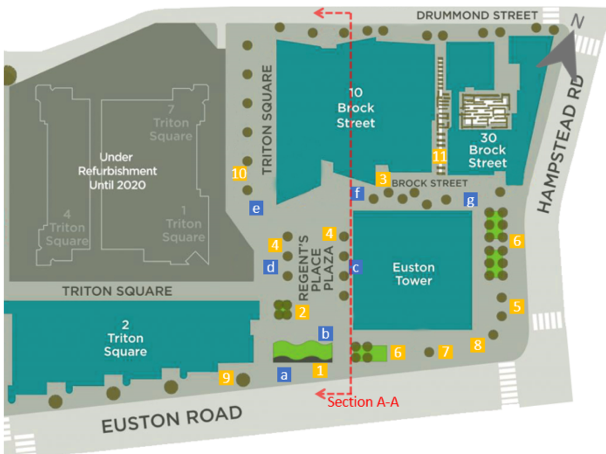

Figure 1: The Regent's Place Plaza.
Locations where the measurements were taken
Location of trees; description provided in table 02
Section A-A illustrated in figure 05

In terms of population density and activities, close to 12,000 visitors, workers, and residents passing through the plaza each day. Despite its mixed-use, the square is mainly being used by office workers throughout the weekdays and getting populated during lunchtime (11:30 am – 3:00 pm). With its high quality and stylish sitting areas which have mainly sited under the trees, more people are attracted to stay, sit, eat, meet, enjoy, and interact with each other. The square also enjoys access to a number of restaurants, and during the summer/warmer season the restaurants offer more tables and chairs for people to have their meals in the outside open air. There is also an annual events programme, involving summer events during lunchtimes, charity events, farmers markets and other social events. For that reason, this study conducted during the lunchtime (11:00 am – 3:00 pm) and over the summer period (August 2018) where the square was expected to be much busier than other times. In that respect, the site divided into two characteristics and the on-site spot measurements were carried out on, first, locations with the highest activities and a greater number of people density, i.e. location b, c, and d, fig. 1. Second, locations which were seen to offer a better understanding of how air pollutants enter the site or disperse from the site, i.e. location a, e, f and g.

The concentration of particulate matter has increasingly become more significant inside the urban canyons where the urban form and urban features (i.e. solid and porous barriers) are intensifying the concentration of pollutants and increasing health problems [6]. For that reason, apart from Nitrogen Dioxide (NO_2) which is a major concern for Euston road; this study has considered to measure and evaluate two further key urban pollutants; these are particulate matter with a diameter of 10 microns (PM_{10}) and particulate matter with a diameter of 2.5 microns ($PM_{2.5}$).

2.1 Micro-meteorological observation and monitoring of street-level air pollutant concentration

In this study, two portable real-time monitoring devices have been used: Aeroqual Series 200, which is a Portable Air Quality Monitor and Vane Anemometer and Thermo hygrometer, Testo 410-2. Air pollutants and micro-meteorological parameters measured for the period of 30 minutes at each point with readings taken every 5 minutes and average values have been logged-in for further use in the computational analysis at modelling stage (Table 01).

	Sunny Day	Meteorological conditions on 3rd August 2018 - Fri								Street-level air pollutant concentration					
Location	Time (hrs:mins)	Air Temperature (°C)		Relative Humidity (%)		Wind Velocity (m/s)		Wind Direction (m/s)		NO_2 (µg/m³)		PM_{10} (µg/m³)		$PM_{2.5}$ (µg/m³)	
		P*	S**	P	S	P	S	P	S	P	S	P	S	P	S
a	11:00 – 11:30	29	27	56	54	2.2	2	SSW	SSW	119	94.6	34	23	14	14
b	11:35 – 12:05	28	27	60	54	1.4	2	SSW	SSW	76	94.6	22	23	6	14
c	12:10 – 12:40	25	28	63	51	0.4	2	-	SSW	51	137.3	47	21.3	29	18.1
d	12:45 – 13:15	24	28	60	51	1.2	2	W	SSW	43	137.3	19	21.3	18	18.1
e	13:20 – 13:50	24	29	67	43	1.0	2	S	SSW	52	94.9	31	24.6	20	19.3
f	13:55 – 14:25	26	29	58	43	2.8	3	WSW	SW	57	94.9	26	24.6	9	19.3
g	14:30 – 15:00	27	30	57	38	1.5	3	-	SW	101	72.5	30	30.4	16	16.3

