EFFECTS OF SPATIAL FORMS OF GREEN INFRASTRUCTURE IN BLOCK SCALE ON PM_{10} AND $PM_{2.5}$ REMOVAL—A CASE STUDY OF THE MAIN CITY OF WUHAN

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1 ABSTRACT

Particulate air pollution is a common challenge in the process of rapid urbanization of developing countries. Under the overall particulate air pollution in urban, there are significant differences in the concentration of particulate air pollution in urban blocks, and green infrastructure is an important factor. This research focused on the spatial forms and influence extent of green infrastructure on PM_{10} and $PM_{2.5}$. PM_{10} and $PM_{2.5}$ data were obtained from eight national controlling points and two self controlling points by a research group in Wuhan. And landscape pattern index of green infrastructure of ten blocks was calculated by Fragstats. Correlation analysis showed that concentration was highly correlated in the urban block, spatial forms of green infrastructure and $PM_{10}/PM_{2.5}$. $PM_{10}/PM_{2.5}$ concentration were negatively associated with the total area of patch (CA), but positively associated with patch mean nearest (MNN), patch density (PD), and edge density (ED). Besides, largest patch index (LPI) was almost not associated with $PM_{10}/PM_{2.5}$ concentration. Stepwise multiple regression analyses indicated that the most significant influencing factor on the moderation of particulate matter was the total area of patch (CA), while mean nearest distance of patches (ENN_MN) exhibited a negative impact. According to our findings, we propose that increasing the area of the UGI patches and decreasing the distance among different green patches are two key strategies to reduce the particulate air pollution, which can enrich a new dimension of green infrastructure planning and design.

1.1 Keywords

Green Infrastructure, Particulate Matter, Spatial Forms, Block Scale

2 INTRODUCTION

Particulate air pollution is a common challenge in the process of rapid urbanization of developing countries. With the high density urban morphology, industrialization and popularization of private cars, the problem is becoming more and more serious. PM_{10} and $PM_{2.5}$ are the main pollutants, also known as inhalable particle and fine particle, whose aerodynamic diameter is less than 10 microns and 2.5 microns respectively. According to Environmental Performance Index (EPI) report published by Yale University and Columbia University, China ranked the last fourth place comparing air quality among 180 countries in the world. Therefore, solving the air pollution problem is imminent.

According to the preliminary data investigation, there were significant differences in the concentration of PM_{10} and $PM_{2.5}$ in urban blocks under the overall particulate air pollution in urban. Air samples taken from sites with less green space frequently had high concentrations of PM_{10} and $PM_{2.5}$ than other sites (Irga et al. 2015). Urban green infrastructure (UGI) was considered an important factor (Pugh et al. 2012). It is an interconnected network composed of natural areas and other open spaces. It emphasizes the preservation of the value and function of natural ecosystems in order to maintain clean air and water (Benedict & McMahon. 2006). Compared to the traditional green space system, the urban green infrastructure contains new greening types, such as greenway and green roof. In urban blocks, UGI which is mainly composed of vegetation, including lawn, shrub and tree helps to decrease particulate air pollution by the way of trap of vegetation's leaves (Ottelé et al. 2010). The leaf secretions and the roughness of the blade and the length of the villi are beneficial to intercept and accumulate atmospheric particulate matter, so as to decrease the airborne particulate matter concentrations (Beckett et al. 2000). Vegetation transpiration can also create a relatively humid and low temperature environment, which is in favor of the deposition of atmospheric particulate matter (Cardelino & Chameides. 1990). The deposition rate of atmospheric particulate matter can also be promoted via several vegetation arrangements, contributing to the alter of wind field through their geometric characteristics, or interception effect by acting as physical barriers (Khan & Abbasi. 2001). In addition, vegetation communities formed by different tree species play more effective role in decreasing particulate air pollution (Freer-Smith et al. 2004). In summary, the reduction effect of green space on particulate matter is a complex process, depending on various aspects. According to statistics, 234.5kg PM_{10} could be removed by 19.8 ha of green roofs in one year, accounting for 14% of the total amount of air pollutants (Yang et al. 2008). Simulate result revealed that increasing total tree cover in West Midlands from 3.7% to 16.5% reduces average primary PM_{10} concentrations by 10% (Mcdonald et al. 2007). In addition, there are other urban factors which could contribute to mitigation of air pollution. The water body such as lakes can also reduce particulate matter by increasing air humidity (Mesut & Bayram. 2010). In residential areas, building density is positive associated with PM_{10} and $PM_{2.5}$ concentration (Fan et al. 2017).

