Atmospheric Environment 120 (2015) 173–181

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Does urban forestry have a quantitative effect on ambient air quality in an urban environment?

P.J. Irga, M.D. Burchett, F.R. Torpy*

Plants and Environmental Quality Research Group, School of Life Sciences, Faculty of Science, University of Technology Sydney, P.O. Box 123, Broadway, NSW 2007, Australia

HIGHLIGHTS

- There were localised differences in PM across different areas within Sydney, Australia.
- Areas with high urban forestry density had lower PM than other sites.
- Associations between PM and meteorological factors were also observed.
- No trends in CO_2, CO, TVOCs, NO, NO_2, or SO_2 were observed.

ARTICLE INFO

Article history:
Received 6 July 2015
Received in revised form
18 August 2015
Accepted 18 August 2015
Available online 22 August 2015

Keywords:
PM_{10}
$PM_{2.5}$
Vehicular traffic
Air pollution
Particulate matter
Urban vegetation

ABSTRACT

Increasing urban greenspace has been proposed as a means of reducing airborne pollutant concentrations; however limited studies provide experimental data, as opposed to model estimates, of its ability to do so. The current project examined whether higher concentrations of urban forestry might be associated with quantifiable effects on ambient air pollutant levels, whilst accounting for the predominant source of localized spatial variations in pollutant concentrations, namely vehicular traffic. Monthly air samples for one year were taken from eleven sites in central Sydney, Australia. The sample sites exhibited a range of different traffic density, population usage, and greenspace/urban forest density conditions. Carbon dioxide (CO_2), carbon monoxide (CO), total volatile organic compounds (TVOCs), nitric oxide (NO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), total suspended particulate matter (TSP), suspended particles <10 µm in diameter (PM_{10}) and particulate matter <2.5 µm ($PM_{2.5}$), were recorded, using portable devices. It was found that air samples taken from sites with less greenspace frequently had high concentrations of all fractions of aerosolized particulates than other sites, whilst sites with high proximal greenspace had lower particulates, even when vehicular traffic was taken into account. No observable trends in concentrations of NO, TVOC and SO_2 were observed, as recorded levels were generally very low across all sampled areas. The findings indicate, first, that within the urban areas of a city, localized differences in air pollutant loads occur. Secondly, we conclude that urban areas with proportionally higher concentrations of urban forestry may experience better air quality with regards to reduced ambient particulate matter; however conclusions about other air pollutants are yet to be elucidated.

1. Introduction

Air pollution is ubiquitous in industrialised and densely populated regions (Begg et al., 2007). Most urban air pollution comes from road traffic, and is comprised of a mixture of airborne particulate matter (PM), oxides of sulfur (SOx), oxides of nitrogen (NOx), carbon monoxide (CO), carbon dioxide (CO_2), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), and ozone (Thurston, 2008). Outdoor air pollution kills approximately 8 million people across the world every year (WHO, 2014), with a global cost of 1.7 trillion dollars (OECD, 2014). Exposure to traffic-related air pollution can have infant respiratory health effects (Saravia et al., 2013), and has even been associated with autism (Volk et al., 2013). In Australia it is estimated that urban air pollution causes over 1400 deaths per

* Corresponding author.
E-mail address: Fraser.Torpy@uts.edu.au (F.R. Torpy).

http://dx.doi.org/10.1016/j.atmosenv.2015.08.050

annum in Sydney alone (Department of Health (2009)), with national health costs estimated to be as high as 1 per cent of gross domestic product (Brindle et al., 1999) or $AUD 12 billion pa, from lost productivity and medical expenses (Environment Australia, 2003).

Whilst Australia has made progressive improvements to its overall air quality through regulatory measures (DEH, 2004), standards set by the National Environment Protection Council are still exceeded on a few days every year. This is usually related to bushfire events, including hazard reduction burns (NSW EPA, 2008), however the impact on air quality of locally sourced pollutants associated with urbanisation, climatic variability, and long periods of drought, are all contributing factors when standards are exceeded (Friend et al., 2013). Clearly, governments and societies in general have a social responsibility to reduce, mitigate or ameliorate urban air pollution for the health of all organisms in urban environments, humans included.

'Urban greening' has been proposed as a means to reduce airborne pollutant levels (Chen and Jim, 2008), with mounting evidence indicating that urban forestry can offer a range of 'ecosystem services' for urban residents that includes the mitigation of air pollution (Brack, 2002; Zheng et al., 2013). Most of the related studies focus on the ability of urban forestry to reduce airborne PM and NO_2 (Vos et al., 2013). The capacity of urban forestry, in particular trees, to reduce air pollutants is through a number of mechanisms. Trees can intercept and accumulate atmospheric particles through leaf pubescence and by providing a large waxy surface on which deposition can occur (Beckett et al., 2000), and also absorb various gaseous pollutants through the stomata Janhäll, 2015. Further, various tree configurations can alter wind profiles or create wind inversions via their geometry which assist in the deposition rate of pollutants from the air, or may act as physical barriers preventing the penetration of pollutants into specific areas (Salmond et al., 2013; Janhäll, 2015).

Many cities have plans for increasing their urban greenspace to reduce air pollution (Andersson-Skold et al., 2015). The City of Sydney council is no exception, the City Council proposing to increase the city's urban canopy by 50 per cent from the current canopy cover of 15.5 per cent by 2030 (City of Sydney (2013)). Such initiatives have been shown to be both economically and environmentally effective, with urban forestry in Canberra, Australia estimated to have a combined energy reduction, pollution mitigation and carbon sequestration value of US$20–67 million between 2008 and 2012 (Brack, 2002). While equivalent estimates for other Australian cities are unavailable, it is likely that the urban forest will have similar if not greater value for cities with higher population densities, such as Sydney.

Sydney's urban forestry has not previously been investigated with respect to its ability to reduce urban air pollution. Further, few studies from any location are available that provide experimental data on the air pollutant removal capacity of urban forestry/greenspace, as opposed to model estimates such as the Urban Forest Effects Model (UFORE) by Nowak (2006). Similarly, few reports provide empirical evidence of the association between overall ambient particulate matter densities and urban forestry densities (Pataki et al., 2011). Efforts to demonstrate or validate the model estimates have either found substantially reduced improvements relative to estimates from models (Tallis et al., 2011) or have shown no positive effects (Setälä et al., 2013).

The current project aimed to determine whether a discernible relationship does exist between higher densities of urban forestry and reduced local ambient air pollutant levels.

