



Effects of Landscape Tree Species and Their Arrangement on PM_{2.5} Sedimentation - A Case Study of Beijing, China

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ABSTRACT

PM_{2.5}, which refers to particles less than 2.5 μm in diameter, pose great health risks. Previous studies have mainly focused on the relationship between land utilization and air quality. Few studies have discussed the effects of landscape tree species on PM_{2.5} sedimentation and explored reasonable tree species arrangement for PM_{2.5} prevention. This study considered the polluted Beijing in China as the study site. This study investigated the PM_{2.5} sedimentation data of 10 shrub and 11 arbor species to understand the PM_{2.5} holding capacities of the landscape tree species. This study also obtained PM_{2.5} concentration data from 35 air quality monitoring sites. The results of linear regression analysis showed that (1) a closely linear relationship exists between PM_{2.5} concentration from air flow and PM_{2.5} sedimentation of various tree species in different seasons and sampling sites, and that (2) shrub trees possess better PM_{2.5} holding capacities than arbor trees in urban and heavy traffic areas, whereas arbor trees exert obvious effects on preventing PM_{2.5} pollution in rural areas. Thus, the proportion of shrub trees should be reduced in urban and heavy traffic regions, whereas that of arbor trees should be increased in rural areas. This study attempted to solve air pollution through landscape tree arrangement for PM_{2.5} sedimentation. The results of this study could serve as a guide for landscape tree species arrangement and plantation in Beijing and other cities.

INTRODUCTION

Particulate matter (PM) refers to air particles that may be large or dark enough to be seen as soot or smoke or so small that they can only be detected individually under an electron microscope. Many manmade and natural sources emit PM directly or emit other pollutants that react in the atmosphere to form PM. These solid and liquid particles have a wide range of sizes. PM_{2.5}, which refers to air PM less than 2.5 μm in aerodynamic diameter, pose great health risks (Wu et al. 2015). PM_{2.5} are produced from vehicle exhaust, marine aerosols, coal and fuel oil combustion, burning of agricultural wastes, paved road dust, and secondary sulfates, etc. (Pui et al. 2014). The PM_{2.5} pollution in China has caused widespread concern. Large cities such as Beijing and Shanghai have suffered from hazes in years, causing certain social, environmental, and ecological losses (Sun et al. 2006). Thus, this problem in China is too urgent to ignore, considering its fast urbanization and population explosion in the coming decades (Chen et al. 2007).

High PM_{2.5} concentrations are associated with increased rates of cardiovascular and respiratory diseases (Dockery et al. 2009, Pope et al. 2006), which result in death or serious harm. Thus, strategies to decrease PM_{2.5} concentration to reduce its adverse impacts have become a hot issue among researchers (Wu et al. 2015).

Recent studies have mainly focused on the source composition, measurement, simulation, and health risk assessment of PM_{2.5} (Sun et al. 2006, Howell et al. 2000, Saveraid et al. 2001, Shao et al. 2004, Wang et al. 2007, Escobedo et al. 2009, Boyd et al. 2010, Wu et al. 2011, Santos-Filho et al. 2012, Schindler et al. 2013, Yu et al. 2014, Xie et al. 2015) and attempted to determine feasible measures to reduce the negative effects of PM_{2.5}. Several studies have also explored the relationship between air pollution and land use (Wu et al. 2015, Pui et al. 2014, Xie et al. 2015, Uemaa et al. 2015, Kashima et al. 2009, Connors et al. 2013, Tan et al. 2013, Li et al. 2013, Carter et al. 2014, Zhou et al. 2014, Shen et al. 2014). However, few studies have determined the relevance of landscape trees within the city and their PM_{2.5}

prevention effects, as well as the reasonable tree arrangement in city landscape planning (Escobedo et al. 2009, Santos-Filho et al. 2012, Ross et al. 2007, Matsuda et al. 2010, Morani et al. 2011, Hwang et al. 2011, Tallis et al. 2011, Zhang et al. 2011).

Compared with other pollutions such as noise and water, $PM_{2.5}$ poses a greater threat to China; thus, studies on $PM_{2.5}$ are worth exploring. Researchers and designers of landscape science should focus on the influence of tree species rather than different landscape patterns on air pollution (Wu et al. 2015, Howell et al. 2000, Tang et al. 2007). One reason is data can be simply and timely collected; other possible reasons may include the appropriateness of method (Sun et al. 2006, Chen et al. 2007, Dockery 2009, Shao et al. 2004, Wang et al. 2007, Ross et al. 2007, Yang et al. 2005, Henderson et al. 2007, Tang et al. 2007).