Among the aforementioned studies on the particulate matter pollution effect of UGI, most of them focused on the indicators of the number of UGI, such as green coverage, but almost no attention was paid to the spatial form of UGI. In addition, parks, forests or road greenbelts were the main study subjects, lacking of study on the UGI in urban common blocks constituting a fabric of urban space. Since the common blocks are the major components of city and are strongly associated with people's daily life, it is necessary to further reveal and emphasize the positive effects of UGI on particulate matter. That can provide evidential bases and available knowledge for landscape architects or urban planners to improve the urban air quality by means of planning and design strategies of green space.

The current work uses on-site data to reflect air quality of different blocks in Wuhan. Meanwhile, using landscape pattern index calculated by Fragstats as criterion of the spatial form of UGI in urban blocks. The landscape pattern indexes include size, shape, concentration and fragmentation. In order to assess the impacts of those UGI indexes on the air quality improving-effect of UGI, the study focuses on the following key contents:

1) Is there a correlation between the spatial forms of UGI and the concentration of particulate air pollution in general urban blocks?

2) What kinds of and to what extent spatial forms of UGI can affect the concentration of PM_{10} and $PM_{2.5}$?

3 METHODS

3.1 Study area

The study was conducted in Wuhan, the largest city in Central China. It is located in the intersection of the Yangtze and Han Rivers and is divided by the two rivers into Wuchang, Hankou and Hanyang. According to the 2016 global air pollution database published by the world health organization, Wuhan was the 12th worst particulate matter air pollution among 210 cities in China. Thereby, it becomes a target site of many studies relevant to urban particulate matter air pollution (Chen et al. 2015, Lu et al. 2017). The total area of the main city of Wuhan is 95515 hectares. By the end of 2015, the green coverage of the built-up area was 39.65%.

3.2 Sample sites

Ten air quality monitoring stations were relatively evenly spread around the main city of Wuhan, including eight national automatic monitoring stations and two self-monitoring stations set by research group (see Figure 1). Since Wuhan is a plain city, the monitoring stations are located in the similar height varying from 5 m to 27 m. The prevailing wind direction is northeast. This paper serves ten blocks of 1000m’s diameter, whose the center is each monitoring station，as study subjects (see Table 1). There are no pollution sources around the blocks, most of which are residential land, commercial land.

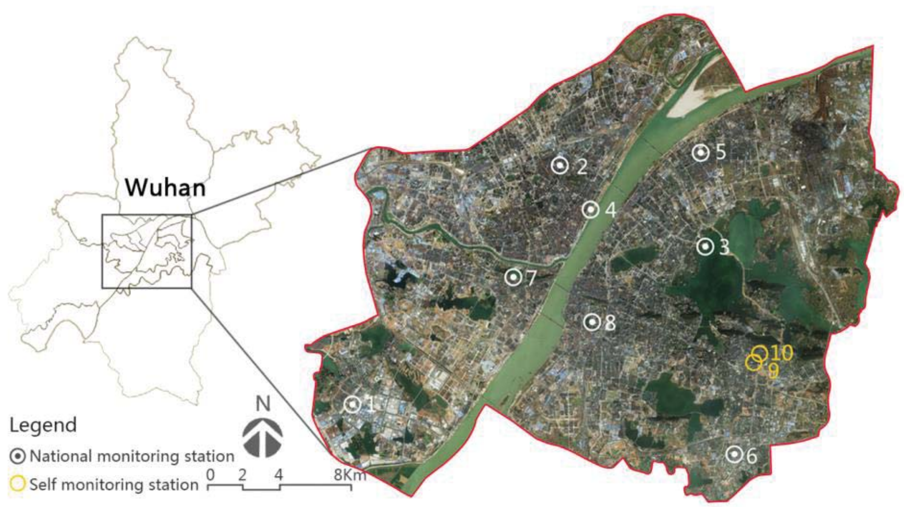

Figure 1. Distribution of 10 monitoring stations in the main city of Wuhan. Diagram by the author.