*Table 01. Meteorological and air pollution data for 3rd August 2018. *P = Primary data, **S = Secondary data related to mereological conditions extracted from www.metoffice.gov.uk and air pollution data obtained from londonair.org.uk 'Westminster - Marylebone Road – kerbside' monitoring station operated by King's College London.*

Both air quality and microclimatic parameters have been compared and ratified against live official data from www.metoffice.gov.uk and the nearest fixed meteorological and air quality monitoring station to the study site. In this case, 'Westminster - Marylebone Road – kerbside' monitoring station *operated by King's College London* has been chosen, which sits within a kilometre distance from the study site. The equipment sets are placed with a reference height of 1.5 meter above ground level. The study also captured data in several days and weather conditions, i.e. sunny, rainy, and relatively windy day. However, in this paper, only data and results pertaining to the 3rd August are used for illustration. On this particular day, the wind direction was the same as London prevailing wind direction, making this day a good representation of typical London wind behaviour for most of the year.

2.2 Computer simulations for validation and prediction

Parallel to the spot measurements and data collection, the complex microclimate phenomena and a range of issues, including air pollution dispersal/concentration, air movement in and around buildings, pedestrian level wind environment and the impacts of non-morphological features on air movement, i.e. vegetation, bus stops and cantilevered shading structures, which project at least one meter beyond the side of a building have been modelled and simulated on ENVI-met version 4.4.3. In order to correlate the relationship between vegetation and pollutants concentration, in addition to modelling the current scenario, a no-green scenario has also modelled and simulated for the plaza.

ENVI-met, which is a 3D CFD (Computational Fluid Dynamics) application, has been selected as air pollution dispersion simulation tool due to its proven reliable outcomes that were examined by previous researchers [7,8,9]. This Eulerian, time- dependant dispersion model uses RANS equation as its turbulence modelling and is capable of computing a large number of air plume particles as they emit from their original source [10]. Moreover, it uses the Finite Difference Method (FDM) to solve the multitude of partial differential equations in the model, which allows ENVI-met to use relatively large time steps but still remaining numerically stable. Moreover, with its fine resolution between half a meter to 10 meters and a typical time frame of 24-48 hours and a time step of 1-5 seconds, the model is able to simulate complicated scenarios and display the interactions between solid and porous barriers at various levels and resolutions in a very graphical format. The graphical representation of various scenarios created and produced by the LEONARDO tool included in ENVI-met package. As it was mentioned, the field spot measurement only conducted for 4 hours (11:00 am – 3:00 pm), therefore, in order to cover the total simulation time the data inserted in ENVI-met collected from 'Westminster - Marylebone Road – kerbside' monitoring station. The result of the ENVI-met simulation were thereafter compared with the field spot measurement values and further analysis and validation is provided in Result & Discussion section of this paper.

Data related to roads, buildings, vegetation, and surfaces material recorded and gathered through conventional field measurement, satellite-based measurement and official GIS documents/maps (Ordnance Survey which is the UK governmental mapping agency). Collected data from official GIS checked and verified against conventional field measurement data, and in some cases, aerial perspective published by Bing Maps and Google Maps used to minimise possible errors. Information related to vegetation characteristics such as species name, height, crown shape/size, clear stem height, and Leaf Area Density (LAD), leaf persistence and surface cover have been described in Table 02.

Vegetation Location	Vegetation Scientific name	Vegetation Common name	Vegetation Height (meter)	LAD (High/Low – Dense/Sparse)	Leaf Surface: Hairiness 0 (Smooth) – 10 (silky)	Leaf Surface: Stickiness 0 (Leathery) – 10 (highly viscid)	Evergreen /Deciduous	Trunk Size	Crown shape/Size	Clear Stem height (meter)
1	Buxus	Box Hedging	1	High	0	1	Evergreen	N/A	Hedge	0
2	Hedera helix	English Ivy	0.3	High	0	1	Evergreen	N/A	N/A	0
3	Platanus × acerifolia	London Plane	10	Low	5	3	Deciduous	Medium	Broadly Oval (Heart-Shaped)	2.5
4	Platanus × acerifolia	London Plane	10	Low	5	3	Deciduous	Medium	Broadly Oval (Heart-Shaped)	2.5
5	Prunus	Cherry Tree	4	Low	3	2	Deciduous	Small	Irregular (Heart-Shaped)	2
6	Tilia	Lime Tree	8	High	4	6	Deciduous	Medium	Broadly Round (Spherical)	2.5
7	Tilia	Lime Tree	8	High	4	6	Deciduous	Medium	Broadly Round (Spherical)	2.5
8	Platanus × acerifolia	London Plane	4	Low	5	3	Deciduous	Small	Irregular (Heart-Shaped)	2
9	Platanus × acerifolia	London Plane	10	Low	5	3	Deciduous	Medium	Broadly Oval (Heart-Shaped)	2
10	Quercus cerris	Turkey Oak	15	Low	2	2	Deciduous	Medium	Broadly Oval (Heart-Shaped)	4
11	Buxus	Box Hedging	2	High	2	1	Evergreen	N/A	Hedge	0