Urban landscape trees are used for several purposes, including wind prevention, aesthetics and economic benefits of ecological greening. Thus, the $PM_{2.5}$ holding ability and arrangement of urban landscape trees, especially those in China, must be clarified to understand the relationship between landscape tree species and their effects on air pollution (Boyd et al. 2010, Matsuda et al. 2010, Morani et al. 2011, Hwang et al. 2011, Lee et al. 2009, Buyantuyev et al. 2010, Schwarz 2010, Gromke 2011, Gulliver et al. 2011).

The present study primarily aims to examine the effects of landscape trees on $PM_{2.5}$ pollution in Beijing, China's capital. This city was selected as the study site because of its limited green space (Yu et al. 2014). The results of this study may serve to improve urban landscape planning and management, and discover measures for addressing air quality problems in the future.

MATERIALS AND METHODS

Study area: Beijing is located in the northeast of the North China Plain (about $115^{\circ}25'0''-117^{\circ}30'0''E$, $39^{\circ}28'0''-41^{\circ}25'0''N$) with a population of approximately 20.693 million and a total area of 16,410.54 km^2 . The climate in this city belongs to a continental monsoon climate with apparent seasons (Wu et al. 2015, Shen et al. 2014). The average temperature is $12.3^{\circ}C$, and the annual precipitation is approximately 570mm. In recent years, Beijing has been undergoing rapid urbanization, which is accompanied by frequent haze events and high pollutant concentrations in this city.

Data acquisition: (1) The $PM_{2.5}$ concentration of 35 monitoring sites (including transportation pollution sampling sites, inner city pollution sampling sites, regional background control sites, and suburb pollution sampling sites) in Beijing was obtained from the website of the Beijing Environmen-

tal Monitoring Center (<http://zx.bjmemc.com.cn/>) (Fig. 1). We used March, April and May; June, July and August; September, October and November; and December, January and February to represent spring, summer, autumn and winter, respectively. Data from 2015 were collected. (2) The $PM_{2.5}$ sedimentation of 10 shrub and 11 arbor trees was obtained using a portable hand-held $PM_{2.5}$ detector (Lighthouse, 3016IAQ, USA). We measured the 0, 15 and 30 cm $PM_{2.5}$ sedimentation values of shrub trees and 0, 30 and 60 cm $PM_{2.5}$ sedimentation values of arbor trees (Equations (1) and (2)). Each spot was sampled three times (Equations (3) and (4)). The comprehensive $PM_{2.5}$ sedimentation value of each pattern (landscape tree species arrangement) was calculated below (Equations (5), (6), (7) and (8)). Fig. 2 shows that $PM_{2.5}$ particles were carried by wind. According to particle size (>0.5 mm movement status: creep; $0.05-0.5$ mm saltation; <0.05 mm suspension), the mass of the $PM_{2.5}$ particles flew in air. Then, $PM_{2.5}$ particles concentrated to the ground and again were blown up repeatedly. Moreover, landscape tree species have certain abilities to prevent $PM_{2.5}$ pollution, and $PM_{2.5}$ can be deposited within the trees. Such a movement process can be referred as sedimentation. However, $PM_{2.5}$ particles remain within the forest and cannot be effectively prevented because of the loose structure of the forest and little wind. Thus, shrubs could theoretically hold the fine particles within the trees, whereas arbor trees could stop particles in the windward side. To verify this theory, experiments were conducted to prove the ideas above.

$$y_s = \frac{h_1 y_{1PM_{2.5}} + h_2 y_{2PM_{2.5}} + h_3 y_{3PM_{2.5}}}{3} \quad \dots(1)$$

Where y_s is the $PM_{2.5}$ sedimentation value of shrub trees, h_1 is 0 cm, h_2 is 15 cm, h_3 is 30 cm, and $y_{1,2,3}$ is the measured $PM_{2.5}$ sedimentation value of shrub trees.

$$y_a = \frac{h_1 y_{1PM_{2.5}} + h_2 y_{2PM_{2.5}} + h_3 y_{3PM_{2.5}}}{3} \quad \dots(2)$$

Where y_a is the $PM_{2.5}$ sedimentation value of arbor trees, h_1 is 0 cm, h_2 is 30 cm, h_3 is 60 cm, and $y_{1,2,3}$ is the measured $PM_{2.5}$ sedimentation value of arbor trees.

$$y_{s-c} = \frac{y_{s1} + y_{s2} + y_{s3}}{3} \quad \dots(3)$$

Where y_{s-c} is the calculated $PM_{2.5}$ sedimentation value of shrub trees, and $y_{s1,2,3}$ is the $PM_{2.5}$ sedimentation value of shrub trees (according to the calculation result of Eq. (1)).

$$y_{a-c} = \frac{y_{a1} + y_{a2} + y_{a3}}{3} \quad \dots(4)$$

Where y_{a-c} is the calculated $PM_{2.5}$ sedimentation value of arbor trees, and $y_{a1,2,3}$ is the $PM_{2.5}$ sedimentation value of

