Exploring the Effects of Urban Green Space in Reducing Ambient Fine Particulate Matter ($PM_{2.5}$)

LWS 548 Major Project

Sabrina Hu

Master of Land and Water System

Faculty of Land and Food Systems

University of British Columbia

Vancouver, British Columbia

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Executive Summary

With rapid urbanization and industrialization, particulate matter has become a concern that brings adverse impacts on human health and the urban ecosystem. $PM_{2.5}$ represents suspended particulate matter particles in the air with a diameter smaller than 2.5 micrometer, which are produced through natural processes and anthropogenic processes. Although natural processes produce large amounts of $PM_{2.5}$, such as wildfire, dust storms, and sea spray, anthropogenic emissions account for the majority of $PM_{2.5}$ production through energy production, construction, industry, power generation, agriculture, transportation, and manufacturing.

$PM_{2.5}$ has an ultrafine size, which enables it to enter the human body through the respiratory system. Short-term and long-term exposure to different levels of $PM_{2.5}$ can increase morbidity and mortality of various diseases including cardiopulmonary diseases such as asthma, respiratory infections, and heart failure, and other diseases such as skin diseases, liver and kidney diseases, and cancer. The health risks caused by $PM_{2.5}$ exposure are higher in specific groups of people, including women, children, and elders. In addition, long-term $PM_{2.5}$ exposure is associated with accelerated aging.

Nowadays, there is a global trend of urban expansion and increasing urban population. Air pollution reduction has become an urgent need for people living in cities. Many studies have shown that urban green space (UGS) has positive impacts on $PM_{2.5}$ removal based on the results of indoor experiments, field experiments, and spatial analysis. Although the $PM_{2.5}$ removal capacity of UGS has a threshold, it can be increased by appropriate UGS configurations, structure, and spatial patterns considering climate conditions and local topography. Therefore, UGS is recommended as a tool to help $PM_{2.5}$ removal in urban areas.

UGS has potential in long-term $PM_{2.5}$ deposition but needs efforts from local governments and the public in the process of planning, design, implementation, and maintenance. Following are four recommendations for governments to increase urban $PM_{2.5}$ removal capacity: (1) Increase the quality of existing UGS; (2) Increase the UGS coverage; (3) Develop local UGS guidelines; (4) Multilevel collaboration and outreach.

This paper emphasized the implication of UGS in ambient $PM_{2.5}$ removal, which provides important insights for decision-makers about urban planning and land use management.

Introduction

With rapid urbanization and industrialization, particulate matter has become a critical issue that threatens people's health and disturbs the balance of the entire urban ecosystem (Gianfredi et al., 2021). Particulate Matter (PM), also known as particulate pollution, consists of small-size particles suspended in the atmosphere, water, and space. PM is not a particular substance with fixed properties, but any particle that has a certain aerodynamic diameter in an aerosol. PM is divided into two categories by its aerodynamic diameter in micrometre, including coarse particle between 2.5 micrometre and 10 micrometres, and fine particle that is equal to or smaller than 2.5 micrometre (Figure 1; US EPA, 2016).

Primary $PM_{2.5}$ sources are derived via two main types of activities, including natural activities and human activities. Natural sources include wildfire, windblown dust, and sea spray, but produce much less $PM_{2.5}$ than human activities.

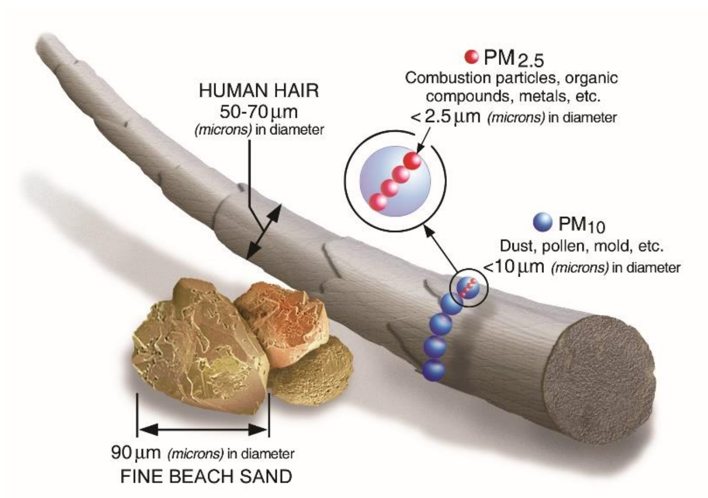

Figure 1 Size of particulate matter particles. Figure from US EPA, 2016.

PM particles are much smaller than human hairs, which enables them to be readily inhaled into the lungs, especially $PM_{2.5}$, which can further be transferred into the bloodstream. $PM_{2.5}$ in the atmosphere can increase health risks, especially for people with lung, asthma, or cardiovascular disease, as well as children and elderly people (K.-H. Kim et al., 2015).

As cities have a high population density, $PM_{2.5}$ control is more important in urban areas with heavy transportation and industry, or regions that frequently suffer from wildfire smoke during wildfire seasons. According to existing studies, urban forests and urban green areas contribute to cutting down air pollution by acting as barriers to absorbing pollutants within air circulation in urban areas (Abhijith et al., 2017, Selmi et al., 2016, Baró et al., 2014). Therefore, urban green space (UGS) can be a potential solution for reducing the excess fine particulate matter from various sources in urban areas.

UGS is all green vegetation located in urban areas, including parks, forests, gardens, green infrastructures, and riparian areas, which provide a variety of ecosystem services (Wolch et al., 2014). Among these types of UGS, urban forests play an important role in depositing and adsorbing airborne pollutant particles as they have large leave surface areas. Also, with different plant species, configurations, and spatial patterns, the efficiency of UGS in $PM_{2.5}$ removal is different. This paper explored the health effects caused by short-term and long-term ambient $PM_{2.5}$ exposure, as well as how urban green space work to mitigate $PM_{2.5}$.

Based on the information above, the focus of this paper is:

1. $PM_{2.5}$ Sources and composition
2. Short-term and long-term (acute and chronic) health issues caused by $PM_{2.5}$
3. Urban green space and the properties that affect the $PM_{2.5}$ capture capacity and efficiency.

Objectives

The main objective of this paper is to synthesize the health risks of short-term and long-term ambient $PM_{2.5}$ exposure and how UGS, as a nature-based solution, can reduce $PM_{2.5}$ in highly compact cities. This paper also aims to provide recommendations to the local government about how to utilize UGS in air pollution control, while providing information related to $PM_{2.5}$ and UGS to the public.

Methods

A literature review was conducted in this project to synthesize the existing studies about PM-related health risks and PM mitigation effects of UGS. The sources were peer-reviewed scientific research, which was selected starting from the most recent years.