Table 02. Description of the study site's vegetation characteristic. Locations shown on fig. 01 in yellow numbered label

It is worth mentioning that the ENVI-met models are not working reliably at their model borders and the grids very close to them. For that reason, the nesting area of all simulation scenarios chosen sufficiently large to increase the accuracy and numerical stability of the simulation result [11]. Based on the guideline prescribed by previous researchers [12] five nesting grid cells were empirically set on each side of the model and accordingly the z-grid set to 3 times higher than the tallest building in the model site [13]. In order to accelerate the computational (rendering) time of the simulation, it was decided to lower the resolution to 4 for all axis (dx, dy and dz). Other setting and configuration considerations have been summarised in Table 03.

Modelling area file (.inx) settings		Simulation file (.sim) settings	
Model Location		**Start and duration of model run**	
Localisation	Central London	Start Date (DD.MM.YYYY)	03.07.2018
Latitude (deg,+N,-S)	51.49	Start time (HH:MM)	05:00
Longitude (deg,-W,+E)	-0.31	Total simulation time (h)	16
Model Geometry		**Initial meteorological conditions**	
Grid dimension (x, y, z)	75 x 75 x 60	Wind speed at 10m height (m/s)	2.5
Grid cells size (dx; dy; dz)	4m; 4m; 4m	Wind direction (deg)	225
Model rotation out of grid north	-19.00	Air Temperature (°C)	17 (min.) – 32 (max.)
		Relative Humidity in 2m (%)	38 (min.) – 94 (max.)
Nesting Grids	5	**Pollution Dispersion**	
Number of nesting grids		Operation mode	Multi Pollutant
		Chemistry (NO-O3-NO2)	Dispersion & Action Chemistry

Table 03. Study site input file in ENVI-met 4.4.3.

3. RESULTS & DISCUSSION

The first item revealed from the fieldwork spot measurement was that, 3rd August which was a sunny day recorded as the most polluted day in comparison to 9th (rainy day) and 24th August (windy day). This is more distinct when we look at the PM_{10} and $PM_{2.5}$ levels and less noticeable in the case of NO_2 levels. Interestingly, the result of 9th August which was the rainy day scenario recorded PM_{10} and $PM_{2.5}$ at even lower level than a windy day, but still, NO_2 was relatively high, and this has been identified as a reoccurring pattern for all other study days. In order to investigate this results further, the results of fieldwork spot measurements for the three study days of 3rd, 9th and 24th August 2018 were compared against the ENVI-met simulation of the same dates and times to firstly validate ENVI-met simulations and secondly to evaluate the effects of trees on the concentration of mentioned pollutants at the monitoring site (Regent's Place) (in this paper only data and results pertaining to the 3rd August are used for illustration). As Table 04 shows, there is a slight difference between the simulation values and measured data. The level and value of the various meteorological parameters and air pollutants simulated by ENVI-met are consistently lower than what has been measured on-site.

Sunny Day		Meteorological conditions on 3rd August 2018 - Fri								Street-level air pollutant concentration					
Location	Time (hrs:mins)	Air Temperature (°C)		Relative Humidity (%)		Wind Velocity (m/s)		Wind Direction (m/s)		NO_2 (µg/m³)		PM_{10} (µg/m³)		$PM_{2.5}$ (µg/m³)	
		FM*	EM**	FM	EM	FM	EM	FM	EM	FM	EM	FM	EM	FM	EM
a	11:00 – 11:30	29	27	56	54	2.2	1	SSW	SSW	119	90	34	15	14	9
b	11:35 – 12:05	28	27	60	54	1.4	0.5	SSW	SSW	76	90	22	10	6	6
c	12:10 – 12:40	25	25	63	57	0.4	0.5	-	NNW	51	30	47	10	29	6
d	12:45 – 13:15	24	25	60	58	1.2	1	W	WSW	43	30	19	5	18	3
e	13:20 – 13:50	24	25	67	59	1.0	1	S	SSW	52	30	31	5	20	3
f	13:55 – 14:25	26	25	58	55	2.8	2.5	WSW	SW	57	30	26	5	9	3
g	14:30 – 15:00	27	25	57	59	1.5	2	-	SSE	101	60	30	10	16	6