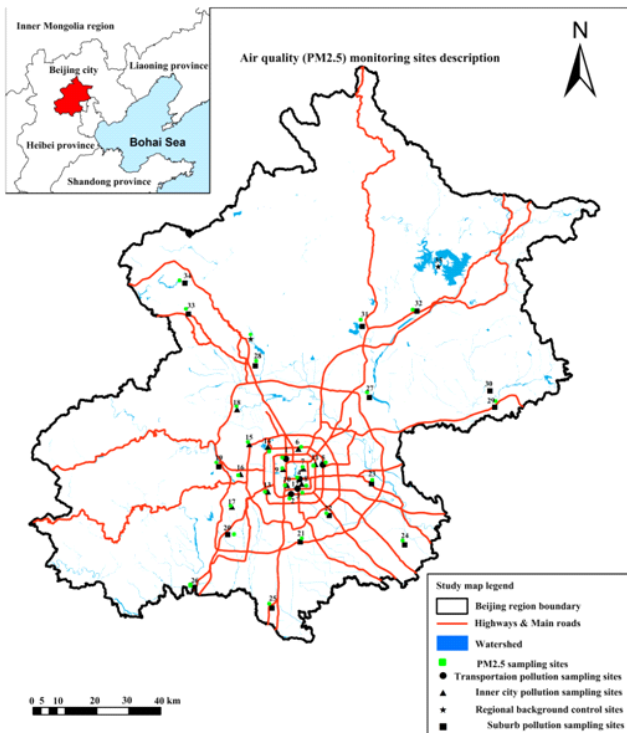


Fig. 1: Classification and distribution of air quality monitoring sites in Beijing area. Note: this original image was from research paper, doi:10.1371/journal.pone.0142449 (Wu et al. 2015)

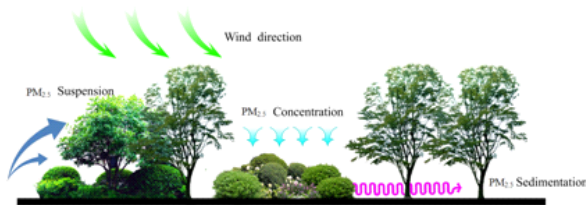


Fig. 2: Sketch map of PM_{2.5} movement track.

arbor trees (according to calculation result of Eq. (2)).

$$y_{original} = \frac{X_{1area}y_{scPM_{2.5}} + X_{2area}y_{acPM_{2.5}}}{X_{total} - area} \quad \dots(5)$$

Where $y_{original}$ is calculated by the PM_{2.5} sedimentation value in existing pattern, and x_{narea} is the area occupied by each tree species, $n=1, 2, 3, \dots$

$$y_{optimized} = \frac{X_{1area}y_{scPM_{2.5}} + X_{2area}y_{acPM_{2.5}}}{X_{total} - area} \quad \dots(6)$$

Where $y_{optimized}$ is the optimized PM_{2.5} sedimentation data. It also takes the following form:

$$y_{optimized} = \frac{X_{1area}y_{sc1PM_{2.5}} + X_{2area}y_{sc2PM_{2.5}}}{X_{total} - area} \quad \dots(7)$$

Where $y_{ac1,2}$ is the PM_{2.5} sedimentation value of shrub trees 1 and 2.

$$y_{optimized} = \frac{X_{1area}y_{ac1PM_{2.5}} + X_{2area}y_{ac2PM_{2.5}}}{X_{total} - area} \quad \dots(8)$$

Where $y_{ac1,2}$ is the PM_{2.5} sedimentation value of arbor trees 1 and 2.

Statistical analysis: The annual and seasonal average concentrations and sedimentations of PM_{2.5} in 35 and 34 sites were determined. The statistical analysis includes linear analysis by using version 21.0 of SPSS software (IBM Inc. NC, USA). Simple calculations on tree arrangement were conducted using Excel (Microsoft Inc. SE, USA). Other data processing and plotting were completed with software Origin 9.0 (Origin Lab Inc., Northampton, MA, USA).