2. Methods

2.1. Study area

Sydney, Australia has a population of 4.5 million and lies on a coastal lowland plain between the Pacific Ocean and elevated sandstone tablelands. The climate for Sydney is warm and temperate. Days on which rainfall events occur are evenly distributed throughout the year, however rainfall volume is at its highest in Autumn. Sydney city's air quality is generally good by international standards, although levels of particulate matter can exceed the national standards on occasion (OEH, 2015). The main source of Sydney's air pollution is fossil fuel combustion, specifically motor vehicle exhaust; however domestic wood smoke in winter, and bush fires in summer can cause severe pollution events for a few days a year (NSW EPA, 2008).

Within the City of Sydney Local Government Area (LGA), the total tree canopy cover has been estimated at 15.5% (City of Sydney (2013)), of which 6.6% of the canopy cover is on private land, 4.9% is street trees, and 4.1% is in parks. The City's street trees are restricted in diversity, with whole lengths of streets planted with single species. *Platanus* × *acerifolia* is (London Plane Tree) is the most common Sydney street tree, comprising 9.5% of the urban forest, followed by *Melaleuca quinquenervia* (Broad-leaved Paperbark) and *Lophostemon confertus* (Brush Box), both of which comprise 8.8% of the urban forest (City of Sydney (2013)).

2.2. Sample sites

In collaboration with the City of Sydney Council, sites were selected so as to encompass a range of different conditions with respect to traffic density, usage, and greenspace/urban forest density (Fig. 1; Table 1). High canopy cover of >20% of the total land area was present in the sample sites at Centennial Park, Sydney Park, Surry Hills, and Rushcutters Bay (City of Sydney (2013)). These sites have high canopy coverage due to both highly planted residential areas and/or extensive public parklands. Sites with moderate canopy coverage (10%–20% of total land area) included Chippendale, Glebe, and Prince Alfred Park. Sites with low canopy cover (0–10% of total land area), included Haymarket, Zetland and Town Hall and Pitt St sites in central Sydney; which are built up, inner city areas. Little variation exists in topography across all selected sites as the central region of Sydney has a relatively constant elevation (approx. 22 m above sea level across the sampled region).

2.3. Traffic density and greenspace assessment

The concentration of greenspace at the sites was estimated using satellite imagery from Google maps, within 100 m, 250 m and 500 m radii from the geographic centre of each sample site, forming areas of 3.14, 19.6 and 78.6 ha respectively. The proportions of these areas under tree cover (including shrubs >1 m in height), grass cover and total greenspace (trees + grass) were calculated using Google Maps Distance Calculator (2013). The zoom capability of the Google maps allowed accurate estimates of greenspace cover to be made. The data is shown in Table 2. Please note that the data are cumulative, meaning that the 250 m data includes the greenspace within the 100 m radius sites etc.

Previous work that has empirically assessed the relationships between urban vegetation and air pollution has not accounted for spatial variation in the primary source of air pollutants. Motor vehicle exhaust is the main contributor to locally sourced pollutants for the sample area, and thus can be expected to be a major determinant of between-site variation in ambient air pollution.

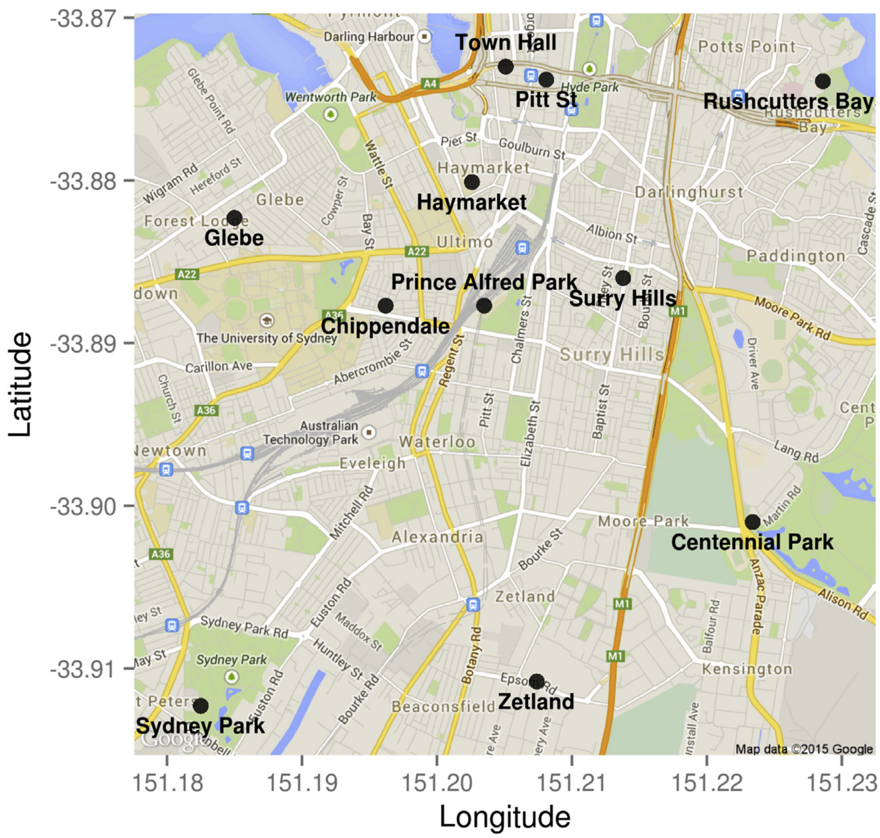

Fig. 1. Map of central Sydney, showing the locations of the eleven sampling sites. Figure made using the packages ggplot2 and ggmaps for the program R (The R foundation, 2015), and static maps from Google Maps.

Table 1
Attributes of the sample sites.

Site	Coordinates	General land use and environment	Relative greenspace	Vegetation type	Vegetation composition
Sydney Park	(−33.9108, 151.2074)	Medium density residential and parkland area	High	Parkland	Grassed lawns and a combination of the following tree species: *Casuarina* spp, *Corymbia maculata*, *Angophora costata*, *Eucalyptus sideroxylon*
Centennial Park	(−33.9010, 151.2234)	Medium density residential and parkland area	High	Parkland	Pond side vegetation and a combination of the following trees: *Ficus macrophylla*, *Araucaria cunninghamii*, *Eucalyptus saligna*, *Melaleuca quinquenervia* and *Liquidambar styraciflua*
Rushcutters Bay	(−33.8739, 151.2286)	Medium density residential harbour side area	Relatively high	Highly planted residential area	*Lophostemon confertus*, *Ficus macrophylla*, *Jacaranda* spp, *Eucalyptus sideroxylon* and *Eucalyptus saligna*
Prince Alfred Park	(−33.8884, 151.2035)	Medium density residential and parkland area	Moderately high	Parkland	*Lophostemon confertus*, *Melaleuca quinquenervia*, and *Ficus* spp.
Surry Hills	(−33.8860, 151.2138)	Medium density residential and commercial area	Moderately high	Planted residential areas	*Lophostemon confertus*, *Liquidambar styraciflua*, *Platanus* × *acerifolia*, *Poplus nigra*
Chippendale	(−33.8877, 151.1962)	Medium density residential and commercial area	Moderate	Street trees and planted residential areas	*Lophostemon confertus*, *Liquidambar styraciflua*, *Platanus* × *acerifolia*
Glebe	(−33.8823, 151.1850)	Medium density residential area	Moderate	Street trees and planted residential areas	*Callistemon* spp, *Lophostemon confertus*, *Liquidambar styraciflua*, *Platanus* × *acerifolia*, *Jacaranda* spp
Haymarket	(−33.8801, 151.2026)	High density residential and commercial area	Moderate low	Only street trees are present	*Platanus* × *acerifolia*
Zetland	(−33.9108, 151.2074)	High density residential and commercial area	Low	Only street trees are present	*Lophostemon confertus* street trees
Town Hall	(−33.8730, 151.2051)	High density commercial area	Very low	Only street trees are present	*Platanus* × *acerifolia* and *Poplus nigra*
Pitt St	(−33.8738, 151.2081)	High density commercial area	Very low	Only street trees are present	*Platanus* × *acerifolia* and *Poplus nigra*