To provide background information about $PM_{2.5}$ and UGS, relevant literature were reviewed by topics including:

1) $PM_{2.5}$ sources, composition, and movement pattern;
2) UGS concepts;
3) UGS's current global pattern;
4) The rationale of $PM_{2.5}$ mitigation by UGS.

Then, PM-related health risks were synthesized by different exposure times including long-term $PM_{2.5}$ exposure and shore-term $PM_{2.5}$ exposure, and by two disease categories that are cardiovascular diseases and respiratory diseases. To summarize the UGS properties that can increase the PM mitigation effect, the following UGS properties were reviewed:

1) Vegetation species characteristics
2) UGS Criteria
    a. UGS structure
    b. Spatial pattern

In addition to documenting the effects of $PM_{2.5}$ on human health and desired UGS properties in PM mitigation, this project also included two case studies to better understand the application of UGS in PM mitigation and UGS effectiveness assessment. Last, according to the literature review and consolidated information, recommendations were provided for local governments to mitigate $PM_{2.5}$ in urban areas with an urgent need for air purification.

Literature Review

Urban Green Space

Defined by WHO, urban green spaces (UGS) are places with a variety of vegetation and UGS may also include "blue spaces" that contain water elements, such as gardens, forests, streams, and beaches (World Health Organization. Regional Office for Europe, 2016). In addition to publicly constructed or preserved green space, informal greenspaces such as street verges also count as UGS (Figure 6).

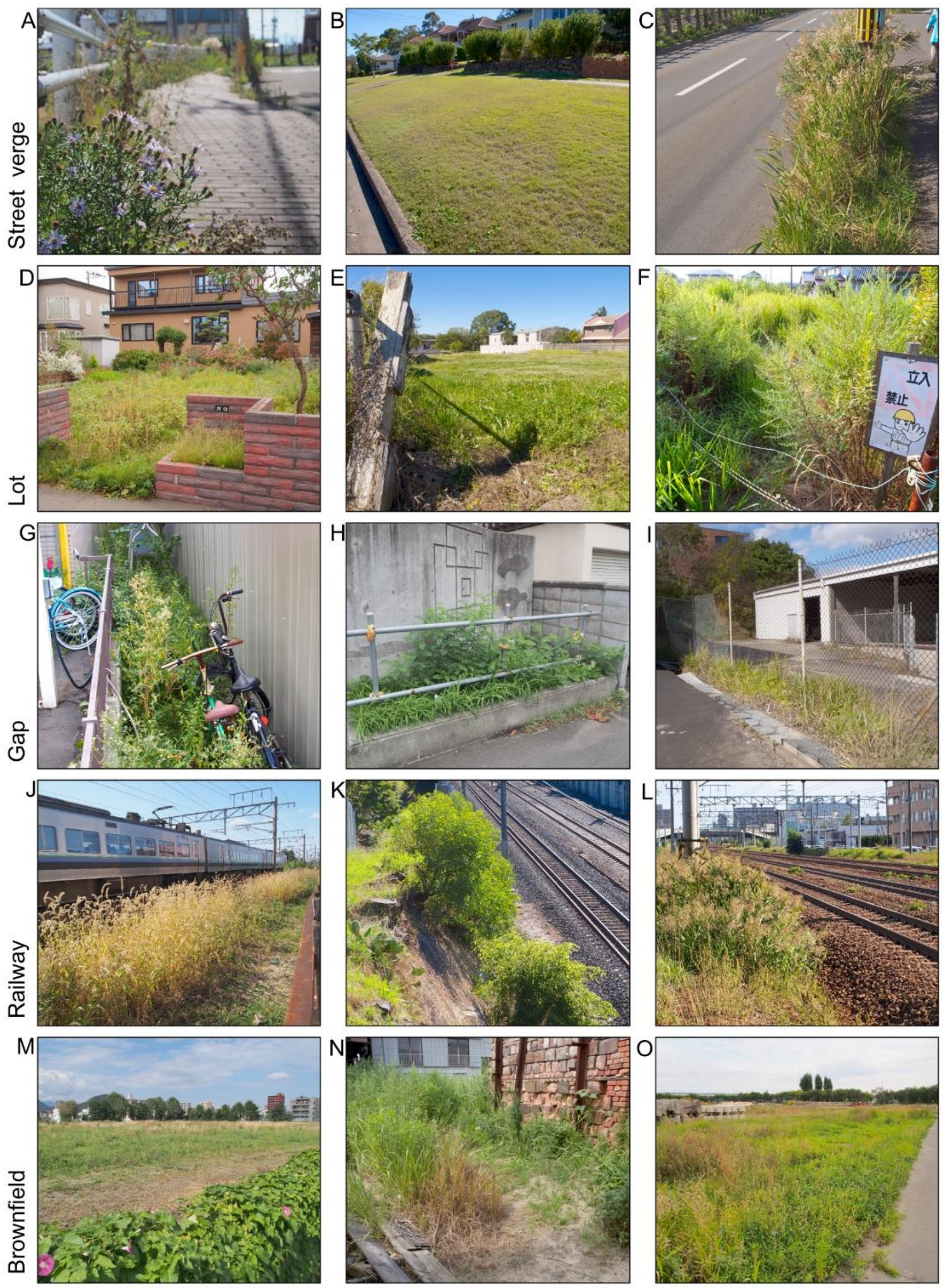

Figure 6 Informal urban green space (UGS) types. Figure from Rupprecht & Byrne, 2014.

Ecosystem services are the benefits and goods obtained from ecosystems which can enrich human life, such as food and water resources, water quality purification, and cognitive development (Stroud et al., 2022). UGS provides a variety of ecosystem services, supporting biodiversity and ecosystem functions that directly or indirectly benefit human well-being (Birkhofer et al., 2015).

Nowadays, more than 55% of the global population lives in urban areas (Heilig, G.K, 2012). The loss of biodiversity and ecosystem degradation has become a global concern in urban areas due to a series of issues brought by rapid urbanization, such as the expansion of impervious surfaces and the aggravated urban heat islands effect. From 2000 to 2015, there was a significant increase in urban expansion across 65 countries in Asia, Mid East, and Europe, including approximately 900 km2 growth in Beijing, China (Pan et al., 2019). At a global scale, the total impervious surface area (ISA) accounts for 60% of the total urban land, primarily distributed in Africa, eastern Asia, and central to southern North America (Kuang, 2019; Figure 7).