RESULTS AND ANALYSIS

Descriptive statistics: All 35 sites were valid samples during 2015. The annual average concentration in 35 sites was 83.04 $\mu\text{g}/\text{m}^3$, which was three times higher than the WHO (World Health Organization) *Level 1* Interim Target of 35 $\mu\text{g}/\text{m}^3$ (Wu et al. 2015). The maximum value of annual average concentration was 71.00 $\mu\text{g}/\text{m}^3$ in the regional background control sites, 118.00 $\mu\text{g}/\text{m}^3$ in the transportation pollution sampling sites, 107.36 $\mu\text{g}/\text{m}^3$ in the inner city pollution sampling sites, and 109.36 $\mu\text{g}/\text{m}^3$ in the suburb pollution sampling sites, whereas the minimum value was 22.64 $\mu\text{g}/\text{m}^3$ in the regional background control sites, 71.00 $\mu\text{g}/\text{m}^3$ in the transportation pollution sampling sites, 79.00 $\mu\text{g}/\text{m}^3$ in the inner city pollution sampling sites, and 75.00 $\mu\text{g}/\text{m}^3$ in the suburb pollution sampling sites. Fig. 3 shows that the PM_{2.5} concentration in all seasons was persistently increased. The average concentrations in the four seasons were 69.54, 80.46, 89.87, and 100.67 $\mu\text{g}/\text{m}^3$, respectively. The average peak concentrations in spring, summer, autumn, and winter were 81.21, 97.47, 107.16, and 117.74 $\mu\text{g}/\text{m}^3$, respectively. Significant differences were observed between different seasons and sites ($P < 0.01$) (data not shown). The spatiotemporal discrepancies of PM_{2.5} concentration in Beijing were evident.

PM_{2.5} concentration and sedimentation correlation analysis: The relationship between all (data include seasons and sites) PM_{2.5} concentration (sources) and PM_{2.5} sedimentation (sinks) was characterized through linear correlation analysis (Fig. 4). The result indicates that the PM_{2.5} sedimentation of plants is closely related to the PM_{2.5} concentration of air

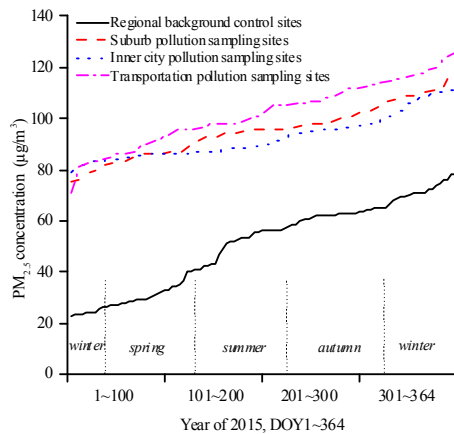


Fig. 3: Seasonal pattern of all categories of 35 sites.

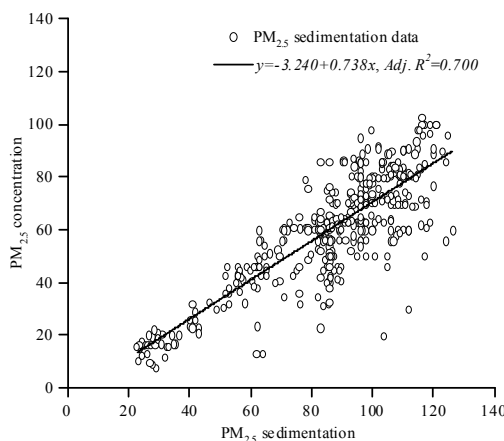


Fig. 4: Correlation between concentration and sedimentation of $PM_{2.5}$ analysis.

flow (Adjust R^2 value equals to 0.700). In other words, the trees have effective $PM_{2.5}$ holding capacities to prevent $PM_{2.5}$ pollution.

Effects of landscape tree species on $PM_{2.5}$ sedimentation:

To investigate the abilities of the different tree species for $PM_{2.5}$ sedimentation, we surveyed typical trees (10 shrubs and 11 arbor trees) in all seasons and sites. The obtained results (Table 1) indicate that the arbor trees have a greater $PM_{2.5}$ sedimentation capability than the shrub trees in all seasons and that minimal differences can be found between the shrubs but not between the arbor trees. Among the shrub trees, *Syringa reticulata* serves in $PM_{2.5}$ prevention, whereas *Ulmus pumila* participates in $PM_{2.5}$ sedimentation. We further investigated four air quality monitoring sites. As given in Table 1, the shrubs and arbor trees display no significant differences in urban and traffic sites, but arbor trees in rural areas exhibit great advantages in preventing $PM_{2.5}$ pollution. Among the shrub trees, *Forsythia geraldiana* is superior to

the other trees, whereas *Ulmus pumila* is advantageous over the other tree species.

As we studied above, arbor trees can hold a mass of $PM_{2.5}$ particles in rural areas, but such an effect is not obvious in urban areas compared with shrubs. Meanwhile, their loose structure (e. g. two trees are planted in distance) renders $PM_{2.5}$ easy to float at a long time and hard to settle in the atmosphere. Thus, a persistent and widespread $PM_{2.5}$ pollution event would not be reduced.

