

Effect of Plant Community Structure and Road Greenbelt Width on PM_{2.5} Concentration

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Received 11 January 2017; Accepted 19 March 2017

Abstract

Road greenbelts can reduce the concentration of airborne fine particulate matter (PM_{2.5}). This effect is highly sensitive to the community structure of vegetation and greenbelt widths. To determine the optimal community structure and appropriate greenbelt width, PM_{2.5} concentrations were tested in four greenbelts with arbor–shrub–grass and arbor–grass plant communities of different greenbelt widths (0, 5, 10, 15, and 20 m) in Suzhou Industrial Park. The daily change law of PM_{2.5} concentration and the effects of community structure and greenbelt width on the reduction of PM_{2.5} concentration were analyzed. Results demonstrated that the road greenbelts significantly reduced the PM_{2.5} concentration. The PM_{2.5} concentration in the road greenbelts was low in the morning and evening. At daytime, the PM_{2.5} concentration in the arbor–shrub–grass community showed two peaks and one valley, and the PM_{2.5} concentration in the arbor–grass community presented a single peak. The PM_{2.5} reduction rate of the greenbelts significantly increased with the increase in greenbelt width. However, the reduction rate decreased gradually when the greenbelt width exceeded 15 m. The greenbelts with different community structures reduced the PM_{2.5} concentration to different extents. When the greenbelt was narrow (≤ 5 m), the arbor–shrub–grass community achieved a high average PM_{2.5} reduction rate. When the greenbelt was wide (5 m to 20 m), the arbor–grass community reduced the PM_{2.5} concentration significantly. When the greenbelt width exceeded 20 m, the arbor–shrub–grass community with reasonable allocation reduced the PM_{2.5} concentration more than the arbor–grass community did. The effects of road greenbelt width and plant community on PM_{2.5} concentration were discussed simultaneously for the first time in this study.

Keywords: road greenbelt, PM_{2.5}, greenbelt width, community mode

1. Introduction

Many moderate, serious, and extremely serious hazes have occurred recently in China. Haze, which has a long duration, large area of influence, and high pollution concentration, has attracted considerable attention from the Chinese government and become a major health concern in the public. Haze is composed of sulfur dioxide, nitric oxygen, and inhalable particles. The first two components are gaseous pollutants, and the last one is fine particulate matter, which intensifies haze pollution. These components combine with fog and make the sky gloomy instantly. Fine particulate matter, also known as PM_{2.5}, refers to aerodynamic particulates in air with a diameter smaller than 2.5 μm [1]. PM_{2.5} has elicited much research attention due to its difficult settlement, large scope of influence, and high control difficulty. By investigating the greenbelt surrounding 39 schools in Barcelona, Spain, Dadvand et al. [2] monitored the concentration of pollutants (including PM_{2.5}) in relation to transportation in the schools and surrounding areas. Yli-Pelkonen et al. [3] used a passive sampler in the surrounding areas of roads in Helsinki City, Finland, and investigated the

relationship between five air pollutants and surface vegetation. Nowak et al. [4] simulated the effects of trees on PM_{2.5} concentration and human health in 10 cities in the United States. Niu et al. [5] detected aerosol levels in air above the northwestern desert in China by installing an APS-3310 laser aerodynamic aerosol particle spectrometer on a plane. Ren et al. [6] studied air particulate matter and microorganism concentrations in different types of forest lands and surrounding roads in the Great Capital of Yuan Dynasty Relics Park in Beijing. Guo et al. [7] observed PM_{2.5} mass concentration with a multifunction precision laser dust instrument in Beijing Forestry University, Olympic Forest Park, and Lufeng National Forest Park. The surrounding main traffic arteries were used as the control group, and the daily variation law of PM_{2.5} mass concentration in different urban greenbelts was analyzed. These research results demonstrated that plants can effectively adsorb and eliminate particulates in air, accelerate PM_{2.5} settlement, and reduce PM_{2.5} concentration. Xiao et al. [8], Li et al. [9], and Cheng et al. [10] performed comparative studies on PM_{2.5} concentration in different greenbelts and obtained similar conclusions.

Therefore, increasing the vegetation biomass and optimizing the plantation structure in large cities are effective means to absorb dust and reduce the frequency of haze occurrence. Given the inconsistent leaf areas, leaf