Table 1. Attributes of the ten blocks.

No.	Site	Coordinates	General land use	The composition of UGI
1	Zhuankou New area	(30.4753, 114.1525)	Commercial area	Street trees
2	Hankou Huaqiao	(30.6197, 114.2836)	Residential area	Street trees and planted residential areas
3	East lake Pear orchard	(30.5719, 114.3672)	Parkland area	Parkland
4	Hankou Marshland	(30.5947, 114.3008)	Residential and parkland area	Parkland, planted public facilities areas and street trees
5	Ganghua, Qingshan	(30.6103, 114.4272)	Residential and commercial area	Street trees and planted residential areas
6	East lake High-tech area	(30.4822, 114.3894)	Residential area	Street trees and planted residential areas
7	Yuehu Lake, Hanyang	(30.5514, 114.2511)	Residential and parkland area	Parkland and planted residential areas

8	Ziyang, Wuchang	(30.5494, 114.3006)	Residential area	Parkland and planted residential areas
9	Nansi, Huazhong	(30.5113, 114.4050)	Educational and residential area	Street trees, planted residential and public facilities areas
10	Design Institute, Huazhong	(30.5162, 114.4085)	Educational area	Street trees and planted public facilities areas

3.3 Particulate matter data measurement

Particulate matter data measurement was from two aspects. PM_{10} and $PM_{2.5}$ concentration of national automatic monitoring stations originated from Wuhan environmental air quality real-time publication system (http://ft.whepb.gov.cn:8090/Default.aspx), which recorded the PM_{10} and $PM_{2.5}$ concentration data per hour. Two self monitoring stations were set in Huazhong University of Science & Technology. Measurement of PM_{10} and $PM_{2.5}$ in air was by Laser Dust Monitor. One group of data is measured once a minute and 9999 groups of data can be measured at a maximum of one measurement period (2 weeks).

According to the pollution situation of Wuhan in 2015, PM_{10} and $PM_{2.5}$ sample data of 36 days was selected with the rate of 10% of the whole year. The data selection criteria was mainly based on 2-4 days per month for different levels of pollution under the sunny, windless weather conditions. The PM_{10} and $PM_{2.5}$ concentration values of the 36 days in 10 blocks were averaged respectively to analyze the overall pollution.

3.4 Spatial form index calculation of UGI

UGI in the current study is defined as “any vegetation found in the urban environment, including parks, open spaces, residential gardens, or street trees” (Kabisch, & Haase, 2013). Trees, grass, and trees, grass in green roof were used as UGI in my research design. UGI of 10 blocks were extracted from remotely sensed imagery (GF-2) taken from a China-made satellite, whose spatial resolution is 0.8 meter and acquisition date is September 1, 2016. The imagery was bought from remote sensing bazaar (http://www.rscloudmart.com/). The imagery was first preprocessed by radiometric and geographical corrections, and was then pan-sharpened to capture the structural features more precisely. Finally, based on the object-oriented classification technique, which is a method to extract different objects according to their features, such as texture, size, length and width, ENVI (The Environment for Visualizing Images) can achieve the automatic recognition and extraction of vegetation target from high-resolution remotely sensed imagery. Thereafter, combined with artificial visual interpretation, the results of extraction were optimized (see Figure 2).

Aforementioned UGI extracted from remotely sensed imagery was applied to Fragstats to calculate the spatial form index. According to former studies (Wu et al. 2015, Shen et al. 2014), Six representative indexes were selected to measure UGI spatial form in ten blocks in Wuhan based on the four aspects (size, shape, concentration, fragmentation) of spatial form based on principles including (1) theoretically and practically important, (2) interpretable, and (3) little redundancy (see Table 2). The selected spatial form indexes were applied to reflect the size, shape, concentration, fragmentation and separation of the UGI class level. The total class area (CA) and largest patch index (LPI) are patch composition index measuring the total area and core patches of landscape. Patch density (PD), edge density (ED) are landscape configuration indexes describing the spatial distribution of patches within the landscape. Landscape shape index (LSI) is a landscape shape index representing the irregularity of the perimeter of patches. Mean euclidean nearest neighbor distance (ENN_MN) at class level signifies the concentration characteristics of all patches.