Effects of landscape tree species arrangement on $PM_{2.5}$ sedimentation:

We adjusted tree species configuration. Tree forms, specific tree structure, and other aspects were not considered because of their complexities and unpredictability. The adjusted landscape tree species are listed in Table 2. To reach the purposes, tree species arrangement was optimized on the basis of the actual demand of $PM_{2.5}$ reduction observed in the monitoring sites. As given in Table 2, the proportion of shrub trees was reduced in rural areas, whereas that of arbor trees was increased in urban areas. Finally, we compared the $PM_{2.5}$ sedimentation values between the original and optimized data (Fig. 5). The simulation results are significantly higher than the original data and air quality sampling data, especially in urban areas.

The concentration of $PM_{2.5}$ is controlled by multiple factors, such as wind, air temperature, precipitation, and traffic conditions (Nolte et al. 2001, Buczyńska et al. 2014, Du et al. 2014). The present study focused on landscape tree species pattern and attempted to give proper suggestions on their arrangement.

The results showed differences among the four seasons and sampling sites. $PM_{2.5}$ pollution is more severe in autumn and winter than in spring and summer partly because of special crop land use. In autumn, the crop could produce smoke by straw burning, either in Beijing or surrounding regions, making it significant in $PM_{2.5}$ emission. This process would last into spring of the next year. Bad $PM_{2.5}$ phenomenon also occurs in winter because of winter heating and firework setting (Wu et al. 2011, Santos-Filho et al. 2012, Schindler et al. 2013, Connors et al. 2013, Tan et al. 2013, Li et al. 2013, Morani et al. 2011, Hwang et al. 2011, Tallis et al. 2011, Zhang et al. 2011, Gulliver et al. 2011, Dzierżanowski et al. 2011, Tu 2011, Zhou et al. 2011, Li et al. 2012, Aowicki et al. 2012, Nowak et al. 2013). Different air quality sampling sites have different $PM_{2.5}$ concentrations in suburb areas, which could be a main source because of the soil or sand dust caused by wind erosion, especially in open fields, where sand storms frequently occur. However, wind is relatively small in urban areas (including traffic areas), and mass of $PM_{2.5}$ particles is prevented by high-rise buildings; such a harm is less severe. However, explaining

Table 1: Effects of landscape tree species on PM_{2.5} sedimentation in different seasons and sites.

LandscapeTree species	PM _{2.5} sedimentation capability (µg/m ³)				Air quality monitoring sites nearby sampling (µg/m ³)				
	Spring	Summer	Autumn	Winter	Average	CV sites	Suburb sites	Urban sites	Traffic sites
Shrub	-	-	-	-	-	-	-	-	-
<i>Prunus × cistena</i>	14.23±0.01	21.63±0.03	30.32±0.32	35.14±0.01	25.33	-	8.63±0.01	28.56±0.00	26.64±0.05
<i>Hibiscus syriacus</i>	15.62±0.03	22.61±0.01	32.46±0.21	39.41±0.01	27.52	21.32±0.31	12.63±0.01	28.62±0.03	30.64±0.45
<i>Syzygium romaticum</i>	16.23±0.05	23.15±0.04	33.45±0.03	40.36±0.31	28.30	22.65±0.43	13.54±0.02	29.63±0.41	32.45±0.34
<i>Cercis racemosa</i>	13.62±0.01	18.63±0.01	28.41±0.11	33.47±0.11	23.53	-	-	18.63±0.06	22.64±0.21
<i>Euonymus fimbriatus</i>	16.23±0.04	18.25±0.01	32.54±0.32	36.41±0.04	25.86	12.32±0.03	18.42±0.00	22.63±1.01	28.64±0.04
<i>Magnolia liliiflora</i>	16.32±0.02	22.85±0.06	35.63±0.21	38.41±0.06	28.30	-	15.63±0.05	35.23±0.54	37.42±0.00
<i>Syringa reticulata</i>	19.63±0.01	23.56±0.08	36.48±0.21	40.32±0.06	30.00	15.63±0.05	20.63±0.01	40.89±0.56	46.58±0.21
<i>Cotinus coggygia</i>	15.63±0.04	22.87±0.01	36.54±0.45	41.25±0.32	29.07	-	-	45.61±0.88	50.63±0.45
<i>Forsythia giraldiana</i>	16.32±0.05	22.74±0.07	33.65±0.01	37.56±0.12	27.57	16.36±0.07	20.63±0.01	52.63±0.75	58.96±2.34
<i>Jasminum nudiflorum</i>	16.39±0.05	26.39±0.01	37.89±0.02	40.63±0.45	30.32	-	28.96±0.00	44.63±0.32	47.89±1.23
Arbor	-	-	-	-	-	-	-	-	-
<i>Magnolia heptapeta</i>	18.63±0.04	30.36±0.06	68.63±0.61	84.23±1.01	50.46	30.63±0.08	40.86±0.41	30.51±0.04	27.98±0.00
<i>Cerasus serrulata</i>	26.36±0.04	38.95±0.03	70.86±0.56	100.63±3.09	59.20	46.63±0.32	76.56±0.21	40.63±0.07	20.74±0.01
<i>Amygdalus davidiana</i>	30.45±0.03	45.75±0.03	85.63±0.78	106.34±3.04	67.04	52.63±0.45	80.56±0.98	36.56±0.03	33.46±0.01
<i>Armeniaca sibirica</i>	22.63±0.02	20.14±0.01	50.54±0.43	86.78±0.81	45.02	37.86±0.67	86.54±1.01	42.31±0.02	25.63±0.54
<i>Amygdalus persica</i>	26.35±0.01	24.67±0.01	60.61±0.56	85.41±1.01	49.26	40.23±0.56	90.54±1.04	47.54±0.43	30.51±0.78
<i>Prunus cerasifera</i>	22.48±0.01	47.89±0.11	77.52±0.77	96.56±9.45	61.11	34.56±0.67	100.54±3.04	43.25±0.32	24.87±0.00
<i>Cerasus cerasoides</i>	18.47±0.01	46.93±0.31	80.65±0.78	102.64±6.01	62.17	40.63±0.32	85.64±1.04	50.64±1.01	34.65±0.04
<i>Ludwigia hyssopifolia</i>	20.41±0.04	50.47±0.51	79.65±0.87	94.63±4.05	61.29	33.46±0.11	77.46±6.06	68.96±3.04	40.61±0.45
<i>Acer palmatum</i>	23.41±0.05	61.25±0.41	88.69±0.65	114.63±6.06	72.00	39.65±0.01	84.65±3.04	65.74±2.01	50.64±0.78
<i>Lonicera maackii</i>	21.63±0.01	77.63±0.034	96.21±0.67	120.63±12.03	79.02	29.64±0.11	86.53±6.02	60.32±3.21	23.54±0.01
<i>Ulmus pumila</i>	23.56±0.012	85.63±0.91	100.41±0.34	122.41±10.45	83.00	31.25±0.56	95.41±1.03	52.63±3.03	36.54±0.05