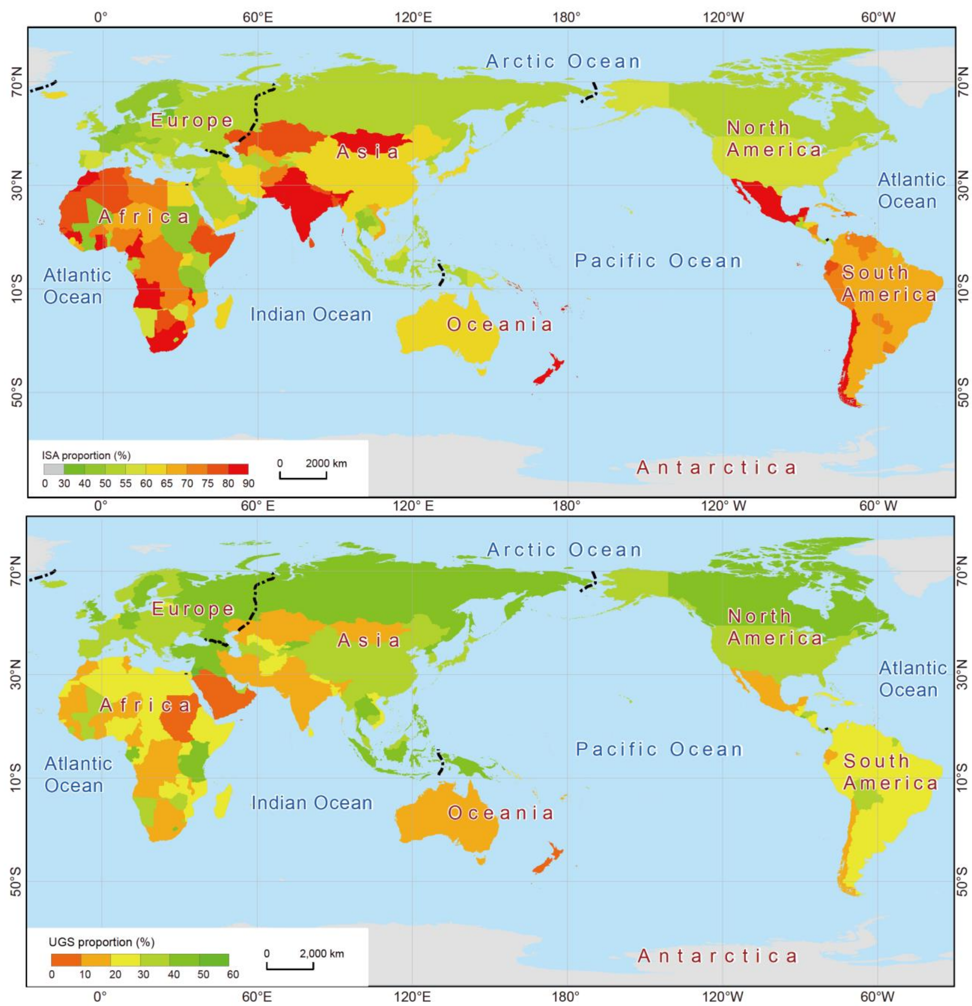

Figure 7 Global distribution of impervious surface area (ISA) and urban green space (UGS). Figure from Kuang, 2019.

Urban Green Space and Air Pollution

Leafy vegetation can directly remove suspended particulate matter in the atmosphere by sedimentation, retardation, absorption, and adsorption on the leaf surface (Wang et al., 2022). These particles can be absorbed by the vegetation, resuspend into the atmosphere, washed off by rain, or back to the ground with vegetation debris such as dried leaves and twigs (Nowak et al., 2013). One common example of the PM removal effect is the road tree leaves covered by a layer of dust (Figure 8). In addition, by providing humidity and mitigating temperature, trees can help reduce evaporative PM emissions as well as accelerate suspended particle deposition (Cardelino & Chameides, 1990; Ryu et al., 2019).

Figure 8 Roadside vegetation covered by dust.

Many studies have observed that UGS has the potential in controlling $PM_{2.5}$ levels in urban areas. Environmental monitoring in the Central Experimental Farm located in the City of Ottawa found that the proximity to the farm was associated with a lower level of $PM_{2.5}$ in winter and summer (Van Ryswyk et al., 2019). It was also found that lake wetlands combined with surrounding urban greenery features have a positive impact in lowering PM_{10} and $PM_{2.5}$, with a positive correlation between increasing wetland buffer zone and reduction in PM (Zhao et al., 2021). By analyzing spatial variations of PM concentration in Zhejiang, China, from 2015 to 2017, Wu et al., (2018) found that at a scale smaller than 5 km, there was a strong correlation between green space and $PM_{2.5}$. Nowak and colleagues also found that the total amount of annual $PM_{2.5}$ removal by trees in 10 U.S. cities ranged from 4.6 tonnes to 64.5 tonnes (Nowak et al., 2013).

However, this doesn't mean that all UGS can always reduce PM levels. As the particles adsorbed by trees can be re-emitted or resuspended to the atmosphere, the total PM concentration can still increase when the resuspension rate is higher than the removal rate (Nowak et al., 2013). In addition, some plant species can produce biogenic volatile organic compounds and form secondary air pollutants by reacting with nitrogen and sulfur oxides in the air (Leung et al., 2011). In addition to the possible increase in air pollution, allergenic plant pollen grains from urban vegetation also trigger allergies, contributing to adverse health effects for some people (Taketomi et al., 2006). Therefore, in order to use UGS as a long-term solution for $PM_{2.5}$ control, while minimizing the possible adverse health effects, the choice of vegetation types, area, density, configuration, and distribution patterns are of vital significance.

Species Characteristics

The efficiency of UGS in PM removal is largely dependent on wind speed, particle size, vegetation species, and different species characteristics such as leaf morphology and transpiration mechanism. At the major tree types level, evergreen trees are more effective in removing particles, especially in winter compared with deciduous plants (He et al., 2020; Pace & Grote, 2020). Among all the evergreen tree types, it was found that coniferous trees have a higher efficiency in accumulating PM as the long, narrow needles are more easily in capturing suspending PM in the air (Räsänen et al., 2013).

Many experiments have been done to investigate leaf physiologic characteristics that affect the particle capture efficiency of plant species. Stomatal density is one factor that determines particle capture efficiency. In broadleaf trees, the higher the stomatal density, the more particles can be captured as the stomata allow more transpiration, producing humidity to deposit airborne particles, however, for coniferous species, it was found that fewer stomata increase the particle deposition (Räsänen et al., 2013). Another example is leaf roughness. Trees with rough leaves have more complex shapes, such as edges and hair, which can enhance the performance in capturing PM particles with an aerodynamic effect (Chen et al., 2017; Sgrigna et al., 2020). Except for leaf morphology, leaf area, leaf density, appropriate leaf angle, and plant height can all affect the PM removal efficiency of UGS (Table 2).