Table 2
Greenspace cover composition (area %) at the sample sites within 100 m, 250 m and 500 m radii. 'Canopy' cover was comprised of tree and shrub species. 'Combined' cover is the sum of canopy and grass cover.

Site	100 m radii			250 m radii			500 m radii		
	Canopy	Grass	Combined	Canopy	Grass	Combined	Canopy	Grass	Combined
Sydney Park	2.1	84.9	87.0	7.3	72.4	79.7	4.3	42.0	46.2
Centennial Park	35.4	37.2	72.6	13.6	54.2	67.8	13.6	58.9	72.5
Rushcutters Bay	40.5	27.1	67.5	30.5	13.8	44.3	11.8	12.3	24.2
Prince Alfred Park	20.0	7.1	27.1	16.7	8.6	25.3	8.6	5.6	14.2
Surry Hills	21.1	2.6	23.7	12.5	0.7	13.2	8.7	1.6	10.3
Chippendale	21.5	2.0	23.5	12.6	0.8	13.4	4.2	12.7	16.8
Glebe	17.9	0.3	18.2	13.9	0.4	14.3	11.1	1.9	13.0
Haymarket	11.0	0.0	11.0	7.4	0.0	7.4	8.6	1.1	9.7
Zetland	8.5	1.8	10.3	4.0	2.1	6.1	7.3	1.2	8.5
Town Hall	3.6	0.0	3.6	5.7	0.2	5.9	1.6	0.8	2.4
Pitt St	1.9	0.0	1.9	8.1	0.6	8.8	18.4	4.5	22.9

Despite all samples being conducted in the city's CBD, the traffic density was not homogenous. To estimate traffic densities at the sample sites, several traffic sampling points were selected within each site: 2 points within the 100 m radius areas, 4 between the 100 and 250 m radii and a further 7 between the 250 and 500 m radii areas. Traffic sampling points were selected based on a stratified random sampling process among high, medium and low traffic density roadways. Traffic was sampled manually by counting vehicles passing the sample point for one 3 h period per location. Samples were taken mid-week, between 1100 and 1400 h (the same time interval during which the air quality samples were taken) to avoid the three daily peak traffic periods. Total traffic density was estimated by calculating vehicle movements per minute and multiplying by the number of streets of each roadway type within each specified radius. Whilst these traffic density estimates do not provide a quantitatively precise measure of the total road transport density at the 11 locations, this method represents a functional proxy for the overall road use in the areas surrounding the sample sites, as the data was collected during the same 'traffic behaviour' periods as the air samples, as well as allowing for the randomization of vehicle type. Traffic densities at the sites are shown in Table 3.

2.4. Air quality sampling

Monthly air samples were taken across eleven sites within the City of Sydney LGA between September 2013 and August 2014. A temporally independent design was implemented, where air samples were collected from different randomly selected points within the 100 m radius of the site centres each month, to negate temporal non-independence and the requirement for repeated measures analysis. Air samples were collected from the sites with several portable instruments. Carbon dioxide (CO_2), carbon monoxide (CO), total volatile organic compounds (TVOCs), nitric oxide (NO) and sulfur dioxide (SO_2) were measured with a *Yessair* 8-channel IAQ Monitor (Critical Environment Technologies Vantage Way Delta, Canada). Total suspended particulate matter (TSP), respirable suspended matter (PM_{10}: suspended particles <10 μm in diameter) and very fine particulate matter ($PM_{2.5}$: particles <2.5 μm in diameter) were recorded with a *DustTrack II* 8532 laser densitometer (TSI, Shoreview, Minnesota). The DustTrak has been shown to overestimate particulate matter for certain particulate materials (Kingham et al., 2006), especially the $PM_{2.5}$ fraction; thus data recorded was corrected with data sourced from the NSW Office of Environment and Heritage (OEH) (explained further below). Meteorological data was obtained from the Australian Government Bureau of Meteorology 2013–2014 (rainfall, wind speed, wind direction and humidity). Nitrogen dioxide (NO_2) was recorded with a *GasAlert Extreme* T2A-7X9 (BW Technologies, Canada). Temperature, light, noise and relative humidity were recorded using a *Digitech Multifunction Environment meter* (Digitech, China). A *Turbometer Davis anemometer* (Davis Weather Gadgets, Cannon Beach, Oregon) was used to measure wind speed.

Table 3
Cumulative traffic movements per minute at the sample sites, within 100 m, 250 m and 500 m radii.

Site	Traffic density (movements. min^{-1})		
	100 m radii	250 m radii	500 m radii
Sydney Park	7.4	105.9	300.9
Centennial Park	1.3	145.9	215.9
Rushcutters Bay	7.3	29.2	319.2
Prince Alfred Park	42.7	217.4	517.5
Surry Hills	11.5	73.6	254.0
Chippendale	61.1	93.2	363.9
Glebe	11.6	75.2	164.5
Haymarket	13.4	82.5	331.5
Zetland	26.8	42.9	199.9
Town Hall	53.4	190.8	562.7
Pitt St	38.9	217.4	424.6

2.5. Quality assurance

Air sample collection was conducted at least 30 m from roadways to allow the dispersal of pollutants sourced from the street. Rainy days were avoided, as rain has been shown to remove particulate matter from the air (Nishihara et al., 1989). Furthermore, no bare soil was present within 30 m proximity of sampling, to avoid any dust contribution to PM concentrations. The order in which sites were sampled was randomised for every sampling day, to remove any systematic temporal variation within the allocated sampling time interval. Reference data from three air quality monitoring sites operated by the OEH were obtained for comparison on the days that samples were collected, for PM_{10}, $PM_{2.5}$, CO, NO_2 and SO_2. The reference sites included: Randwick (1 km from the closest sample site); Rozelle (3.5 km from the closest sample site) and Earlwood (10 km from the closest sample site). The OEH air quality monitoring sites utilise a tapered element oscillating microbalance (TEOM) for particulate matter quantification as per the Australian Standard (AS 3580.9.8–2001), approved by the NSW EPA (2007). The average TEOM data sourced from these monitoring sites was used to correct the over estimation of particulate matter data obtained from the *DustTrak*, as per the recommendation of Kingham et al. (2006), by calculating the difference in recorded data with the mean from the three OEH sites and applying it as a correction factor for each sampling event.