all different variables between seasons and sites was difficult because of the complicated influences of other factors, such as meteorological factors and human interference. Nevertheless, certain and stable regularities are still presented.

Furthermore, we could determine the effect of landscape tree species on PM_{2.5} directly. The linear regression model showed that landscape tree species patterns correlate with PM_{2.5} concentration. The coefficient of source PM_{2.5} pollution and sink landscape tree species pattern in the simple linear relationship model is 0.7 because the coefficient is positive in the model. In fact, the role of trees on PM_{2.5} is easy to understand. In general, the land use type most frequently associated with PM_{2.5} concentration is vegetation, followed by water body and cropland, and then bare land and construction land (Kong et al. 2010). Vegetation mainly absorbs particulate matter through leaves by dry and wet deposition to reduce ambient PM_{2.5} concentration (Wu et al. 2015). Tree planning has been introduced by the Beijing municipal government as a major measure to improve air quality (Sun et al. 2006). Yang et al. 2005 used an urban forest effects model to explore the effect of urban forest on air pollution. Results showed that trees in central Beijing removed 1261.4 tons of pollutants, most of which were particulate matter. Research in 10 U.S. cities also showed similar results in that the amount of PM_{2.5} removed by trees

ranged from 4.7 to 64.5 tons annually, saving about 60 million dollars in healthcare costs and mortalities of New York State because of cleaner air (Nowak et al. 2013). Gromke 2011 found using a new vegetation model that trees negatively influence pollutant dispersion. Dzierzanowski et al. (2011) further focused on the various functions of different tree species on particulate matter. The results of the above studies revealed that vegetation significantly influences PM_{2.5} mitigation, which agrees with the results of this study.

The percentage of specific areas could be changed to solve PM_{2.5} problems thoroughly. For example, sink landscape can absorb PM_{2.5}, and construction land can produce particulate matter; altering their areas could increase or decrease PM_{2.5} (Wu et al. 2015). According to the "Beijing urban planning project," the possibility to increase greening area or decrease construction land area is small (Wu et al. 2015). Thus, the positive role of landscape tree species configuration should be maximized to solve serious haze problems. However, few studies have investigated the effect of configuration on PM_{2.5}. In the present study, 10 shrubs and 11 arbor trees were selected, the PM_{2.5} sedimentation capability of each tree was analyzed, and then the configuration of landscape trees to ease haze was optimized. We only focused on tree arrangement by simple calculations and concluded that shrub trees can effectively prevent fine particles in urban areas while arbor trees can significantly re-

Table 2: List of before and after landscape tree species arrangement.

