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Exploring the potential for air pollution mitigation by urban green infrastructure for high density urban environment

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Abstract. Air pollution has increased in the last decade in China. Urban green infrastructure, such as trees, could help to mitigate air pollution by the dry deposition process. The aim of this paper is to develop an assessment method for improving air quality by appropriate urban green infrastructure for high density urban environment in north China. Based on a literature review of relevant researches, an evaluation method of PM_{10} removal has been improved.

1. Introduction

The question 'how much green spaces should a city have?' has been asked since the 1920s, but the idea of urban green spaces became more important and popular after World War II. Harnik[1] defined and classified different kinds of urban green spaces and their size, and the number of facilities and programs that a city wanted. The overall plans for the whole city was given and studied for decades, but more detailed and micro-scale plans are need for various built environment. Green ratio methods seem an appropriate way to standardise urban green spaces on this purpose to improve air quality in this research. Many researchers suppose that landscape design is playing a significant role in fields of ecology and biology[2-4], which asks strategies that could measure the ecological effectiveness of different types of urban green spaces[5-6]. In some European countries, Biotope Area Factor has been used as a guideline to sustainably manage urban landscapes[7], which shows the ratio of the ecologically effective surface area (areas covered by green vegetation and/or permeable to rainwater) to the total land area under consideration[8]. Seattle Green Factor, which is developed from Biotope Area Factor, is a score-based code requirement that improves the quantity and quality of urban landscapes in new development[9]. Malmo Green Factor has been designed and used in an international housing exposition, called 'The Sustainable City of Tomorrow' or Bo01 held in Malmo in 2001[10]. Based on these green factors, green plot ratio (GPR) has been developed and chosen for this research to evaluate Urban Green Infrastructures (UGI).

The green plot ratio (GPR) is proposed as a new planning and architectural metric for cities and buildings, which is based on the leaf area index (LAI). It would bring a new idea to architects and designers to 'meet greenery into their designs'[11]. GPR is an appropriate tool to be used in the model of evaluating plants in urban air pollution removal. More specifically, it could act as a variable value in the model to show how different levels of Urban Green Infrastructures (UGI) affect air quality. Two studies[12-13] show urban air pollution could be removed by plants through photosynthesis and dry deposition. Specifically, the process of photosynthesis (with CO2 and O3) could help to assimilate gaseous contaminants[13]. And dry deposition can absorb particulate contaminants through gravity sedimentation or impaction[14]. So, these two processes absorb air pollutants through leaves. The other study[15] in Australia used the i-Tree Eco software to assess air quality improvement by different UGI, such as trees, green roofs and green walls. It indicated that trees make significant improvement on air pollution mitigation.

One key aim of this study is to explore the potential of nature-based solutions, for example Urban Green Infrastructure(UGI)[16-17] for air pollutant removal for high-rise buildings. A generic research framework is introduced in section 2, then a case study in Taiyuan city is presented in section 3. This paper concluded with an initial propose for urban trees planning around high-rise buildings.

2. The model of quantifying air pollution mitigation

The model aims to develop a new process to evaluate different types of UGI and their proportion. Also, it would quantify the efficiency of air pollution mitigation. So, that could help to find a more appropriate way to plan trees in built environment. The research framework (Figure 1) shows a whole process to simulate and evaluate through various tools. Usage of different digital tools are also pointed out. Specifically, computational fluid dynamics models are used to analyze and simulate various situations of green ratio; And system dynamics models, which have been used for building physics modeling in the past decade[18], are used for estimating pollution removal. Data is required for each step, which could be collect in many ways, such as satellite images and local weather stations.