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structures, branch structures, and 3D green biomasses of different plants, different community structures possess different capacities to reduce fine particulate matter. Tong et al. [11] quantized the effects of trees on suspending particulates in air. They indicated that if such differences are not understood, inappropriately planting trees would intensify air pollution. Providing large green area along urban roads, greenbelts can reduce pollution produced by traffic. This effect is dependent on the biological structure of vegetation community (e.g. plant species and density), plant layout, and greenbelt width. Therefore, it is important to scientifically plan, design and manage urban road greenbelt for maximum benefit. This can only be achieved when this dependency is thoroughly understood. Hagler et al. [12] selected three monitoring points in the center of North Carolina and tested more than 50 quadrants. The variations in the concentrations of superfine particulate matter in roads, surrounding areas, and road greenbelts were tested. The results demonstrated that the reduction of superfine particulate matter is related to the density and vegetation continuity within the road greenbelts. Chen et al. [13] evaluated the effects of vegetation species, plantation structure, and wind on PM concentration in Beijing and local streets and discovered that shrub and arbor-grass community structures are highly effective in reducing horizontal PM concentrations. Li et al. [14] estimated the PM_{2.5} reduction capabilities of three green lands with typical plant community types near Sihuan Main Street in Beijing and found that multi-layer green lands are superior to single-layer green lands with low canopy densities in terms of PM_{2.5} reduction. Under unpolluted weather conditions, greenbelts 26 and 36 m wide reduce PM_{2.5} concentrations effectively. Zhang and Qin [15] estimated the effects of the allee tree community in Chongqing on PM_{2.5} concentrations and revealed the order of PM_{2.5} dust-detaining capacities of road greenbelts with different community allocations. The order is arbor-grass community > arbor community > lawn community > arbor-shrub community > arbor-shrub-grass community > shrub-grass community. The optimal street tree greenbelt width is 6 m. Nevertheless, no agreement has been established about the best community structure and greenbelt width along roads. Previous research results cannot be directly applied in practice. The author claims that the PM_{2.5} reduction rate varies significantly due to the complicated production and reduction mechanism of PM_{2.5}, different regions, and different plant species. Therefore, the characteristics of different haze regions must be studied. In addition, the same plant community may present different PM_{2.5} reduction rates when road greenbelt widths vary. The effect of road greenbelts on PM_{2.5} reduction determined in combination with greenbelt width should be explored thoroughly; this subject has not been investigated thus far.

Suzhou is an important tourist city with a long history. The frequent occurrences of haze in recent years have significantly damaged the reputation of the city and adversely affected the living quality of local residents. However, no sufficient scientific research has been conducted in this area. In this study, PM_{2.5} concentrations in road greenbelts with different plant communities in Suzhou Industrial Park were tested. Issues addressed include the biological structure of vegetation community, and the width of greenbelt. The data obtained through this testing allows for analyzing the influencing factors of PM_{2.5} concentration, and for understanding the mechanism of the PM_{2.5} reduction within road greenbelts. The goal was to determine the best

plant community and road greenbelt width for PM_{2.5} reduction. The results of the study can provide fundamental knowledge for the optimal design and management of road greenbelt in Suzhou and similar cities supported by the scientific findings on reducing air pollution using greenbelts.

2. Materials and methods

2.1 Study area

The studied area is located in Suzhou Industrial Park in Jiangsu Province, China (119°55'–121°20' E, 30°47'–32°02' N). It possesses a subtropical monsoon climate, abundant precipitation, and humid air. Xinghu Street is a main street in the industrial park. There is a high traffic volume, a wide greenbelt, high construction quality for the greenbelt, and diversified community structures. The area is suitable for a concentrated large-scale test.

2.2 Selection of sample plots

The road greenbelts in Suzhou Industrial Park are composed of arbor-grass and arbor-shrub-grass plant communities showing abundant elevation effects. A few lawn and shrub-grass communities are present. Two community structures and four sample plots in Xinghu Street in Suzhou Industrial Park were selected as the test points according to the main types of road greenbelts and road distribution characteristics.

2.2.1 Sample plot of the arbor-shrub-grass community

The plant allocation in A1 is an “arbor-shrub-grass” community. The ground layer is mainly *Festuca elata*; the shrub layer is *Camellia sasanqua*, *Rhododendron simsii*, and *Nandina domestica*. The arborous layer is *Cinnamomum camphora* and *Nerium indicum* L. The *Cinnamomum camphora* is 10.5 m high with an 8.5 m canopy (Fig. 1).

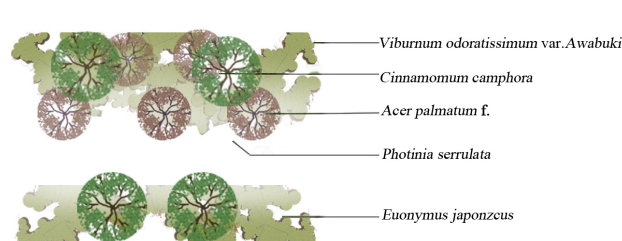


Fig. 1. Current plant community in A1

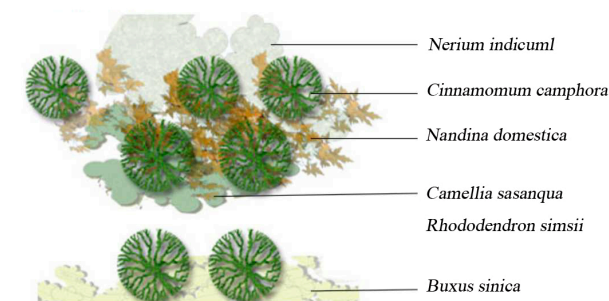


Fig. 2. Current plant community in A2

The plant allocation in A2 is an “arbor-shrub-grass” community. The ground layer is the lawn composed of *Cynodon dactylon*. The shrub layer is composed of *Viburnum odoratissimum* and *Photinia serrulata* accompanied by *Acer palmatum* f. The arborous layer is *Cinnamomum camphora*. The entire community possesses diversified layering structures (Fig. 2).