Site	Original landscape tree species			Adjusted landscape tree species		
	Suburb sites	Urban sites	Traffic sites	Suburb sites	Urban sites	Traffic sites
1	-	-	A ₁ B ₁ , A ₂ B ₂	-	-	A ₁ A ₁ , A ₃ A ₇
2	-	-	A ₅ B ₁₀ , A ₇ B ₈	-	-	A ₅ A ₈ , A ₇ A ₈
3	-	-	A ₃ B ₉ , A ₃ B ₆	-	-	A ₃ A ₃ , A ₃ A ₇
4	-	-	A ₃ B ₉ , A ₅ B ₆	-	-	A ₃ A ₂ , A ₅ A ₁
5	-	-	A ₅ B ₉ , A ₂ B ₆	-	-	A ₅ A ₃ , A ₂ A ₁₀
6	-	A ₃ B ₁ , A ₃ B ₄	-	-	A ₃ A ₈ , A ₃ A ₄	-
7	-	A ₅ B ₈ , A ₂ B ₇	-	-	A ₅ A ₈ , A ₂ A ₅	-
8	-	A ₅ B ₈ , A ₄ B ₅	-	-	A ₅ A ₉ , A ₄ A ₂	-
9	-	A ₈ B ₅ , A ₇ B ₉	-	-	A ₈ A ₈ , A ₇ A ₉	-
10	-	A ₆ B ₇ , A ₄ B ₈	-	-	A ₆ A ₈ , A ₄ A ₉	-
11	-	A ₄ B ₉ , A ₂ B ₃	-	-	A ₄ B ₉ , A ₂ A ₆	-
12	-	A ₆ B ₃ , A ₂ B ₆	-	-	A ₆ A ₉ , A ₂ B ₆	-
13	-	A ₇ B ₉ , A ₃ B ₈	-	-	A ₇ B ₉ , A ₃ A ₈	-
14	-	A ₄ B ₈ , A ₉ B ₂	-	-	A ₄ A ₅ , A ₆ A ₂	-
15	-	A ₆ B ₇ , A ₃ B ₅	-	-	A ₆ B ₇ , B ₄ B ₅	-
16	-	A ₂ B ₃ , A ₆ B ₈	-	-	B ₂ B ₃ , A ₆ B ₈	-
17	-	A ₅ B ₈ , A ₂ B ₇	-	-	A ₅ A ₈ , A ₂ A ₉	-
18	-	A ₆ B ₇ , A ₄ B ₆	-	-	A ₆ A ₇ , A ₄ B ₆	-
19	A ₂ B ₃ , A ₅ B ₆	-	-	B ₂ B ₅ , B ₅ B ₆	-	-
20	A ₁₀ B ₆ , A ₆ B ₉	-	-	B ₁₁ B ₆ , B ₄ B ₉	-	-
21	A ₆ B ₇ , A ₇ B ₆	-	-	B ₅ B ₇ , B ₃ B ₆	-	-
22	A ₅ B ₉ , A ₃ B ₇	-	-	B ₅ B ₉ , A ₄ B ₇	-	-
23	A ₇ B ₇ , A ₃ B ₁	-	-	A ₅ B ₇ , B ₃ B ₁	-	-
24	A ₇ B ₃ , A ₅ B ₇	-	-	B ₁ B ₃ , A ₈ B ₇	-	-
25	A ₆ B ₈ , A ₂ B ₇	-	-	B ₆ B ₈ , A ₂ B ₇	-	-
26	A ₇ B ₈ , A ₂ B ₉	-	-	B ₂ B ₈ , A ₇ B ₉	-	-
27	A ₆ B ₃ , A ₁ B ₈	-	-	B ₁ B ₃ , A ₁ B ₈	-	-
28	A ₄ B ₉ , A ₂ B ₈	-	-	B ₄ B ₉ , B ₆ B ₈	-	-
29	A ₂ B ₈ , A ₁ B ₆	-	-	B ₂ B ₈ , B ₃ B ₆	-	-
30	A ₆ B ₃ , A ₄ B ₉	-	-	A ₁ B ₃ , B ₈ B ₉	-	-
31	A ₇ B ₆ , A ₄ B ₃	-	-	B ₂ B ₆ , A ₅ B ₃	-	-
32	A ₅ B ₃ , A ₁ B ₆	-	-	A ₅ B ₃ , A ₁ B ₆	-	-
33	A ₇ B ₇ , A ₁ B ₇	-	-	B ₁ B ₇ , A ₁ B ₁₁	-	-
34	A ₈ B ₉ , A ₃ B ₆	-	-	B ₈ B ₉ , B ₃ B ₈	-	-