Table 2 Examples of major species traits that affecting $PM_{2.5}$ deposition efficiency.

Species traits	**$PM_{2.5}$ deposition efficiency**	**Source**
Stomatal Density	Increase with higher stomatal density increase in broadleaf trees; increase with fewer stomata in coniferous trees	Räsänen et al., 2013
Leaf roughness	Increase with higher leaf roughness	Chen et al., 2017; Sgrigna et al., 2020
Leaf wettability	Increase with higher leaf wettability	Redondo-Bermúdez et al., 2021
Canopy density	Increase with higher canopy density	Grote et al., 2016
Leaf size	Increase with smaller leaf size	Corada et al., 2021
Evergreen	Higher with evergreen species	He et al., 2020; Pace & Grote, 2020
Leaf contact angle	Decrease with increasing leaf contact angle	Li et al., 2022
Tree height & Crown width	Increase with greater tree height and wider crown	Yin et al., 2022

Considering these species' properties, specific tree species were found that have high PM capture efficiency. Chen and colleagues selected five species commonly found in north China to compare their deposition velocity and found that S. *japonica* had the highest capacity to remove PM (Chen et al., 2017). Among four representative roadside evergreen plants, He and colleagues found that *Taxus baccata* was the most efficient species for both PM_{10} and $PM_{2.5}$ deposition in winter (He et al., 2020). A systematic review of urban trees in air pollution mitigation also ranked the most common urban tree species by evaluating their functions, which indicates that *Picea abies* is most efficient in PM removal (Grote et al., 2016; Figure 9).

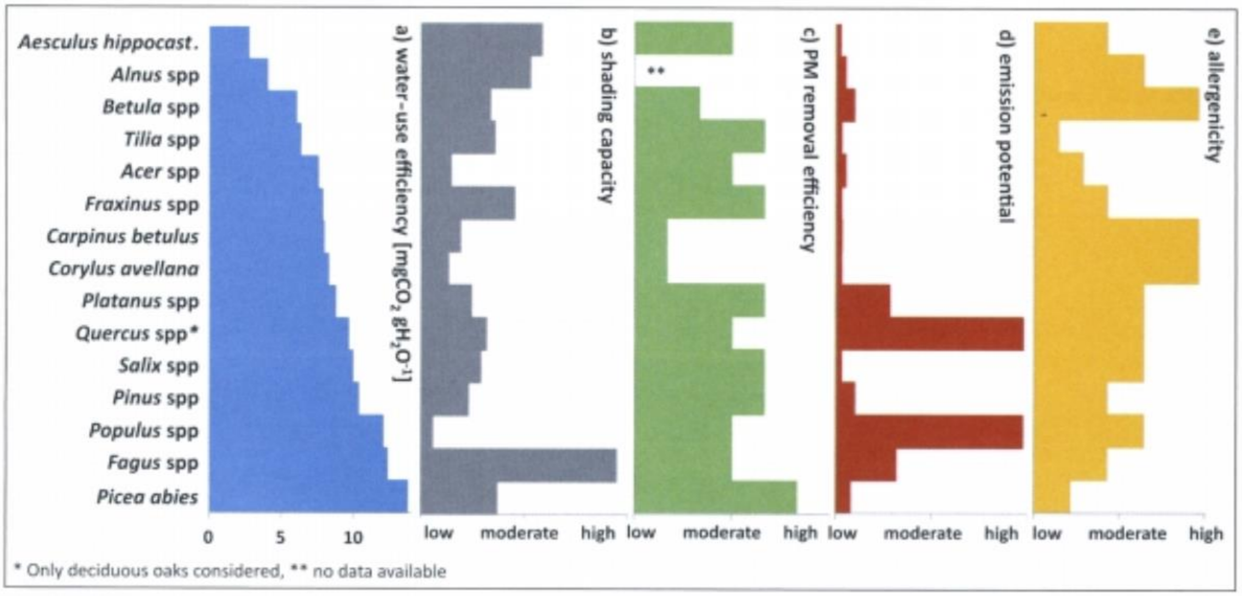

Figure 9 The most common urban tree species ranked by a) Water-use efficiency; b) shading capacity; c) PM removal efficiency; d) Organic emission potential; e) allergenicity. Figure from Grote et al., 2016.

UGS Criteria

The PM removal efficiency of UGS is not determined by single traits of a single species, but an outcome of co-existing traits as well as combinations of multiple species with effective UGSs structures and spatial patterns.

The most common structure of UGS is a combination of grass and trees. Trees perform better than grass in PM removal with aerodynamic effect, and this may be due to the relatively higher leaf density and heights of tree species (Chen et al., 2019; Jeanjean et al., 2016). However, with high dispersion, grasslands can have better PM removal efficiency in riparian green (Wang et al., 2021). With different UGS types and environmental conditions, different green space structures have been studied to find the optimal configuration that has the best $PM_{2.5}$ removal efficiency at the local scale. From Table 3, it can be seen that with a windy condition, an arbour-shrub-grass structure was recommended in windy and dusty urban areas. Also, as found by J and colleagues, evergreen shrubs, broadleaved forests, and needle-leaved forests had outstanding PM removal effects separately in a green area from small to large (J et al., 2019).

Table 3 Examples of optimal UGS structures at the local scale.

UGS type	Research scale	Optimal Structure	Environmental condition	Source
Greenbelt	City	Rough bush-shrub-grass; arbor-shrub-grass	Windy and dusty	Zhao et al., 2018
Urban riparian green spaces	City	1) Open grassland along the riverside 2) Combination of arbor-grass and arbor-shrub-grass in the middle of woodland	1) static wind (hourly wind speed <0.2m/s) 2) all ranges of wind speed	Wang et al., 2021

Urban vegetation	City	1) Evergreen shrubs 2) Evergreen broadleaved forests 3) Evergreen needle-leaved forests	1) Within < 100m 2) Between 100 and 300 m 3) Larger than 300 m	J et al., 2019
Roadside tree	Street canyon	Tree crown with high porosity and low-stand density	Perpendicular or parallel car parking	Abhijith & Gokhale, 2015

Many studies have investigated the correlation between UGS spatial patterns and PM concentrations. First, PM removal efficiency is associated with UGS coverage. A strong negative correlation between PM concentration and UGS with a radius smaller than 2 km was found by Wu and colleagues, and this negative correlation was stronger when the UGS has a radius larger than 4km (Wu et al., 2018). At the neighbourhood scale, when the size of green space is smaller than 200 m, the $PM_{2.5}$ mitigation effects disappeared but were maximized when the size was between 400 to 500 m (Chen et al., 2019). In addition to UGS coverage, the lower degree of UGS fragmentation is also associated with lower $PM_{2.5}$ concentration (Cai et al., 2020; Chen et al., 2022).