*Table 04. Comparison between data gathered during fieldwork measurement and data extracted from ENVI-met simulation result. *FM = Field measurements **EM= ENVI-met simulation.*

This ratio changes depending on the given meteorological conditions on the given days; however, in general, the pollution values in ENVI-met are always lower in value than the fieldwork spot measurement data. For example, the NO_2 and PMs concentration are respectively 1.4 and 3.2 times higher in recorded fieldwork spot measurements. In the case of meteorological parameters in most cases, the values are closely similar. These differences were expected as the background concentration data (for pollutants) and meteorological data which have been added in ENVI-met were extracted from the meteorological station which was located about a kilometre away from the study site ('Westminster - Marylebone Road – kerbside'), moreover, there were various simplification and assumption had to be made while modelling the site in ENVI-met. However, the most interesting aspect of this comparison which is also the main interest of this research is that the measured data and simulation data conclusively and broadly correspond to each other and more precisely confirmed and aligned over the pollution concentration zones.

In order to analyse the simulation results in more detail and understand the impact of trees on air pollution concentration, it was decided to compare the microclimate parameters both in the current urban configuration and in a scenario where there are no trees or vegetation. In this paper, the simulations with a greater significance have been presented in the next pages. For that reason, the data selected for illustration is also related to the busiest (activity and population wise) time of the plaza, which was 1 pm (lunchtime).

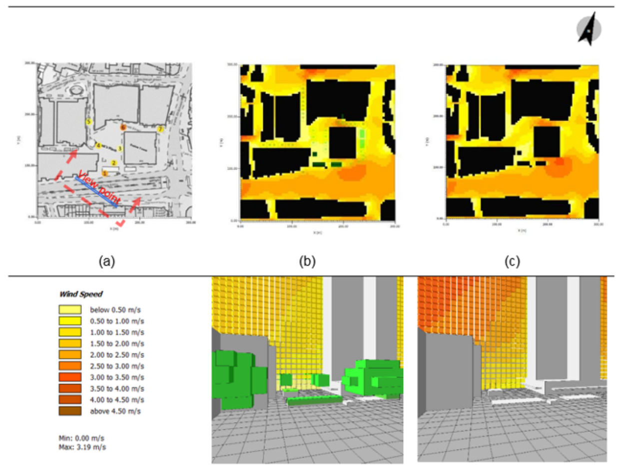

Figure 02. Snapshot of wind velocity and direction map at pedestrian level (1.5 m height from ground) for August 3rd, 2018, 13:00 h. (a) fieldwork spot measurements (b) ENVI-met simulation of current scenario (c) ENVI-met simulation of no-green scenario.

The simulation outcomes are quite revealing in several ways. First, the relative humidity is much lower in the no-green scenario, and this supports previous findings which have shown a decrease in relative humidity in no-green scenarios. Meanwhile, in the case of air temperature, the changes are not noticeable, and we do not see a great temperature difference between the two scenarios. This can be related to the low leaf area index of the trees and their clean stem height. This has been highlighted in Table 02. The wind aspect is the most interesting finding. Based on the result of the fieldwork and ENVI-met simulation, it is clear that trees in high and low density urban areas affect the wind velocity and its behaviour. As illustrated in Fig. 03 wind velocity and vegetation have inverse correlation meaning that the wind velocity decreases with an increase in vegetation volume especially in the case of trees with high leaf area density (LAD). This drop of velocity has a direct impact on a higher concentration of pollutants, and in the case of Regent's Place, the high level of pollutants concentration can be found around the sets of trees which are located on the east and west side of the plaza (fig. 01 - location c and d). This scenario is exacerbated during the London prevailing wind direction of SSW and those trees planted in north and northeast of the square (fig. 01 – location e and f) slow down air velocity further and avoid pollutants to disperse from the plaza, therefore, led to a higher concentration of pollutants under the group of trees located in the east and west side of the plaza. Specifically, $PM_{2.5}$ is 120% greater around the group of trees in location (c) and PM_{10} values are even higher and stand at 175%. It has been noted that there is not much difference in NO_2 concentration values and the two scenarios (current and no-green) are almost the same but still around trees we can observe that the values are slightly higher than no-green scenario. It is worth mentioning that, the impact of trees on wind flow greatly depend on the vegetation shape and species, as well as the density of the urban context, i.e. planting high LAD heart-shape or spherical crown shape trees with low clear stem height and little space from each other, could slow down air velocity at pedestrian level (the urban canopy layer) and increase the concentration of pollutants. Previous research done by Edward NG [14] and several other studies [5,15,16] on designing for urban ventilation and urban thermal comfort, has established that a high-density urban area induces a weak wind flow and the current study shows that planting more trees will only exacerbate this already-slow wind speed reducing it even further.