Figure 2. Spatial form of UGI in ten blocks. Diagram by the author.

Table 2. Class metrics and descriptions.

First class index	Second class index	Index connotation
Size of patches	CA	Total area of patches
	LPI	Dominance of core patch
Shape of patches	LSI	The extent of irregularity of the perimeter of patches
Concentration of patches	ENN_MN	The extent of concentration of patches
Fragmentation of patches	PD	The extent of fragmentation of patches
	ED	The extent of separation of patches

3.5 Statistical analyses

First, the trends for PM_{10}, $PM_{2.5}$ and UGI spatial form were conducted to understand the characteristic of the ten blocks. Second, bivariate relationship was evaluated between the air quality indexes (the values of PM_{10} or $PM_{2.5}$ concentration) and the UGI spatial form indexes including CA, LPI, LSI, ENN_MN, PD, and ED, where UGI spatial form indexes are independent variables and air quality indexes are dependent variables. Finally, stepwise multivariate regression analysis was conducted to assess the contribution of those indexes to PM_{10} and $PM_{2.5}$ concentration quantitatively, according to a predictive equation (Eq. 1).

$$Y=b_0+b_1CA+b_2AREA+B_3PARA+b_4ENN+b_5LPI+b_6DIVISION \quad (1)$$

Where Y stands for the values of PM_{10} or $PM_{2.5}$ concentration, CA, LPI, LSI, ENN_MN, PD, and ED are the indexes previously described, b_1-b_6 are the coefficients for each variable, b_0 is the constant. The statistical analyses were carried out using SPSS 19.0 software.

4 RESULTS

Trends for PM_{10} and $PM_{2.5}$ are displayed in Figure 3. The concentration of PM_{10} and $PM_{2.5}$ in the ten blocks has great difference and similar tendency. Samples taken from the sites that exhibited the lowest concentrations of green space, such as Zhuankou New area, Hankou Huaqiao, generally had the highest concentrations of PM_{10} and $PM_{2.5}$. Conversely, the site that had the most green space, such as Design Institute, Nansi, recorded the lowest PM_{10} and $PM_{2.5}$, which were significantly lower than other eight sites.

Trends for UGI spatial form indexes of ten sample sites are displayed in Figure 4. The configurations of UGI spatial form varied significantly. The maximum values of CA, LPI, LSI, ENN_MN, PD, and ED were all regarded as “1”, and the maximum values of these six indexes were appeared in Design Institute, East lake Pear orchard, East lake High-tech area, Yuehu Lake, Zhuankou New area, Ziyang. The minimum values of these six indexes were only 0.14 (e.g., Zhuankou New area), 0.10 (e.g., Zhuankou New area), 0.08 (e.g., East lake Pear orchard), 0 (e.g., East lake Pear orchard), 0.005 (e.g., Design Institute), 0 (e.g., East lake Pear orchard), respectively.

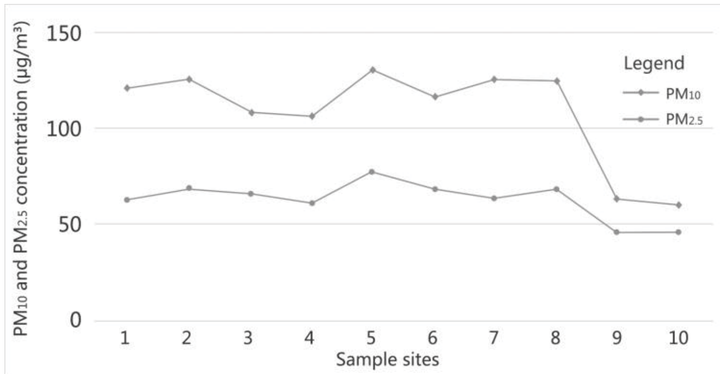

Figure 3. Average concentrations of PM_{10} and $PM_{2.5}$ for each sample site. Diagram by the author.