2.6. Data analysis

All data are expressed as means ± standard error. All analyses were performed using Minitab Ver. 14. To allow us to determine the relationship between proximal greenspace and air quality, it was necessary to account for inter-site variability related to pollutant density associated with road traffic. Thus a stepwise multiple linear regression was used to determine the traffic variable that had the strongest relationship with the air quality variables, which was traffic density within the 100 radii in all instances. The air quality variables were corrected for the effects of traffic by performing subsequent analysis on the residuals from linear regressions between the air quality variables (TSP, PM_{10}, $PM_{2.5}$, CO, NO_2 and SO_2) and this traffic variable.

The presence and strength of linear associations between pollutant concentrations, as above, and environmental conditions (listed in Section 2.4) were examined by computing Pearson correlation coefficients. Stepwise multiple linear regression was carried out to determine the relative influence of the environmental variables on the inter sample variance in all pollutant concentrations. For this analysis we treated all samples as independent (ie. samples were collected using a temporally independent design), and thus it did not allow the distinguishing of any seasonally-dependent interaction effects between air quality and environmental variables, should they be present.

3. Results

Site and monthly trends for PM are displayed in Figs. 2 and 3. Samples taken from the sites that exhibited the lowest concentrations of greenspace, i.e. Town Hall, Pitt St and Haymarket, generally had the highest concentrations of total suspended particles; recording 34.0 ± 4.0 µm/m^3, 33.3 ± 3.3 µm/m^3 and 28.4 ± 4.9 µm/m^3 respectively. In comparison, the sites that had the most greenspace (Centennial Park and Rushcutters Bay), recorded the lowest total suspended particle concentrations relative to other sites, with 17.5 ± 2.1 µm/m^3 and 19.3 ± 4.2 µm/m^3. These levels were significantly lower than the three sites with the lowest greenspace (GLM ANOVA, both $P < 0.000$ compared with Town Hall, Pitt St and Haymarket sites). This same trend was observed in the other fractions of particulate matter, with Town Hall, Pitt St and Haymarket consistently recording significantly higher concentrations of PM_{10} and $PM_{2.5}$ than sites with higher density of greenspace (GLM ANOVA, all $P < 0.000$ compared with Chippendale, Glebe, Rushcutters Bay, Centennial Park).

Little seasonal variation was observed in particulate concentrations other than significantly higher concentrations in TSP and PM_{10} in September and May (GLM ANOVA, both $P < 0.000$ compared to all other months). The high concentrations observed in September are attributable to the hazard reduction burns that took place during that time (OEH, 2015). A secondary peak was observed across all sited during the month of May, a probable consequence of the low precipitation rates at the time (OEH, 2015). No seasonal trend was observed with $PM_{2.5}$ across the sites (GLM ANOVA, $P > 0.000$).

Trends for CO_2 and NO_2 are displayed in Figs. 4 and 5. Some significant differences were present in CO_2 and NO_2 concentrations between months. No consistent pattern was observed across months, and amongst sites, the pattern of CO_2 concentrations (Fig. 5) was variable, the only statistically significant difference observed being Pitt St, Prince Alfred Park and Town Hall recording significantly higher concentrations than those recorded for Sydney Park and Zetland (GLM ANOVA, $P < 0.05$ for all differences mentioned). There was no variation in NO_2 concentrations amongst sites. No seasonal trend in CO_2 was observed, with mean concentrations ranging from 377 ppm to 414 ppm. No seasonal trends in NO_2 were observed other than significantly higher concentrations in August and September which were once again attributable to the hazard reduction burns that take place during that period (GLM ANOVA, $P < 0.05$). The temporal and spatial variation amongst CO_2 and NO_2 samples was not of a magnitude that warranted detailed multivariate analysis.

Data for NO, TVOC, CO and SO_2 were consistently below detection limits, and were thus not analysed individually. However, these air quality variables were used for the multivariate analyses, since there is evidence that multiple air pollutants may have additive effects (eg. Dominici et al., 2003).

3.1. Relationships with environmental variables

Correlations between particulate matter measurements acquired from the Bureau of Meteorology and our samples were positive and significant ($r \geq 0.836$, $P = 0.000$), indicating that our instrument readings were closely proportional to the TEOM data, and any variation between the readings was thus likely attributable to spatial separation.

To test the potential effect of prevailing and local wind direction measured at each site, wind direction was used as a categorical variable and collated and assessed univariately. No significant difference was observed between all pollutant concentrations for the different prevailing wind directions, indicating that wind direction had no major effect on the observed differences between pollutant

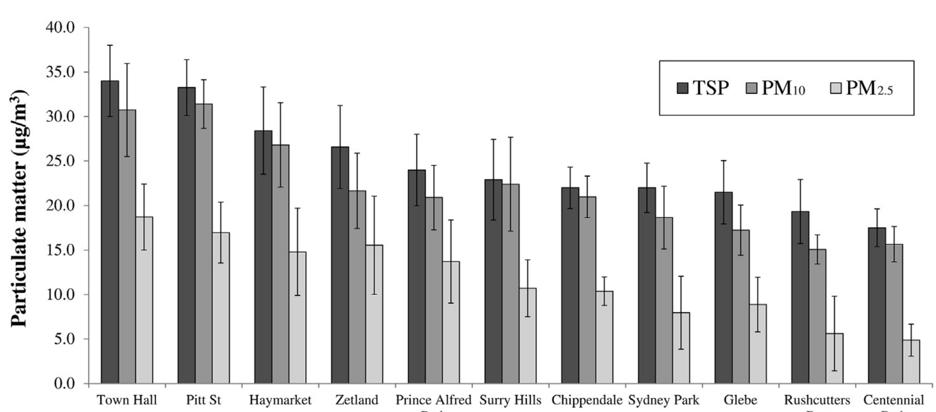

Fig. 2. Average levels of atmospheric particulate matter fractions for each sampling site, over a 12-month period (Means ± SEM, n = 12).