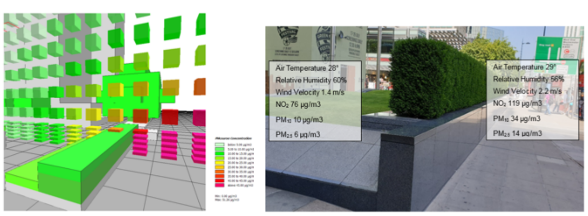

Figure 03. Snapshot of PM_{10} concentration map around hedgerow at the south side of the Regent's Place (left). Fieldwork spot measurements (right). August 3, 2018, 11:00 h.

Further analysis of the result showed that the large hedgerow located at the south side of the site (fig. 01 – location a) is the most effective element in dispersing or blocking (depositing) pollutants. In accord with the result of fieldworks, the ENVI-met simulation with the exception of NO_2, have indicated the same and showed a substantial improvement in air quality in location (b) (immediately after the hedgerow) (Fig 04). Previous studies conducted by a number of researchers [16,17] are in support of the above findings. In addition to that, in 2018 similar experiment conducted by King's College London has found levels of NO_2 reduced by 23% when an ivy screen wall was installed and placed between school playground and a busy road [18]. For that reason, it has been decided to take this strategy a step further and pilot scenarios where hedgerows which have proven to be even more effective than ivy screen [19] can be employed as a barrier and stop the PMs from congregation under the group of trees at Location (c).

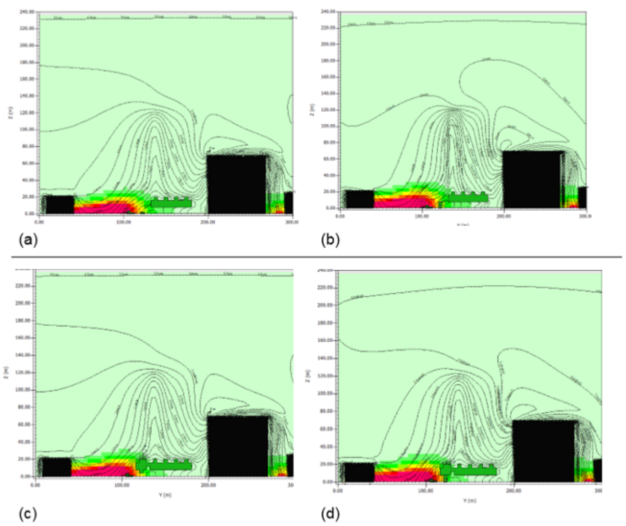

Figure 04. Section a-a illustrating PM_{10} concentration map at pedestrian level with (a) adding a 2-meter height hedgerow; (b) adding a 4-meter height hedgerow; (c) adding an 8 meter Tilia tree (lime tree); (d) adding a 2-meter height hedgerow and an eight-meter lime tree, immediately after the existing hedgerow on the south side of the site.

The first scenario (a) was to add a parallel hedgerow immediately after the 'near wake' of the existing hedgerow (fig 04 - a). the result shows a pronounced reduction in pollution level (PM_{10}) and has limited the distance which air pollution can travel (downwind). Furthermore, it has been noticed that the inlet airflow partly blocked by the two rows of hedges and partly separated upward and generated skimming flow. In the second attempt and in order to avoid the formation of skimming flow, the 2-meter hedgerow increased to 4-meter height. However, the simulation outcome showed that 4 meter height porous barrier is not enough to influence the flow turbulence as minimal reduction in terms of pollution level has been observed. In the third attempt, a 4 meter hedgerow has been replaced with an eight meter Tilia tree (lime tree, similar species as to the group of trees at East side of the site) to offer protection over a larger distance downwind. The result showed a further reduction in the distance which air pollution can travel but not much difference in terms of air pollution concentration at pedestrian level. For that reason and as a final mitigation strategy, both hedgerow and tall trees put back in their suggested places to provide the maximum protection in terms of distance, downwind and pollution concentration at the pedestrian level (Fig 04 d).