Wu et al., (2018) also found that at the small scale, the shape of the green space especially the linear shape is a more dominant factor affecting the PM deposition velocity. And this corresponds to the common use of greenbelts in transportation, such as roadside trees and shrubs. In Beijing, two greenbelts were constructed around the city to control the atmospheric $PM_{2.5}$, which slows down $PM_{2.5}$ transport and increases particle accumulation (Zhao et al., 2018). Another study also explored the passive PM control of hedgerows in street canyons to reduce pedestrian PM exposure, and it was found that medium-sized trees with small leaf density and low stand density are most efficient in PM removal (Abhijith & Gokhale, 2015).

UGS plant diversity and density are important factors as well. As discussed above, a variety of leaf characteristics can improve particle deposition efficiency. With increasing plant diversity, $PM_{2.5}$ can be deposited through different mechanisms, such as adsorption and absorption depending on the leaf surface structures, leaf density, and surface area, which enables PM to be removed at different heights and sizes (Gao et al., 2020). Through a country-wide study, it was found that the more vegetation types the green space has, the fewer days of unhealthy air quality within urban communities, which can improve residents' life satisfaction (Wu & Chen, 2023).

Table 4 Examples of effective UGS criteria in PM deposition.

UGS types	**Criteria**	**Research Scale**	**PM deposition efficiency**	**Other important factors**	**Source**
Urban Forest	Increasing perimeter; more irregular shape	City	Increase	Urban forest maintenance	Zhai et al., 2022
Trees and grass	Increasing coverage	Community	Increase	$PM_{2.5}$ concentration	Chen et al., 2019;

					Jeanjean et al., 2016
Urban green space	Increasing coverage	City	Increase	Population Density and GDP	Li et al., 2023
Urban green space	High density; high diversity	Country	Increase	Heterogeneity of air pollution in the urban area	Wu & Chen, 2023
Green space	Increasing total edge length (at 2 km scale or less)	Province	Increase	Elevation	Wu et al., 2018
Greenbelt	Increasing density and plants with hairy leaves and exuberant foliage	City	Increase	Wind and dust	Zhao et al., 2018
Roadside tree	Evergreen hydrophilic leaves	City	Increase	Tree species and seasons	He et al., 2020
Urban green space	Increasing green space coverage and decreasing forestland fragmentation (within 1-3 km)	Country	Increase	Financial reasons	Cai et al., 2020

Case study

Urban Green Space Prioritization to Mitigate Air Pollution and the Urban Heat Island Effect in Kathmandu Metropolitan City, Nepal

Bhandari et al., 2022

Due to few studies about how UGS can mitigate air pollution as well as the urban heat island effect in Kathmandu Metropolitan City (KMC) in Nepal, Sabina Bhandari and Chuanrong Zhang conducted a study focusing on the importance of UGS prioritization and implementation in KMC in 2022.

With rapid urbanization and social development in KMC, there is an increasing number of private vehicles, combustion devices for household use, and industrial facilities. Accompanied by frequent wildfires, air pollution has been a concern in KMC. By reviewing previous studies, Bhandari and colleagues recognized the potential of UGS in mitigating air pollution and the urban heat island effect (Bhandari et al., 2022). It was highlighted that UGS is not only directly associated with air pollution but also may improve air quality by decreasing air temperature as it is a determinant factor in the atmospheric reactions that produce secondary pollutants. Therefore, the research team decided to prioritize areas in KMC for air pollution and urban heat island effect mitigation.

The prioritization process has three steps. The first step was assessing the land surface temperature and air pollution in KMC by using the Landsat image and Air Quality Index data from 2017 to 2021. Second, the index for UGS establishment was created by considering a series of indicators in KMC, including population, built-up area, land surface temperature, residential area, industrial area, and transportation. Accompanied by data on existing green areas in KMC and the Normalized Difference Vegetation Index (NDVI), the research team created a map showing the prioritized area for UGS establishment (Figure 10). Third, the potential solutions were identified to increase the UGS coverage according to the order of prioritized areas. As KMC is a highly compact city, it is difficult to enlarge the ground-level UGS area. Therefore, existing UGS types in KMC with high values (identified by NDVI) and green roofs were selected to maximize the UGS functions with a vertical dimension (Bhandari et al., 2022).

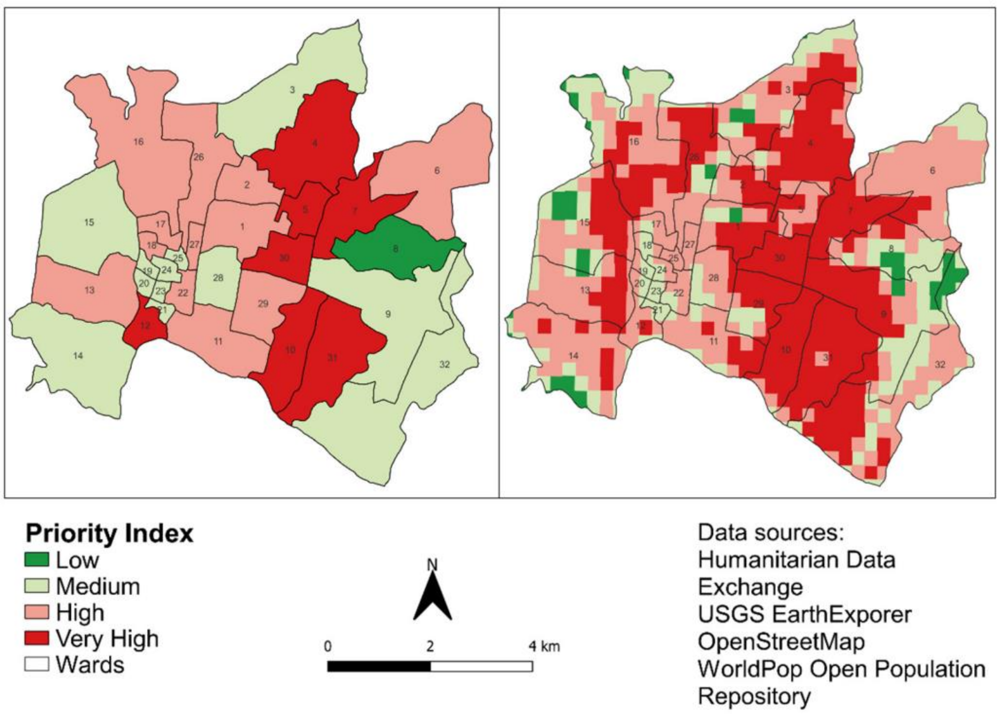

Figure 10 Prioritized area for UGS establishment in KMC. The left is at the ward level and the right is at the fishnet level. Feagure from Bhandari et al., 2022.