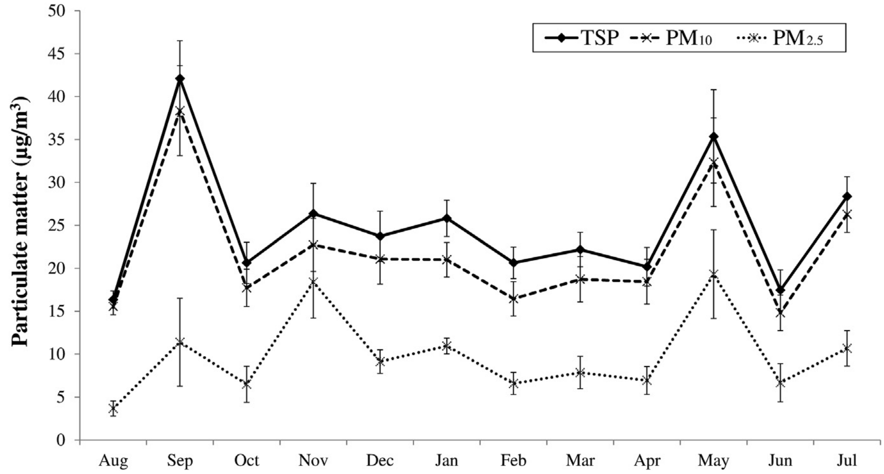

Fig. 3. Average levels of atmospheric particulate matter fractions averaged across sites, over the 12-month sampling period (Means ± SEM, n = 11).

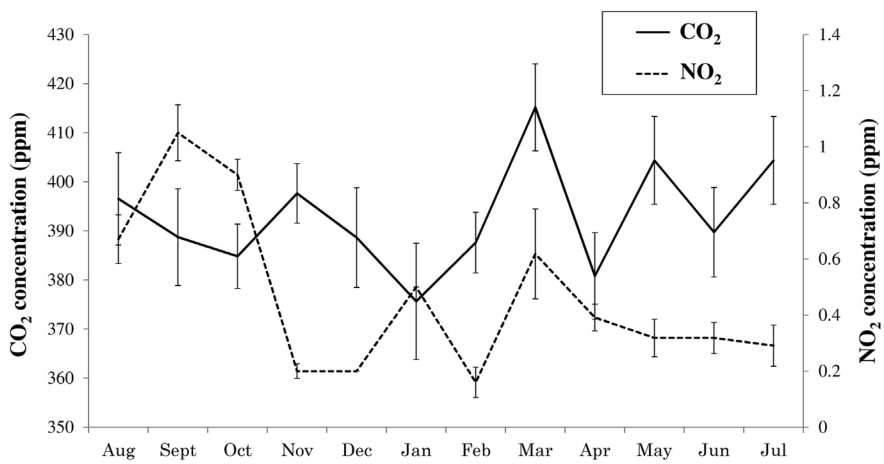

Fig. 4. Temporal concentrations of ambient atmospheric CO_2 and NO_2 averaged across sites, over the 12-month sampling period (Means ± SEM, n = 11).

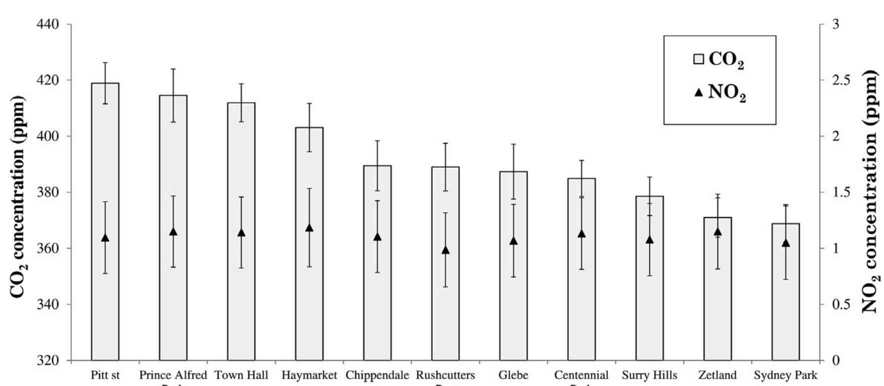

Fig. 5. Average concentrations of atmospheric CO_2 and NO_2 for each sampling site, averaged over the 12-month period (Means ± SEM, n = 12).

response variables.

Traffic corrected total suspended particle concentrations were significantly negatively correlated with canopy coverage within a radius of 100 m (r = −0.293, P = 0.001), canopy coverage within 250 m (r = − 0.221, P = 0.011), percentage total greenspace cover measured at 100 m radii (r = −0.189, P = 0.03), 250 m radii (r = −0.191, P = 0.028) and 500 m radii (r = −0.181, P = 0.038). However, total suspended particle data was also significantly negatively correlated with monthly total rain recorded per the sampling period (r = −0.244, P = 0.005), total rain recorded in the preceding week (r = −0.244, P = 0.005), and significantly positively correlated with time duration since last rain event (r = 0.417, P = 0.000). Traffic corrected PM_{10} data were significantly negatively correlated with canopy coverage within 100 m (r = −0.250,

$P = 0.004$), canopy coverage within 250 m ($r = -0.213$, $P = 0.014$), and percentage greenspace cover measured at 100 m radii ($r = -0.179$, $P = 0.04$). However, PM_{10} data was also significantly negatively correlated with wind speed ($r = -0.180$, $P = 0.039$), monthly total rain recorded during the sampling period ($r = -0.226$, $P = 0.009$), total rain recorded in the preceding week ($r = -0.141$, $P = 0.004$), and significantly positively correlated with time duration since last rain event ($r = 0.461$, $P = 0.000$). Traffic corrected $PM_{2.5}$ data was not significantly correlated with any greenspace variable, but was significantly negatively correlated with monthly total rain recorded per the sampling period ($r = -0.226$, $P = 0.009$), total rain recorded in the preceding week ($r = -0.232$, $P = 0.008$), and significantly positively correlated with time duration since last rain event ($r = 0.443$, $P = 0.000$).

Multiple stepwise linear regression analysis was used to determine which environmental variables were the strongest predictors of the aerosolized particulate matter. The analysis ranked the variables in order of predictive power, with backward elimination performed to check the significance of each variable. Only predictor values that contributed to over 2% of the overall explanatory power and were significant ($P < 0.05$) were considered.