Note: A₁ presents *Prunus × cistena*, A₂ presents *Hibiscus syriacus*, A₃ presents *Syzygium romaticum*, A₄ presents *Cercis racemosa*, A₅ presents *Euonymus fimbriatus*, A₆ presents *Magnolia lilijflora*, A₇ presents *Syringa reticulata*, A₈ presents *Cotinus coggygria*, A₉ presents *Forsythia giraldiana*, A₁₀ presents *Jasminum nudiflorum*, B₁ presents *Magnolia heptapeta*, B₂ presents *Cerasus serrulata*, B₃ presents *Amygdalus davidiana*, B₄ presents *Armeniaca sibirica*, B₅ presents *Amygdalus persica*, B₆ presents *Prunus cerasifera*, B₇ presents *Cerasus cerasoides*, B₈ presents *Ludwigia hyssopifolia*, B₉ presents *Acer palmatum*, B₁₀ presents *Lonicera maackii*, B₁₁ presents *Ulmus pumila*

duce PM_{2.5} concentration in rural areas. Such processes are too complex; thus, future studies should focus on these processes and provide further information in the future.

The present study analyzed data from 35 sites because the number of monitoring sites in Beijing cover all important areas. However, typical areas may have been overlooked. Moreover, the mechanisms and processes responsible for the effects of landscape tree species on PM_{2.5} pollution and seasonal differences could not be clearly identified from the statistical calculations applied in this study. However, air pollution data are influenced by time and location; thus, the timeliness and stability of the results were not easily assessed. PM_{2.5} is controlled by many factors that are difficult to measure (Wu et al.

2015). Xie et al. (2015) conducted a case study in 31 Chinese cities and found that PM_{2.5} concentration is related to chemical components such as SO₂, NO₂, CO, and O₃. Recent research has considered meteorological factors, such as humidity, wind speed, and wind direction (Sun et al. 2006, Howell et al. 2000, Zhou et al. 2014, Dzierjanowski et al. 2011, Nowak et al. 2013). Other research focused on the spatiotemporal characteristics of the effects, the impact scale and intensity, and mechanisms of seasonal differences (Wu et al. 2015). With the rapid development of technique and data sharing around the world, potential solutions could be expected (Wu et al. 2015). Such experiments would definitely be included in our further studies and research directions.

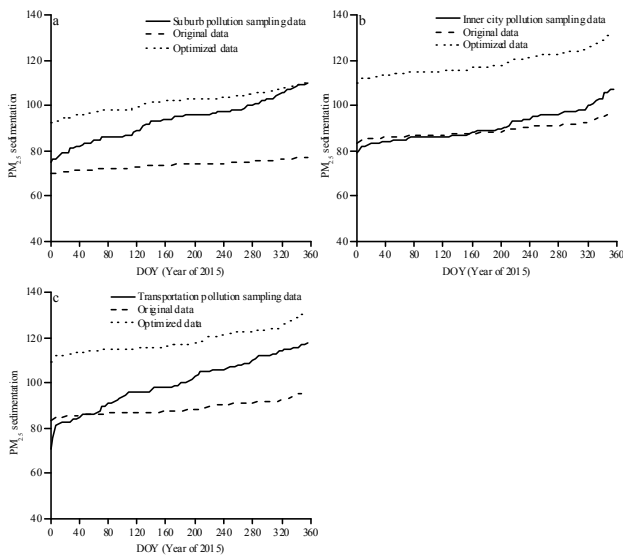


Fig. 5: Comparison of PM_{2.5} sedimentation values of before and after landscape tree species arrangement.

CONCLUSION

Among all the pollution sources, PM_{2.5} is the core pollutant of haze formation. These problems are faced in China, particularly in Beijing and Shanghai. To solve this increasingly problematic issue, we quantitatively investigated the effects of urban landscape tree species patterns on PM_{2.5} concentration with Beijing as the study site and realized a reasonable arrangement of tree species. Our study yielded the following conclusions:

1. Vegetation can absorb particulate matter to reduce pollutants. Among all landscape tree species composition, a close relationship exists between PM_{2.5} concentration from air flow and PM_{2.5} sedimentation of various tree species in different seasons and sampling sites.
2. Shrub trees have greater PM_{2.5} holding capacities than arbor trees in urban areas (heavy traffic areas), whereas arbor trees exert better effects than shrub trees in preventing PM_{2.5} pollution in rural areas.
3. The proportion of shrub trees should be reduced in urban and heavy traffic regions, whereas that of arbor trees should be increased in rural areas.

We studied the effect of each landscape tree species on PM_{2.5} holding capacity and explored reasonable tree species arrangement for the first time. However, this study is limited by tree structure, and typical land use was not considered. These limitations should be overcome in our future studies. Overall, the above results can provide additional useful information for better urban landscape planning and management.

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