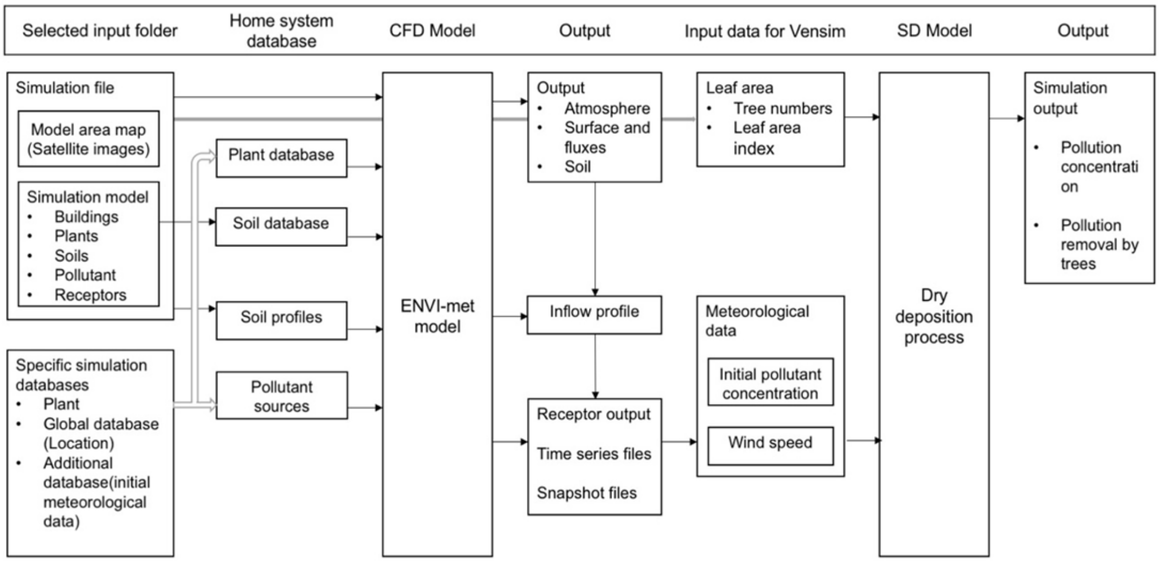

Figure 1. Research Methodological Framework.

2.1. Three keys steps

2.1.1. Step 1: Identification of land types and local microclimate zones. Satellite imagery and field surveys will be needed in this part. Satellite images can be found from lbsyun.baidu.com (in Chinese) for China. It clearly shows distribution of buildings, green covered areas, and traffic information to give a general idea for establishing a digital model in EVIN-met. Firstly, this research will not analyse a whole city but select certain research areas. So a stratified random sampling method[19-20] would be used for its advantages in the following areas 1) gains precision over simple random sampling method; 2) estimates each stratum separately; 3) cuts down the sampling cost and time[12]. In this part, field surveys might be required to locate the research areas and estimate the area types more accurately. A concept, ‘local climate zone’, could help to classify different land use types during field surveys. Local climate zones contain all classes that emerge form logical division of landscape universe, and the classification bases on regional surface cover, structure, material and human activity[21]. in this research, 100 x 100 m areas will be selected from satellite map on the basis of field survey results. Then these areas will be used to build digital models by ENVI-met software.

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2.1.2. Step 2: Collection of meteorological and air quality data. The meteorological data will be collected in two ways. First, a local weather station (AQIcn.org) will be used, as it provides general data in certain districts, such as temperature, relative humidity, wind, pressure and concentration of $PM_{2.5}$, PM_{10}, SO_2 and CO_2. Secondly, field surveys could collect the data the research areas, so that would lead a more accurate simulation result. However, due to limitation of meteorological and air pollution sensors, field surveys are unable to collect all required data. Hence, it is necessary to combine field surveys data with weather station data for an integrated data base. ENVI-met models, which are built in step 1, will run simulations based on the collected data to show variations of wind speed, temperature, and relative humidity hourly. Moreover, due to different building types (building scales, height, density) and tree density, wind speed and direction would change. So, that could affect pollutants concentration in research areas. These simulation results could increase the precision to calculate air pollution removal amount. Lastly, plant leaves are a key factor to absorb air pollutants, so it is important to estimate leaf area. This research will use the direct measurement, which is the area of leaves to ground covered[11].