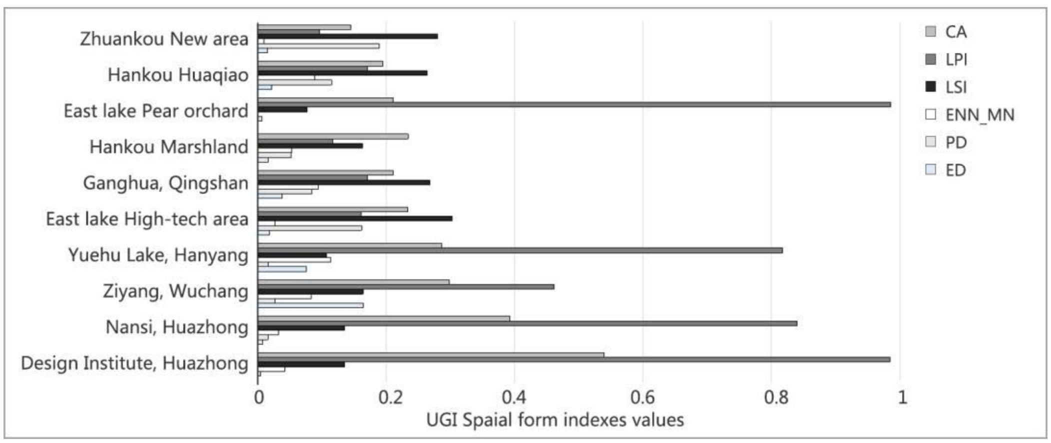

Figure 4. Trends for UGI spatial form indexes of ten sample sites. Diagram by the author.

4.1 Relationship between UGI spatial form and PM

There was a certain relationship between UGI spatial form indexes and concentrations of PM_{10} and $PM_{2.5}$ (see Table 3). CA had the most significant impacts on particulate matter (negative relationship, $P<0.01$), but there was no apparent relationship between LPI ($r=-0.085$, -0.116), which illustrated that UGI spatial form affected particulate matter air pollution mainly through a large size. ENN_MN, LSI, PD and ED were weakly positively correlated with concentrations of PM_{10} and $PM_{2.5}$ ($0.3<r<0.5$). The results illustrated that the more patches are, the greater the edge density is, and the more serious the degree of fragmentation is, the more serious particulate matter pollution is. We could improve air quality through increasing the area and aggregation of patches.

Table 3. The correlation coefficient (r) between UGI spatial form indexes and PM.

	CA	ENN_MN	LSI	PD	LPI	ED
PM_{10}	-0.824**	0.420	0.436	0.463	-0.085	0.460
$PM_{2.5}$	-0.756**	0.474	0.344	0.305	-0.116	0.428

** Significance at the 0.01 level.

4.2 The kind of UGI spatial form that significant influence on the PM

Stepwise multiple regression analyses of those aforementioned UGI spatial form indexes on PM_{10} and $PM_{2.5}$ values were conducted to evaluate the contributions of those indexes on the air quality modification effect. Result is displayed in Table 4. The correlation coefficient (R^2) serves to describe the proportion that can be explained by the variables (difference UGI spatial form indexes) of the regression model. The coefficient (B, Beta) of each variable allows assessing the variation and contributions extent of the target parameters (i.e. PM_{10} and $PM_{2.5}$ values in the current case) upon the corresponding variable. In that respect, more than 80% of the variation in PM_{10} and $Pm_{2.5}$ values can be explained by those UGI spatial form indexes, since the R^2 value is 0.878 and 0.819, respectively.

Total area of patches (CA) was the strongest influential indexes toward air quality improvement, since the corresponding significance level is lower than 0.01. The values of B coefficient of the CA was -1.843 and -0.662 respectively, which means that 10 hectares increased in the total area of UGI patches would decrease about 18.43 μg/m^3 and 6.62 μg/m^3 in PM_{10} and $PM_{2.5}$ concentrations. Since the main vegetation type is street trees, this positive effect of UGI patches area reflects that UGI plays an important role in decreasing the particulate matters through vegetation leaves (Hagler et al. 2012, Tong et al. 2016).