The results of land surface temperature (LST) and air quality assessments show that there was a 5-7 K increase in LST from 2017 to 2021, while the air quality was at unhealthy levels in the winter months in KMC. Areas with high NDVI value in wards with high priority index were proved to be discontinuous patches of open green spaces with sparse vegetation, which have better potential in mitigating air pollution and UHI. In addition, the average rooftop coverage in wards with a high priority index was approximately 35%, which indicates a large potential for rooftop greenery development.

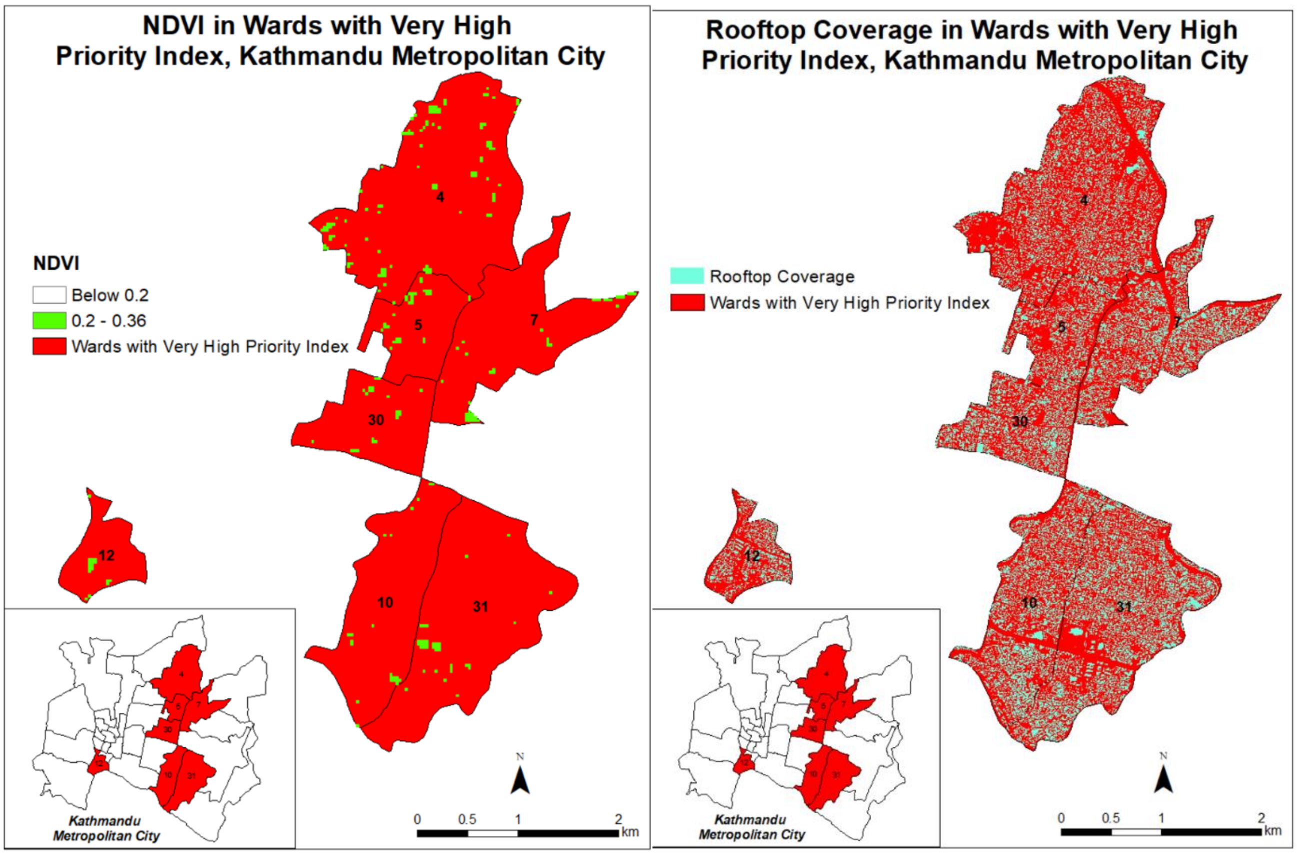

Figure 11 NDVI and rooftop coverage in KMC's wards with very high priority index. Feagure from Bhandari et al., 2022.

Table 5 Rooftop coverage in highly prioritized wards in KMC. Table from Bhandari et al., 2022.

Wards	Rooftop Coverage (%)
4	28.36
5	31.47
7	35.80
10	36.90
12	31.71
30	39.28
31	39.21

This study provides an approach to identify the priority of areas for UGS establishment in highly compact cities. By establishing an index based on the local environment and socio-economic conditions, this approach can provide high-resolution data for decision-makers to develop local UGS development strategies, which can be downscaled to specific communities according to the map illustrations (Figure 11). One key piece of information from this study is that improving the quality of existing UGS is of vital significance. In highly developed areas, such as the city center, it is almost impossible to find available land for new UGS establishments. Therefore, analyzing NDVI is an effective way to evaluate the vegetation condition of existing UGS.

Quantifying the Potential Contribution of Urban Forest to $PM_{2.5}$ Removal in the City of Shanghai, China

Zhang et al., 2021

Shanghai is located on the southern estuary of the Yangtze River, which is the most urbanized city in China with a high population density. With rapid increases in vehicles and biomass burning, air pollution has become a concern in Shanghai, which had a $PM_{2.5}$ level of 39 μg/m^3 in 2017. Although the city government published policies to limit the emissions of major industries in the Yangtze River Delta regions, the significance of urban forests in air pollution mitigation was not recognized. Therefore, Biao Zhang, Zixia Xie, Xinlu She, and Jixi Gao initiated this study to quantify the effect of urban forests on $PM_{2.5}$ removal in Shanghai.