ENVI-met is a suitable software for this research method comparing with other environmental software, such as ADMS that provides by Cambridge Environmental Research Consultants. ENVI-met is designed to simulate the surface-plant-air interactions in an urban environment, with a typical resolution down to 0.5 m in space and 1- 5 sec in time[22]. Specifically, modelling research areas in ENVI-met could simplify land cover, thereby it would increase standardization of land analysis. Moreover, ENVI-met could provide hourly data for next system dynamics models, also, it presents results visually. It is also simple to use and free for general meteorological simulation. ADMS 5 is dispersion model used to model the air quality impact of existing and proposed industrial installations. It is good at modelling air quality; however, this research aims to calculate air pollution through system dynamics models. In addition, this software is very expensive and complicated. Hence, ENVI-met is the best choice for the current stage in this research.

2.1.3. Step 3: Calculation of air pollution removal. The rough aerodynamic surface of trees, such as leaves and branches, is effective for the removal of air pollutants directly by the dry deposition process[14]. The amount of PM_{10} removal at a unit in a certain period could be calculated as[19]:

$$Q = F \times L \times T \tag{1}$$

where Q is the amount of a particular air pollutant removed by a certain area of green space in a certain time period (g), F is the pollutant flux (g/m2/s), L is the total area of green spaces, which is leaf area in this research (m2), and T is the time period (s).

The pollutant flux F is calculated as[19]

$$F = V_d \times C \times 10^{-8} \tag{2}$$

where V_d is dry deposition velocity of a particle pollutant (cm/s), and C is concentration of the pollutant in the air (μg/m3). This study assumes that particles adhere to surface of vegetation upon contact, the dry deposition velocity is decided by transport properties in the air, so canopy resistance could be ignored [23].

$$V_d = \left(\frac{1}{R_a + R_b + R_a R_b V_g} + V_g\right) \times 10^{-2} \tag{3}$$

where R_a is aerodynamic resistance, R_b is resistance of molecular scale diffusive transport at quasi-laminar boundary layer, and V_g is a gravitational settling velocity (m/s).

A System dynamics model is built based on dry deposition equations by Vensim software to calculated amount of air pollution removal. In last step, the CFD model simulated meteorological changes with different green ratios. These data would be used to calculate the pollutant removal amount based on each green ratio scenario, which would assist in proposing a standard of efficient urban green areas around high-rise buildings.

3. Calculation of PM_{10} removal by trees

3.1. Background of PM10 concentration in China

Anthropogenic activities and natural sources could create Particulate matter (PM)[24]. PM mainly affects the health of the respiratory and cardiovascular systems. Currently, PM_{10} as general data is measured by the most routine air quality monitoring systems. It indicates the particle mass that could enter the respiratory tract, so it has been used in many epidemiological studies as the exposure indicator[25]. The 24-hour and annual average air quality guidelines (AQG) for PM_{10} are 50µg/m3 and 20µg/m3 respectively[25]. According to multi-city studies in Europe, mortality effects will increase by 0.62% if 24-hour average of PM_{10} rises 10 µg/m3[26]. PM_{10} in most European countries[27] is under 30µg/m3, but many cities in northern China are between 70 µg/m3 and 170 µg/m3 [28]. The PM_{10} concentration in China is bad for people's health. This research will predominantly measure PM_{10} mitigation by trees and try to develop UGI planning in urban environment.

A field study is needed to collect meteorological data and local PM_{10} concentration by anemometers and air quality monitor. These data can be used to estimate absorptive PM amount through dry deposition. Air quality data can be collected by Dylos DC1100[29]. It is able to count two sizes of particles, which respectively have diameters between 2.5 to 10 micrometres (µm) and 0.5 to 2.5 µm [30]. However, Dylos PM show particle numbers in .01 cubic foot of air. This data need to be converted to micrograms per cubic meter (µg/m3) for the later calculation by dry deposition equations. Particulate Matter mass concentration of micrograms per cubic meter could be calculated from Dylos numbers as [31],

$$\mathrm{C_{PM}} = \mathrm{N} \times 3531.5 \times \mathrm{P_{PM}} \times \mathrm{H} \times \mathrm{c} \tag{4}$$

Where CPM is a certain particle concentration; N is the number of particles; PPM is the mass of a particle, which $PM_{2.5}$ is 5.89E-7 µg and PM_{10} is 1.21E-4 µg; H is the relative humidity percentage; and c is the correction factor (6.4) [31].