4. CONCLUSION

Whilst many studies agree in general on the mitigation of urban air pollutants by vegetation through their deposition and dispersion properties, the result of the current research contradicts this common understanding and demonstrates drastic increases in the concentration of particulate matters in the vicinity of trees. The results highlight that trees reduce wind velocity and air movement, causing pollutants to settle around and under trees' canopy. This is more distinct when we look at the PM_{10} and $PM_{2.5}$ levels and less noticeable in the case of NO_2 levels. Therefore, planting more trees does not necessarily mean less pollution, at least locally. Instead, to alleviate air quality problems, more attention should be given to vegetation configuration, type, scale and most importantly, their locations and distributions within the given active urban pocket. The findings from this research provide a fruitful area for further work to determine the exact effectiveness of vegetation in urban spaces throughout the year (summer and winter scenarios). Further investigation and modelling in different urban form with diverse vegetation type and spatial quality are required to be conducted to establish a better understanding of this matter. Needless to say that, we need more effective tree planting policy which takes the above challenges into account, and urban planners need to consider the impact of urban trees and green spaces on air quality at hyperlocal scale.

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REFERENCES

1. Hankey, S. and Marshall, J.D. (2017). Urban Form, Air Pollution, and Health. Environmental health reports, 4 (4): p. 491–503.
2. Berardi, U., G. Hoseini. 2013. State-of-the-art analysis of the environmental benefits of green roofs. *Journal of Applied Energy* 115: p. 411–428.
3. Nowak, D. and Heisler, G. (2010). Air Quality Effects of Urban Trees and Parks. *National Recreation and Park* Association, 1 (1), p. 48.
4. Gehl, J. (2011). Life between buildings: using public space. Washington, DC: Island Press, 200.
5. Edussuriya, P., Chan, A. and Malvin, A. (2014). Urban morphology and air quality in dense residential environments: Correlations between morphological parameters and air pollution at street-level. Journal of Engineering Science and Technology, 9 (1), p. 64–80.
6. WHO (2018), Amibiant (outdoor) Air Pollution, available from https://www.who.int/news-room [June 2019]
7. Jin, H. et al. (2017). The effects of residential area building layout on outdoor wind environment at the pedestrian level in severe cold regions of China. Sustainability (Switzerland), 9 (12), p. 1–18.
8. Vos, P.E.J. et al. (2013). Improving local air quality in cities: To tree or not to tree? Environmental Pollution, 183. Elsevier Ltd113–122.
9. Tsoka, S., Tsikaloudaki, K. and Theodosiou, T. (2017). Urban space's morphology and microclimatic analysis: A study for a typical urban district in the Mediterranean city of Thessaloniki, Greece. Energy and Buildings, 156. Elsevier B.V.96–108.
10. Bruse, M. (2004). ENVI-met 3.0: Updated Model Overview (March), p. 1–12.
11. ENVI-met (2019). Nesting Grids. envi-met.info. available from http://www.envi-met.info/doku.php?id=kb:nesting [June 2019]
12. Conry, P. et al. (2015). Chicago's heat island and climate change: Bridging the scales via dynamical downscaling. Journal of Applied Meteorology and Climatology, 54 (7), 1430–1448.
13. Evyatar, E., David, P. and Terry, W. (2011). Meteorology and Urban Design Erelletal 1950_2010., p. 23–24.
14. Ng, E. et al. (2011). Improving the wind environment in high-density cities by understanding urban morphology and surface roughness: A study in Hong Kong. Landscape and Urban Planning, 101 (1), Elsevier B.V.59–74.
15. Chatzidimitriou, A. and Yannas, S. (2017). Street canyon design and improvement potential for urban open spaces; the influence of canyon aspect ratio and orientation on microclimate and outdoor comfort. Sustainable Cities and Society, 33 (June), Elsevier85–101.
16. Abhijith, K. V. et al. (2017). Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments – A review. Atmospheric Environment, 162, Elsevier Ltd71–86.
17. Hewitt, C.N., Ashworth, K. and MacKenzie, A.R. (2019). Using green infrastructure to improve urban air quality (GI4AQ). Ambio,. Springer Netherlands.
18. Temper, A.H. and Green, D.C. (2018). The impact of a green screen on concentrations of nitrogen dioxide at Bowes Primary School, Enfield Prepared for the London Borough of Enfield (January), 1–19.
19. Chen, L. et al. (2017). Variation in Tree Species Ability to Capture and Retain Airborne Fine Particulate Matter (PM2.5). Scientific Reports, 7 (1), Springer US1–11.