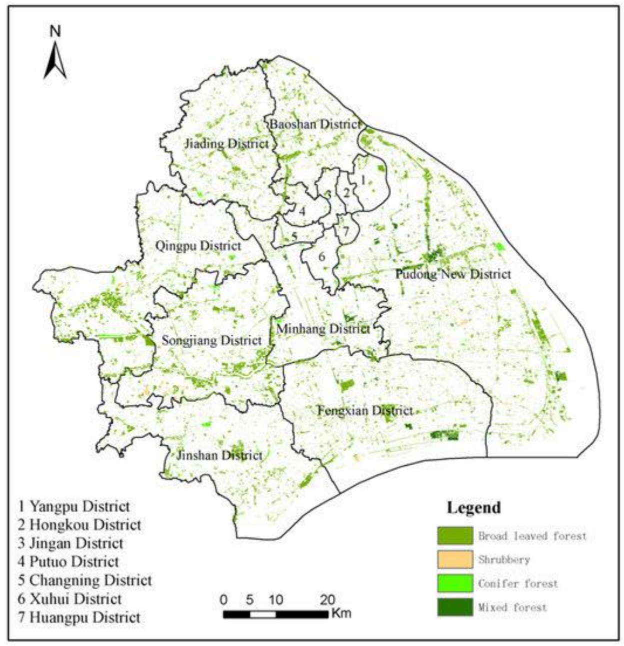

Figure 12 Map of forest communities in Shanghai. Figure from Zhang et al., 2021.

The research team produced a digital forest map to investigate the spatial distribution of forests in Shanghai in 2017 (Figure 12). The UGS in Shanghai is mainly evergreen broad-leaved forest and mixed forest, which occupied approximately 39.1% of the urban area. By 2017, the UGS had rapidly expanded to 136,327 ha, however, the native vegetation species were replaced by more than 1000 non-native species. Then, they calculated the $PM_{2.5}$ removal by urban forest by estimating the total leaf area index and PM deposition velocities according to the average wind speed, resuspension, and precipitation in Shanghai. As the $PM_{2.5}$ concentration is affected by terrain, plant species, and other meteorological factors, they utilized a coupling degree of air purification supply and demand spatially to estimate the spatial coordination of the $PM_{2.5}$ removal effect of urban forests in Shanghai, which was determined by human population density, $PM_{2.5}$ concentration, and removal capacity.

The results show that 874.09 t $PM_{2.5}$ can be removed by the urban forests in Shanghai, and the average retention capacity was 18.94 kg/ha. Comparing the removal capacity of different forest communities, it was found that broad-leaved forest, mixed forest, and conifer forest had relatively the same removal capacity of $PM_{2.5}$ at 18 kg/ha, whereas the shrubbery forest had the lowest removal capacity (Figure 13). Also, due to the high percentage of broadleaved forest among all the urban forests, it had the highest total amount of $PM_{2.5}$ removal as well. In addition, the coupling degree analysis indicates that the spatial patterns of urban forests in Shanghai failed to satisfy the air purification demand, especially in western areas which have the highest $PM_{2.5}$ concentrations. Although, there were high coupling degrees between $PM_{2.5}$ removal and human population over all areas in Shanghai, imbalanced air purification demand and $PM_{2.5}$ removal were still significant in southwest suburban areas.

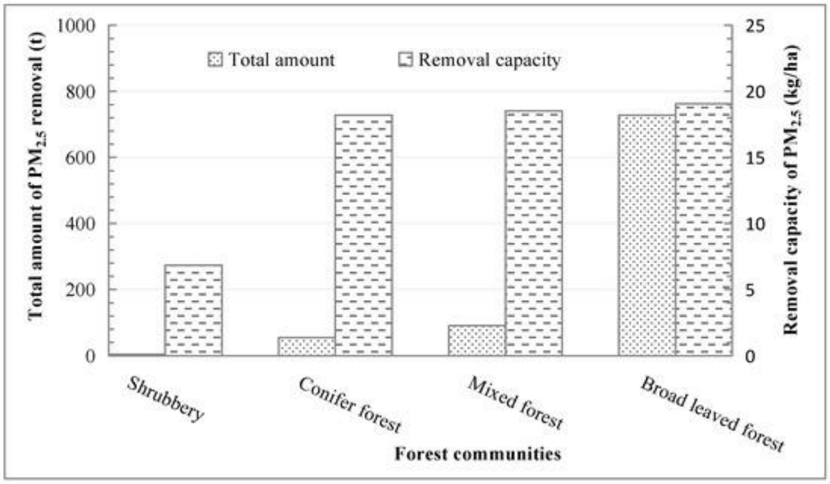

Figure 13 PM $_{2.5}$ removal amount and removal capacity of four forest communities in Shanghai. Figure from Zhang et al., 2021.

Overall, this study showed that urban forests can reduce $PM_{2.5}$ and the total amount of removal was affected by season, forest community types, and locations. It is worth noting that the air purification demand is different in different areas, so the UGS distribution should also be adjusted to satisfy the demand instead of evenly distributed all around the urban area. This study did not discuss how non-local species affect the urban forest $PM_{2.5}$ removal capacity, but non-local species may function not as well as local species in fragile urban ecosystems, thus indirectly affecting the air pollution mitigation service provided by the urban ecosystem. Nevertheless, this study provides a process to quantify the air purification function of UGS in a city-wide range, which can help the city government to evaluate the existing UGS and develop new UGS accordingly.

Main Findings

Based on the existing studies, $PM_{2.5}$ has significant adverse impacts on human health that cause acute and chronic cardiopulmonary diseases, especially among women, children, and elder people. As a positive correlation between green space and $PM_{2.5}$ removal efficiency was found among all the reviewed literature, UGS should be considered as a tool by the government to reduce the health risks caused by air pollution.

To enhance the $PM_{2.5}$ removal effect of UGS, the key is to increase the contact area. Therefore, larger and denser UGS patches can promote PM deposition. In addition to the spatial distribution, the complex structure and plant morphology of UGS help to increase the PM removal efficiency, which can be achieved by selecting appropriate vegetation, UGS configuration, and spatial pattern.

There are limited studies of UGS $PM_{2.5}$ mitigation efficiency based on long-term monitoring data due to the lack of attention in the past decades. Also, most of the current research focusing on the effect of UGS on $PM_{2.5}$ mitigation is from Asian countries, especially China, because China is experiencing serious air pollution issues due to rapid development and urban expansion. The mechanism of PM deposition with different configurations of UGS under different geographic conditions and climate conditions is very complex, therefore, there is a lack of general argument for all the findings about effective UGS structures and spatial patterns in $PM_{2.5}$ removal.

Unfortunately, most studies reviewed in this paper mentioned that UGS is not a solution for air pollution. The mitigation effects of UGS on the PM level are reported to be significant in some areas, but in most cases, they can not offset air pollution. The main efforts should still be controlling the $PM_{2.5}$ pollution sources. However, considering the co-benefits of UGS in providing various ecosystem services which benefit people, the local ecosystem, and in a larger picture, the climate change adaptation, UGS establishment should be prioritized in urban planning and management.