A weak negative impact of the mean nearest neighbor distance (ENN_MN) on PM_{10} and $PM_{2.5}$ concentrations was observed (Sig.= 0.012, 0.017). And it can be concluded that 10 meters increase of the mean distance of patches would increase about 29.60 μg/m^3 and 12.9 μg/m^3 in PM_{10} and $PM_{2.5}$ concentrations. It indicates that UGI patches' nearest distance is also associated with atmospheric particulate matter concentrations. This also means that fragmented patches are not good for air quality.

According to the results of stepwise multiple regression analyses, it also could be concluded that the impact of LSI, PD, LPI and ED are indeterministic toward the reduction of PM_{10} and $PM_{2.5}$ in the current case.

Table 4. Stepwise multiple regression profiles of UGI spatial form indexes with regard to PM_{10} and $PM_{2.5}$ values.

PM_{10} Variables	Coefficient B	Beta	R^2	Sig.	$PM_{2.5}$ Variables	Coefficient B	Beta	R^2	Sig.
Constant	141.480			0.000	Constant	74.877			0.000
CA	-1.843	-0.838		0.000	CA	-0.662	-0.771		0.002
ENN_MN	2.960	0.446		0.012	ENN_MN	1.290	0.498		0.017
LSI		0.002	0.878	0.993	LSI		-0.078	0.819	0.706
PD		0.014		0.946	PD		-0.177		0.458
LPI		0.107		0.594	LPI		0.136		0.577
ED		0.268		0.098	ED		0.177		0.411

5 DISCUSSION

Based on these results obtained from the work, some measures suggested should be taken by landscape designers, policy makers and city managers for improving the urban air quality as follows.

1) Increasing the area of the UGI patches, including trees, grass, bushes, and so on. Although it is common sense that larger coverage of vegetation can always bring benefits for urban particulate matters, our results further show a strong correlation between the area of vegetation and the values of PM_{10}, $PM_{2.5}$ concentration in the urban common blocks. This means that the vegetation, especially great trees, should be protected positively, which is beneficial for increasing the vegetation quantity and its coverage. In addition, strengthening the three-dimensional greening, mainly through the construction of the vertical landscape interface, such as green roof, vertical greening and other ways increases green quantity, improve the green coverage.

2) Decreasing the distance between different green patches, so as to increase the connectivity between patches. It indicates that the closer between the patches, the more significant of their air quality modification effect. That requires not only as much UGI as possible, but also an encouragement for planting trees with large canopy so that they can bond together to form a unitive integer.

In addition, the limitations of this study cannot be ignored. Although the current work used eight national air quality monitoring stations and two self monitoring stations in Wuhan, the number of sample sites is less slightly. The PM_{10} and $PM_{2.5}$ concentration of ten blocks were measured with their centers, how to represent the whole block need a further research. Further works can also be focused on much sample sites so as to reveal the clear and deep relationship between particle matter concentration and UGI spatial form in urban common blocks.

6 CONCLUSION

The current study investigated the effects of urban green infrastructure on particulate matter in views of ten common blocks and the individual spatial form indexes (CA, ENN_MN, LSI, PD, LPI, ED). Using on-site data measured by national air quality monitoring stations and our research group, combined with UGI of ten blocks extracted from remotely sensed imagery, a relationship between UGI spatial form and particulate matters had been obtained. This study contributes to the growing literature concerning air quality improvement via UGI. This study provides a method to explore the relationship between air pollution and UGI spatial form for other cases. It also provides important implications for urban neighborhood planning, design, and management; landscape designers and city managers should consider the strong benefits of using UGI to accomplish environmental goals.

7 REFERENCES

Beckett, K. P., Freer-Smith, P. H., & Taylor, G. (2000). Particulate pollution capture by urban trees: effect of species and wind speed. *Global Change Biology*, 6, 995-1003.

Benedict, M., & McMahon, E. (2006). *Green infrastructure: linking landscapes and communities*. London: Island Press.

Cardelino, C. A., & Chameides, W. L. (1990). Natural hydrocarbons, urbanization, and urban zone. *Journal of Geophysical Research*, 95, 13971-13979.