For traffic corrected TSP concentrations, the time since last rain event was the largest contributor to the overall variation in the model, explaining 17.41% of the linear pattern in the TSP data ($R^2 = 17.41$). Adding canopy coverage within 100 m to the model explained an additional 9.86% of the variation, and adding canopy coverage within the 500 m radii added 2.94% explanatory power. The three variable model thus explained 30.45% of the variability in the data set ($R^2 = 30.45$). When traffic corrected PM_{10} was used as the response variable, six combined predictors were detected: time since last rain event was the largest contributor to the overall variation in the model, explaining 21.24% of the linear pattern in the PM_{10} data ($R^2 = 21.24$). Adding canopy coverage within 100 m to the model explained an additional 6.25% of the variation, adding wind speed explained an additional 4.80% of the variation, adding canopy coverage within 500 m radii of the site centres explained an additional 4.9% of the variation, and adding monthly total rain explained an additional 3.69% of the variation. Combined, the six variable model thus explained 41.08% of the variability in the data set ($R^2 = 41.08$). For traffic corrected $PM_{2.5}$, the analysis indicated that only three predictors were worthy of consideration, as these variables were the only ones that were statistically significant and adding further predictors to the model made little contribution to its overall explanatory power. Time since last rain event was the largest contributor to the overall variation in the model, explaining 19.59% of the linear pattern in the $PM_{2.5}$ data ($R^2 = 19.59$). Adding canopy coverage within 100 m to the model explained an additional 6.16% of the variation, and adding and wind speed added 3.20% explanatory power. The three variable model thus explained 28.59% of the variability in the data set ($R^2 = 28.59$).

4. Discussion

This study provides data on a range of ambient and seasonal air pollutants for sites across central Sydney, Australia, and is the first study to use a competitive model to determine the relative importance of environmental predictors for air quality, including proximal greenspace.

Sites that frequently had high concentrations of PM; Town Hall, Pitt St and Haymarket, all had low greenspace densities, with proximal greenspace coverage within 100 m radii measuring 1.9%, 3.6% and 11.0% respectively. Conversely, sites that had the lowest concentrations of PM; Centennial Park, Rushcutters Bay and Glebe had both the highest greenspace recorded and the highest canopy coverage, with proximal tree coverage within 100 m radii measuring 35.4%, 40.5% and 17.9% respectively. Additionally, all fractions of particulate matter were significantly negatively correlated with greenspace; thus increasing greenspace was associated with decreasing particulate matter despite the data being corrected for traffic density. The strongest associations with decreasing PM were canopy coverage within 100 m radii of the sample sites. However, associations were also found between all fractions of particulate matter and environmental elements such as wind speed, time since last rain event and quantity of rain recorded in the time proximal to the samples being taken. Clearly, these meteorological factors are also important factors in determining ambient particulate concentrations, as demonstrated previously by Cavanagh et al. (2009). In the current study, when these factors were analysed for their combined effects utilising stepwise multiple linear regression, time since last rain event was the strongest predictor of the concentrations of all PM types; however in all models, canopy coverage within 100 m radii was the next strongest contributing factor. Thus, whilst meteorological factors had the strongest influence in determining particulate matter concentrations; greenspace, and especially canopy coverage proximal to the sample sites, were integral influences on reduced ambient particulate matter concentrations. This outcome is in agreement with most of the studies that have assessed the ability of urban forestry to reduce particulate concentrations, with Freiman et al. (2006) finding that ambient PM concentrations were lower in neighbourhoods with dense vegetation, and Cohen et al. (2014) demonstrating reduced pollutant concentrations including PM levels in an urban park compared to proximal street canyons. Similarly, Cavanagh et al. (2009) observed decreasing particulate concentrations with increasing distance inside an urban forest patch in Christchurch, New Zealand. However, whilst these studies demonstrated that urban vegetation may have benefits in regards to pollution mitigation, they lacked spatial and temporal replication, with Freiman et al. (2006) sampling 6 sites, Cohen et al.'s (2014) total study duration was 6 days at 4 sites, and Cavanagh et al. (2009) only studying one forest patch with nested sites within the site. The only study with substantive replication was Setälä et al. (2013), who did not detect a relationship between urban vegetation and air pollutants in Finland; subsequently concluding that the effect of greenspace was minor in northern conditions.

A recently developed tool to measure urban forest ecosystem services is the Urban FORest Effects (UFORE) model developed by the U.S Forest Service (Nowak, 2006). Although the model was specifically designed for US studies, it has been widely applied across the world, with use in Barcelona, Spain (Baró et al., 2014), Shenyang, China (Liu and Li, 2006) and Perth, Australia (Saunders et al., 2011). However, as detailed by Baró et al. (2014), the model has limitations, as it is based on PM deposition rates for specific plant species which limits the usefulness of the model to areas dominated by the species included in the database. Further the model has uncertainty in relation to particle re-suspension rates and fine scale spatial variability in air pollutant concentrations; thus Baró et al. (2014) concluded that the model should be used for approximate estimations rather than precise quantification. Although the dry deposition velocity of PM on urban forestry was not documented in the current study, we did, however, find that areas with proportionally higher densities of urban forestry were quantifiably associated with reduced ambient particulate matter levels, thus providing empirical evidence that could verify the UFORE ecosystem service approximations.

The statistical model utilised in this experiment did not fully explain majority of the variation in the data set, indicating that there were other variables not accounted for, and that determining all, or even most of the causative factors associated with urban air pollution experiments can be challenging. Thus there are clearly manifold environmental variables that influence air quality in a city environment at any one time and in any specific location. Whilst we cannot account for majority of the temporal and spatial variation in air quality with the environmental variables chosen for analysis in this study, the identification of greenspace as an important determinant of city airborne pollutants is a significant contribution to our understanding of UAQ, and should assist in future air quality modelling exercises.

Model estimates indicate that areas with high greenspace could have lower NO_2 concentrations (Pugh et al., 2012), however empirical data to demonstrate this is lacking and efforts to demonstrate this trend have failed to find effects of the magnitude detected by empirical estimates (Grundström and Pleijel, 2014; Setälä et al., 2013). Similarly, substantial reductions in NO_2 were not evident in the current study. Additionally, no associations with NO_2 and any measured environmental variable were found. Increases in NO_2 were seen in the Spring months, whilst all other months showed no seasonal trends. Atmospheric NO_2 is associated with combustion, and thus the increased concentrations during Spring appears to be associated with hazard reduction burning (OEH, 2015).

Variation in temporal and spatial ambient atmospheric CO_2 concentrations is influenced by a range of seasonal, meteorological and land usage factors (Henninger and Kuttler, 2010). In urban environments, variations in ambient atmospheric CO_2 concentrations are mainly associated with combustion processes (Idso et al., 2001), leading to peak CO_2 concentrations in the centre of cities. Whilst the city centre sites had high CO_2 concentrations, this pattern was not consistent across the full sample. Restrictions in the upward movement of pollutants released at ground level has been demonstrated in areas constricted with tall buildings; therefore, accumulation of pollutants may occur in built up areas (Gratani and Larone, 2005); which may also explain the high inner city CO_2 concentrations we detected on occasion. Higher wind speeds facilitate increased CO_2 advection in the atmosphere, which also could be a contributing factor to the reduced levels observed in less built up areas. Clearly, there are many challenges in relation to assessing urban CO_2 fluxes (Grimmond et al., 2002), and further research on this air pollutant are needed. Whilst CO_2 levels varied considerably between months in our study (Fig. 4), there was no explainable pattern observed.