Recommendations

1. **Increase the quality of existing UGS.**

Evaluation of UGS type and distribution is important before taking action. Departments of Environment should utilize spatial data and analyzing tools such as GIS and ENVI to identify the existing UGS. Also, the $PM_{2.5}$ removal capacity of different UGS patches and demand for air purification should be calculated to determine the adjustment strategies. When the $PM_{2.5}$ concentration is beyond the simple green space mitigation threshold, more designs on green space such as tree arrangement and different vegetation configurations are needed to improve the PM removal efficiency. Consultation with specialists is recommended. (Chen et al., 2019)

It is difficult to increase the UGS area in cities with a high density of development, therefore, City governments should maintain the existing UGS, such as parks and forests as much as possible, while seeking for opportunities to increase the vegetation coverage in urban areas. For example, the roadside trees are closer to air pollution and transportation disturbance, which require better maintenance compared with other types of UGS.

2. **Increase the UGS coverage.**

The $PM_{2.5}$ removal effect of UGS increases with increasing green patch parameters and less fragmentation, therefore, an increase in the green space coverage and connectivity should be considered. Although it is challenging to have available open spaces for new UGS with large connected impervious surfaces such as buildings and impermeable pavement in urban areas, innovative green infrastructures (GI) can be implemented to increase the total urban greenery. As shown in Figure 14, except for traditional urban green spaces, such as forests and parks, green roofs, green walls, retention ponds, bioswale, and domestic rain gardens can all contribute to UGS coverage, which also promotes ecosystem services, biodiversity, and human well-being (Russo & Cirella, 2018).

Figure 14 Urban green space designs in compact cities. Figure from Russo & Cirella, 2018.

3. Develop local UGS guidelines.

Local UGS development guideline is important to standardize the process of UGS construction. The guideline should include optimal UGS criteria such as vegetation type, structures, and spatial patterns (Table 3; Table 4). As the $PM_{2.5}$ removal performance of UGS is affected by local conditions such as population, precipitation, wind, pollutant sources, and so on, research on appropriate UGS criteria considering local conditions should be conducted before any adjustment or establishment to maximize the UGS functions. In addition to the physical environmental conditions, the guideline should also provide a methodology for UGS planning for different purposes such as roadside pollution mitigation and indoor air biofiltration (Choi et al., 2021).

4. Enhance collaboration and outreach.

Vertical greenery development needs collaboration and engagement from the government as well as the public. UGS evaluation, adjustment, and establishment are not short-term processes, so the government should build partnerships with non-governmental organizations, such as non-profit organizations, stewardship groups, and other stakeholders to initiate long-term projects or grants to develop UGS. For example, the U.S. Department of Agriculture has initiated the Urban & Community Forestry Program, which is a technical, financial, and educational assistance program, and has built partnerships with more than 30 national groups and more than 150 community tree groups (*Urban and Community Forestry Program*, 2016).

Limitation

In terms of health risks, this paper did not cover all the diseases and risks associated with $PM_{2.5}$. The association between health risks and $PM_{2.5}$ was discussed mainly based on morbidity and mortality inventory analysis. As mentioned above, UGS cannot be treated as the solution for air pollution. The key is still restricting anthropogenic $PM_{2.5}$ sources. Although UGS is recommended to be adopted as a potential method for air pollution considering the co-benefits of green space to human well-being and urban ecosystem, the evaluation of ecosystem services provided by UGS, and cost-benefit analysis were not included in this paper. In addition, implementing green space to mitigate $PM_{2.5}$ may not be applicable for rural areas considering the government capacity, local economic conditions, and different $PM_{2.5}$ sources.

Conclusion and Implications

Short-term and long-term exposure to different levels of $PM_{2.5}$ has become a global concern that causes adverse health effects, increasing morbidity and mortality of various diseases including cardiopulmonary diseases, skin diseases, liver and kidney diseases, and cancer, which is also associated with accelerated aging. The health risks caused by $PM_{2.5}$ exposure are higher in specific groups of people, such as women, children, and elders.

Many studies have shown that UGS has positive impacts on $PM_{2.5}$ removal based on the results of indoor experiments, field experiments, and spatial analysis. The $PM_{2.5}$ removal capacity of UGS has a threshold, which is also dominated by UGS configurations, structure, spatial patterns, climate conditions, and local topography.

UGS has potential in long-term $PM_{2.5}$ deposition but needs multilevel efforts from governments and the public in the process of planning, design, implementation, and maintenance. Following are four recommendations for governments to increase urban $PM_{2.5}$ removal capacity: (1) Increase the quality of existing UGS; (2) Increase the UGS coverage; (3) Develop local UGS guidelines; (4) Enhance multilevel collaboration and outreach.

Although the air purification function of UGS has been widely studied in the past decades, the potential of UGS in $PM_{2.5}$ removal is not well-recognized by the government. This paper provided information about $PM_{2.5}$-induced health risks, and effective UGS properties in reducing $PM_{2.5}$, which can assist in decision-making in urban planning and management strategies. It provides initiatives in evaluating UGS ecosystem services related to human well-being while providing UGS examples and recommendations for multilevel governments to utilize various forms of UGS to reduce air pollution and therefore the rising health risks, especially for developing regions with ongoing urbanization and industrialization.

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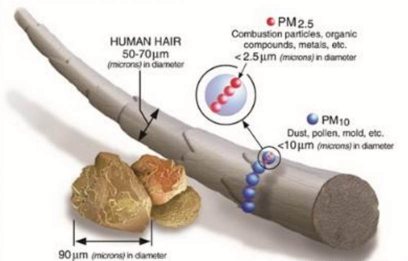
What is PM2.5?

Particulate Matter (PM), also known as particulate pollution, consists of small-size particles suspended in the atmosphere, water, and space. PM2.5 is a fine particle that is equal to or smaller than 2.5 micrometer in diameter.



US EPA, 2016

Where it comes from?

Natural source: wildfires, dust storms, sea spray, etc.

Anthropogenic source: energy production, construction, transportation, industry, power generation, agriculture, manufacturing, etc.

Why it is a problem?

PM2.5 can enter the body through the respiratory system, leading to **increased morbidity and mortality in diseases** such as asthma, respiratory infections, and cancer, as well as accelerated aging. Vulnerable groups including **women, children, and the elderly** are facing higher health risks.

URBAN GREEN SPACE

> **"Urban green space (UGS) can effectively alleviate PM."**
> ——Chen et al., 2019

PM2.5 natural deposition through UGS

Optimal UGS properties

- Increasing UGS size
- More irregular shape
- High vegetation density
- High species diversity
- Less fragmentation

Optimal species properties

Larger crown size
Higher leaf density

Evergreen
Coniferous

More stomata in broadleaf
Less stomata in conifer

Higher leaf roughness
e.g. More irregular edges

Recommendations

- Increase the quality of existing UGS
- Increase the UGS coverage
- Develop local UGS guidelines
- Collaboration and outreach

Scan for full report and more references!!