Chen, X. P., Pei, T. T., Zhou, Z. X., Teng, M. J., He, L., Luo, M., & Liu, X. X. (2015). Efficiency differences of roadside greenbelts with three configurations in removing coarse particles (PM10): A street scale investigation in Wuhan, China. *Urban Forestry & Urban Greening*, 14(2), 354-360.

Fan, S., Li, X., Han, J., Cao, Y., & Dong, L. (2017). Field assessment of the impacts of landscape structure on different-sized airborne particles in residential areas of Beijing, China. *Atmospheric Environment*, 166, 192-203.

Freer-Smith, P. H., El-Khatib, A. A., & Taylor, G. (2004). Capture of particulate pollution by trees: a comparison of species typical of semi-arid areas (Ficus nitida and Eucalyptus globulus) with European and North American species. *Water Air & Soil Pollution*, 155(1-4), 173-187.

Hagler, G. S.W., Lin, M. Y., Khlystov, A., Baldauf, R., Isakov, V., Faircloth, J., & Jackson, L. E. (2012). Field investigation of roadside vegetative and structural barrier impact on near-road ultrafine particle concentrations under a variety of wind conditions. *Science of the Total Environment*, 419,7-15.

Irga, P. J., Burchett, M. D., & Torpy, F. R. (2015). Does urban forestry have a quantitative effect on ambient air quality in an urban environment?. *Atmospheric Environment*, 120, 173-181.

Kabisch, N., & Haase, D. (2013). Green spaces of European cities revisited for 1990-2006. *Landscape and urban planning*, 110(1), 113-122.

Khan, F. I., & Abbasi, S. A. (2001). Effective design of greenbelts using mathematical models. *Journal of Hazardous Materials B*, 81, 33-65.

Lu, M. M., Tang, X., Wang, Z., Gbaguidi, A., Shen, S. W., Hu, K., Wu, L., Huang, H. J., Huang, Z., & Shen, L. J. (2017). Source tagging modeling study of heavy haze episodes under complex regional transport processes over Wuhan megacity, Central China. *Environmental Pollution*, 231(1), 612-621.

Mcdonald, A. G., Bealey, W. J., Fowler, D., Dragosits, U., Skiba, U., Smith, R. I., Donovan, R. G., Brett, H. E., Hewitt, C. N., & Nemitz, E. (2007). Quantifying the effect of urban tree planting on concentrations and depositions of PM_{10} in two UK conurbations. *Atmospheric Environment*, 41(38), 8455-8467.

Mesut, D., & Bayram, K. (2010). A preliminary assessment of the water and air quality parameters in and around the Lake Yenicaga coast. *Journal of the Black Sea Mediterranean Environment*, 16(2), 167-194.

Ottelé, M., Bohemen, H. D. V., Fraaij, A. L. A., Jonkers, H. M., & Loosdrecht, M. C. M. V. (2010).

Quantifying the deposition of particulate matter on climber vegetation on living walls. *Ecological Engineering*, 36(2), 154-162.

Pugh, T. A., Mackenzie, A. R., Whyatt, J. D., & Hewitt, C. N. (2012). Effectiveness of Green Infrastructure for Improvement of Air Quality in Urban Street Canyons. *Environmental Science & Technology*, 46(14), 7692-7699.

Shen, Z., Hou, X., Li, W., & Aini, G. (2014). Relating landscape characteristics to non-point source pollution in a typical urbanized watershed in the municipality of Beijing. *Landscape & Urban Planning*, 123(1), 96 – 107.

Tong, Z. M., Baldauf, R. W., Isakov, V., Deshmukh, P., & Zhang, K. M. (2016). Roadside vegetation barrier designs to mitigate near-road air pollution impacts. *Science of the Total Environment*, 541,920-927.

Wu, J. S., Xie, W. D., Li, W. F., & Li, J. C. (2015). Effects of Urban Landscape Pattern on $PM_{2.5}$ Pollution —A Beijing Case Study. *Plos One*, 10(11), 1-20.

Yang, J., Yu, Q., & Gong, P. (2008). Quantifying air pollution removal by green roofs in Chicago. *Atmospheric Environment*, 42(31), 7266-7273.