Concentrations of NO, TVOC, CO and SO_2 were frequently below the detection limits of the devices utilised in this experiment. This may be a testament to the efficacy of the governmental regulatory efforts imposed to improve Sydney's air pollutant levels (DEH State of the Air Report, 2004). If these pollutants do not exceed concentrations of concern, the ability of urban greenspace to reduce them will not be realised. Whilst it cannot be deduced from this experiment, it is possible the Sydney's urban forestry is biomitigating NO, TVOC, CO and SO_2 concentrations so as to maintain low concentrations. Yin et al. (2011) demonstrated that densely vegetated areas within urban environments in a city in China had reduced atmospheric concentrations of SO_2 and NO_2. However, it remains unknown if Sydney's urban forestry is having a quantifiable influence on ambient NO, TVOC, CO and SO_2 concentrations.

We also tested the effect of wind direction on the variation in pollutant levels during the study by using wind direction as a categorical variable for univariate assessment of air pollutant levels. Whilst there were minor differences in pollutant levels when the prevailing winds varied, none of these effects approached statistical significance, and thus could not explain a meaningful proportion of the overall variability in air quality during the study.

Many tree species that comprise Sydney's urban forestry are deciduous, and thus have no leaves during winter, consequently affecting their ability to intercept and accumulate atmospheric particulates, and to absorb various gaseous pollutants. It is difficult to evaluate whether the seasonal behaviour of Sydney's urban forestry had a quantifiable influence on proximal ambient air pollutants from this study. Further, different vegetation types are known to have different deposition rates for particulates (Beckett et al., 2000; Sæbø et al., 2012). Thus, future work that documents the density and type of greenspace, as well as calculating approximate total leaf area based on allometric equations, whilst monitoring ambient urban air pollution could be of value.

Using a simulation model, Wania et al. (2012) determined that dense tree cover in deep street canyons inhibit the upward flow of particulate matter, and thus diminish its dispersal rates. Their model indicated that particulates created from traffic are increased in street canyons with large height-to-width ratios, and that vegetation within these street canyons could compound the issue. As it was not the focus of the current study to examine such phenomena, these scenarios were avoided when sampling. Thus, future research that considers such factors as streetscape design when assessing the effects of urban vegetation on ambient air quality in urban environments would be of value.

In the current study, the volume of accumulative traffic movements was used as a measure of the primary local pollutant source. As vehicle derived exhaust pollution is known to vary between vehicle type, fuel type and vehicle age (Rhys-Tyler et al., 2011), further work that takes into account the potential differences in vehicle pollution due to traffic variables such as traffic lights as well as the continuousness of traffic flow may also be of value.

5. Conclusion

Samples taken from low greenspace sites frequently had higher concentrations of all fractions of aerosolized particulate matter than other sites. Comparatively, sites with high proximal greenspace had lower particulates, even when pollutant sources were corrected for and factored into the analysis. Further, all fractions of particulate matter were significantly negatively correlated with greenspace, with increasing greenspace associated with decreasing particulate matter, even when meteorological and traffic density being considered. This is the first study to comprehensively demonstrate, with substantial temporal and spatial replication, that areas with proportionally higher concentrations of urban forestry are quantifiably associated with reduced ambient particulate matter levels. Conclusions concerning other air pollutants (CO_2, NO_2, NO, TVOCs or SO_2) are yet to be elucidated.

Acknowledgements

Peter Irga conducted majority of this work with the support of an Australian Postgraduate Award, funded by the Australian Government and a grant from the City of Sydney's Environmental Grants Program (Reference: 2013/110464). The authors would like to thank Gabe O'Reilly, Ian Berry and Kirsty Milner for their assistance. This manuscript is dedicated to the memory of Phillip Edgar Torpy, 19 November 1926–15 May 2015, who was of great assistance throughout the last fifteen years' to the Plants and Environmental Quality Research Group's investigations.

References

Andersson-Sköld, Y., Thorsson, S., Rayner, D., Lindberg, F., Janhäll, S., Jonsson, A., Moback, U., Bergman, R., Granberg, M., 2015. An integrated method for assessing climate-related risks and adaptation alternatives in urban areas. Clim. Risk Manag. 7, 31–50.

Baró, F., Chaparro, L., Gómez-Baggethun, E., Langemeyer, J., Nowak, D.J., Terradas, J., 2014. Contribution of ecosystem services to air quality and climate change