3.2. *Simulation Process*

First, an area will be selected from satellite images in a Chinese city, which is approximately 24,000 m^2 (120m×200m), as this is a high-efficiency scale for ENVI-met to simulate. The area will mainly choose for residential use or office use to limit that main pollution source comes from human activities. Then, this area will be substituted into ENVI-met for digital simulation based on current land use, tree density and local meteorological data. The simulation will provide hourly data for further calculations in Vensim. For instance, ENVI-met can show detailed wind speed levels in research areas. It is clear to locate high wind speed zones and low wind speed zones to compare pollution concentration in these zones. The hourly data will be entered to the operational model in Vensim to calculate total amount of PM_{10} mitigation through the dry deposition process.

During dry deposition process, leaf area and leaf area index is required to calculate pollutant removal. In many cities in north China, about half of urban trees are boreal deciduous broad leaf (BoDBL), and around 30% is boreal evergreen needle leaf (BoENL)[32]. BoDBL mainly covers the selected area, which is observed through satellite imagery, so the mean LAI data is 2.58[33](Table 1). Leaf area in each area can be calculate as:

$$s_c \times LAI_{BoDBL} = s_t \tag{5}$$

where S_c is the tree crown areas (m^2), and it will be estimated as the same area as a grid in ENVI-met model; LAIBoDBL is the mean LAI of Forest/BoDBL; and s_t is total leaf area.

$$\mathrm{N_t} \times \mathrm{r_c}^2 \times \pi = \mathrm{s_c} \tag{6}$$

where N_t is number of trees in each zone; r_c is radius of a tree crown, which is measured from the satellite images in this research.

The calculation process of Vensim model is based on dry deposition equations. In this model, hourly PM_{10} concentration in the research areas will be put in every two hours. The adjustment factors may be needed to regulate the different units between various inputs. This model is used to calculate total amount of pollutant removal by dry deposition based on the pollutant concentration at each level.

And it will also show variations based on different pollution concentration, leaf areas and wind speed. Various scenarios will be simulated in the model to try to find out a better way of urban green planning for air pollution removal. Scenarios can be designed by various green covered areas with impacted wind speeds, which might help to show relationship between pollution concentration and wind speed.

Table 1. Statistical distribution of leaf area index by biome for the original data compilation and after removal of statistical outliers using Inter-Quartile Range (IQR) analysis [33].

	Original data				Data after IQR analysis			
Biome	Number of observation	Mean	Min	Max	Number of outliers removed	Mean	Min	Max
All	931	5.23	0.002	47.0	53	4.51	0.002	12.1
Forest/ BoDBL	58	2.64	0.28	6.0	5	2.58	0.6	4.0
Forest/ BoENL	94	3.50	0.48	21.6	8	2.65	0.48	6.21

4. Discussion and conclusion

The issue of air pollution is becoming increasingly urgent in China, so this research attempts to provide an initial strategy. It represents that more urban green infrastructures are needed to improve air pollution removal. Moreover, the model of quantifying air pollution mitigation may also point out relationships between green ratios and wind speed and how do they impact pollution concentration in a certain area. Nevertheless, it also can be used for different urban environment, such as street canyons.

To sum up, this research preliminarily explores the potential of trees in air pollution removal through dry deposition. And initial results will be compared and discussed based on various scenarios to quantify pollutant removal and suggest high-efficiency ways of planning trees in urban environments. For further study, more pollutant types, such as $PM_{2.5}$ and CO_2, will be tested. Moreover, different urban environment, such as street canyons will be studied and compared with others. Finally, air pollution absorption by plants can be affected by many factors, such as humidity, soil and tree types, and temperature, which is more complicated in actual built environment. That will require more researches across discipline.

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