mitigation policies: the case of urban forests in Barcelona, Spain. Ambio 43, 466–479.
Beckett, K.P., Freer-Smith, P.H., Taylor, G., 2000. Particulate pollution capture by urban trees: effect of species and windspeed. Glob. Change Biol. 6, 995–1003.
Begg, S., Vos, T., Barker, B., Stevenson, C., Stanley, L., Lopez, A., 2007. The burden of disease and injury in Australia 2003. Cat. no. PHE 82. In: Australian Institute of Health and Wellbeing (AIHW). Australia, Canberra.
Brack, C.L., 2002. Pollution mitigation and carbon sequestration by an urban forest. Environ. Pollut. 116 (Suppl. 1), S195–S200.
Brindle, R., Houghton, N., Sheridan, G., 1999. Transport Generated Air Pollution and its Health Impacts. A Source Document for Local Government. ARRB Transport Research, Vermont South, Victoria.
Cavanagh, J., Zawar-Reza, P., Wilson, J., 2009. Spatial attenuation of ambient particulate matter air pollution within an urbanised native forest patch. Urban For. Urban Green. 8, 21–30.
Chen, W., Jim, C.Y., 2008. Assessment and valuation of the ecosystem services provided by urban forests. In: Carreiro, M., Song, Y.C., Wu, J. (Eds.), Ecology, Planning, and Management of Urban Forests. Springer, New York, pp. 53–83.
City of Sydney, 2013. Urban forest strategy 2013. Available at: http://www.cityofsydney.nsw.gov.au/__data/assets/pdf_file/0003/132249/Urban-Forest-Strategy-Adopted-Feb-2013.pdf.
Cohen, P., Potchter, O., Schnell, I., 2014. A methodological approach to the environmental quantitative assessment of urban parks. Appl. Geogr. 48, 87–101.
Daft Logic GoogleMaps Distance Calculator, 2013. http://www.daftlogic.com/projects-google-maps-distance-calculator.htm accessed 25.10.14.
Department of Health NSW, 2009. Air pollution health risks, New South Wales. Available at: http://www.health.nsw.gov.au/PublicHealth/environment/air/air_pollution.asp. accessed 21.11.11.
Department of the Environment and Heritage (DEH), Australian Government, 2004. State of the Air: National Ambient Air Quality Status and Trends Report 1991–2001. ACT, Canberra.
Dominici, F., Sheppard, L., Clyde, M., 2003. Health effects of air pollution: a statistical review. Int. Stat. Rev. 71, 243–276.
Environment Australia, 2003. BTEX personal exposure monitoring in four Australian cities, Technical paper No. 6. In: Australia, E. (Ed.). Australia, Canberra, ACT.
Freiman, M.T., Hirshel, N., Broday, D.M., 2006. Urban-scale variability of ambient particulate matter attributes. Atmos. Environ. 40, 5670–5684.
Friend, A.J., Ayoko, G.A., Kokot, S., 2013. Source apportionment of airborne particulate matter: an overview of Australian and New Zealand studies. Air Qual. Clim. Change 47, 13–19.
Gratani, L., Larone, L., 2005. Daily and seasonal variation of CO_2 in the city of Rome in relationship with the traffic volume. Atmos. Environ. 39, 2619–2624.
Grimmond, C.S.B., King, T.S., Cropley, F.D., Nowak, D.J., Souch, C., 2002. Local-scale fluxes of carbon dioxide in urban environments: methodological challenges and results from Chicago. Environ. Pollut. 116 (Suppl. 1), S243–S254.
Grundström, M., Pleijel, H., 2014. Limited effect of urban tree vegetation on NO_2 and O_3 concentrations near a traffic route. Environ. Pollut. 189, 73–76.
Henninger, S., Kuttler, W., 2010. Near surface carbon dioxide within the urban area of Essen, Germany. Phys. Chem. Earth Parts A/B/C 35, 76–84.
Idso, C.D., Idso, S.B., Balling Jr., R.C., 2001. An intensive two-week study of an urban CO_2 dome in Phoenix, Arizona, USA. Atmos. Environ. 35, 995–1000.
Janhäll, S., 2015. Review on urban vegetation and particle air pollution – deposition and dispersion. Atmos. Environ. 105, 130–137.
Kingham, S., Durand, M., Aberkane, T., Harrison, J., Gaines Wilson, J., Epton, M., 2006. Winter comparison of TEOM, MiniVol and DustTrak PM_{10} monitors in a woodsmoke environment. Atmos. Environ. 40, 338–347.
Liu, C., Li, X., 2006. Carbon storage and sequestration by urban forests in Shenyang, China. Urban For. Urban Green. 11, 121–128.
Nishihara, T., Miyaji, T., Nasu, M., Takubo, Y., Kondo, M., 1989. Fungal flora in rainwater. Biomed. Environ. Sci. 2, 376–384.
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, 115–123. http://dx.doi.org/10.1016/j.ufug.2006.01.007.
NSW Environment Protection Authority, 2007. Approved Methods for the Sampling and Analysis of Air Pollutants in New South Wales (Sydney NSW).
NSW Environment Protection Authority, 2008. Biogenic and Geogenic Emissions: Results. In Air Emissions Inventory for the Greater Metropolitan Region in New South Wales. Environment Protection Authority, Sydney.
Office of Environment and Heritage (OEH), 2015. New South Wales Air Quality Statement 2014. The State of NSW and Office of Environment and Heritage (Sydney NSW).
Organisation for Economic Co-operation and Development (OECD), 2014. The Cost of Air Pollution Health Impacts of Road Transport. OECD Publishing, Paris France.
Pataki, D.E., Carreiro, M.M., Cherrier, J., Grulke, N.E., Jennings, V., Pincetl, S., Pouyat, R.V., Whitlow, T.H., Zipperer, W.C., 2011. Coupling biogeochemical cycles in urban environments: ecosystem services, green solutions, and misconceptions. Front. Ecol. Environ. 9, 27–36.
Pugh, T.A.M., MacKenzie, A.R., Whyatt, J.D., Hewitt, C.N., 2012. Effectiveness of green infrastructure for improvement of air quality in urban street canyons. Environ. Sci. Technol. 46, 7692–7699.
Rhys-Tyler, G.A., Legassick, W., Bell, M.C., 2011. The significance of vehicle emissions standards for levels of exhaust pollution from light vehicles in an urban area. Atmos. Environ. 45, 3286–3293.
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.
Saravia, J., Lee, G.I., Lomnicki, S., Dellinger, B., Cormeir, S.A., 2013. Particulate matter containing environmentally persistent free radicals and adverse infant respiratory health effects: a review. J. Biochem. Mol. Toxicol. 27, 56–68.
Saunders, S.M., Dade, E., Van Niel, K., 2011. An urban forest effects (UFORE) model study of the integrated effects of vegetation on local air pollution in the western suburbs of Perth, the integrated effects of vegetation on local air pollution in the western suburbs of Perth, WA. In: 19th International Congress on Modelling and Simulation, Perth, Australia.
Setälä, H., Viippola, V., Rantalainen, A.-L., Pennanen, A., Yli-Pelkonen, V., 2013. Does urban vegetation mitigate air pollution in northern conditions? Environ. Pollut. 183, 104–112.
Sæbø, A., Popek, R., Nawrot, B., Hanslin, H.M., Gawronska, H., Gawronski, S.W., 2012. Plant species differences in particulate matter accumulation on leaf surfaces. Sci. Total Environ. 427–428, 347–354.
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.
Thurston, G.D., 2008. Outdoor air pollution: sources, atmospheric transport, and human health effects. In: Kris, H. (Ed.), International Encyclopedia of Public Health. Academic Press, Oxford, pp. 700–712.
Volk, H.E., Lurman, F., Penfold, B., Herz-Picciotto, I., McConnell, R., 2013. Traffic-related air pollution, particulate matter and autism. JAMA Psychiatry 70, 71–76.
Vos, P.E.J., Maiheu, B., Vankerkom, J., Janssen, S., 2013. Improving local air quality in cities: to tree or not to tree? Environ. Pollut. 183, 113–122.
Wania, A., Bruse, M., Blond, N., Weber, C., 2012. Analysing the influence of different street vegetation on traffic-induced particle dispersion using microscale simulations. J. Environ. Manag. 94, 91–101.
World Health Organisation (WHO), 2014. Burden of Disease from Ambient Air Pollution for 2012. The World Health Organisation, Geneva Switzerland.
Yin, S., Shen, Z., Zhou, P., Zou, X., Che, S., Wang, W., 2011. Quantifying air pollution attenuation within urban parks: an experimental approach in Shanghai, China. Environ. Pollut. 159, 2155–2163.
Zheng, D., Ducey, M.J., Heath, L.S., 2013. Assessing net carbon sequestration on urban and community forests of northern New England, USA. Urban For. Urban Green. 12, 61–68.