2.2.2 Sample plot of the arbor-grass community

In B1, the ground layer is *Ophiopogon japonicus*, and the arborous layer is a group plantation of *Osmanthus fragrans* with 2.5 m height and 2.6 m canopy (Fig. 3).

In B2, the ground layer is *Coleus blumei*, and the arborous layer is *Cinnamomum camphora* with 12.5 m height and 9 m canopy. The elevation is relatively simple (Fig. 4).

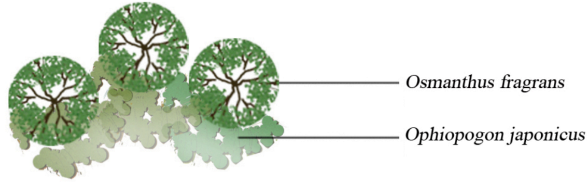


Fig. 3. Current plant community in B1



Fig. 4. Current plant community in B2

2.3 The monitoring points

Five monitoring points were set on a line perpendicular to the road, with distances of 0, 5, 10, 15, and 20 m respectively (Fig 5). The monitoring point at 0 m was set as the control point. Three parallel samples were set at each monitoring point. All the monitoring points were set to be 1.5 m higher than the ground surface.

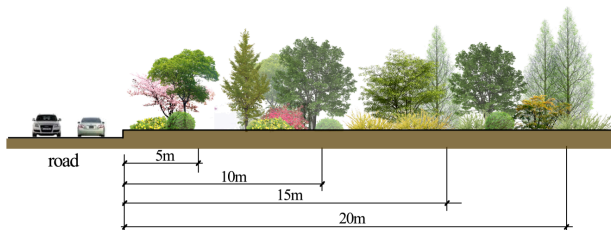


Fig.5. Monitoring points

2.4 Detection period and method

After several pre-experiments, $PM_{2.5}$ concentrations in the studied area were tested with a CEM DT-9880 $PM_{2.5}$ tester on a sunny and calm day in August 2016. Five tests were conducted at an time interval of 2.5 hours from 9:00 to 19:00. Each monitoring point was tested three times, and the average value was calculated.

2.5 Data processing

All test data were organized in Microsoft Excel. The dust-detaining capability of different greenbelt communities was measured with the $PM_{2.5}$ reduction rate (Q). Q is the $PM_{2.5}$ reduction proportion between test and control points in the sample plots. The calculation formula of Q is

$$Q = \left(\frac{V_0 - V_i}{V_0} \right) \times 100\% \quad (1)$$

where Q is the $PM_{2.5}$ reduction rate of the road greenbelt, V_0 is the average $PM_{2.5}$ concentration at the control point ($\mu g/m^3$), and V_i is the average $PM_{2.5}$ concentration at different monitoring points ($\mu g/m^3$).

3. Result analysis and discussion

3.1 Daily variation in $PM_{2.5}$ concentration in the monitoring points

3.1.1 Greenbelt with the arbor-shrub-grass community

Two “peaks” of $PM_{2.5}$ concentrations were observed in the greenbelt with the arbor-shrub-grass community during daytime (Figs.6 and 7). In the morning, $PM_{2.5}$ concentration increased gradually with the increase in the traffic volume and reached the peak at about 11:30. According to observations, the traffic during this period decreased gradually, and the $PM_{2.5}$ reduction rate within the greenbelt was higher than the accumulation rate of fine particulate matter, resulting in a continuous reduction of $PM_{2.5}$ concentration in the air. The $PM_{2.5}$ concentration decreased to the minimum at about 14:00. The traffic volume increased again during the rush hour. Although plants continued to reduce the $PM_{2.5}$ concentration, the reduction rate was lower than the $PM_{2.5}$ concentration speed, so another $PM_{2.5}$ concentration peak was formed at around 16:30. The pollution source subsequently decreased due to the traffic volume reduction in the evening. The $PM_{2.5}$ reduction rate of plants was higher than the accumulation speed again. The $PM_{2.5}$ concentration in the greenbelt also decreased significantly.

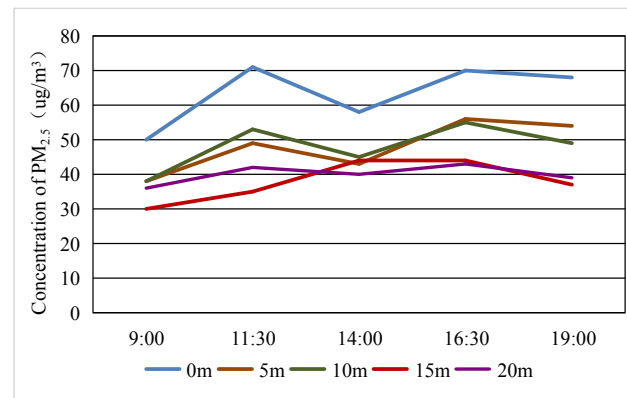


Fig. 6. Diurnal variation in $PM_{2.5}$ concentration in the arbor-shrub-grass community(A1)

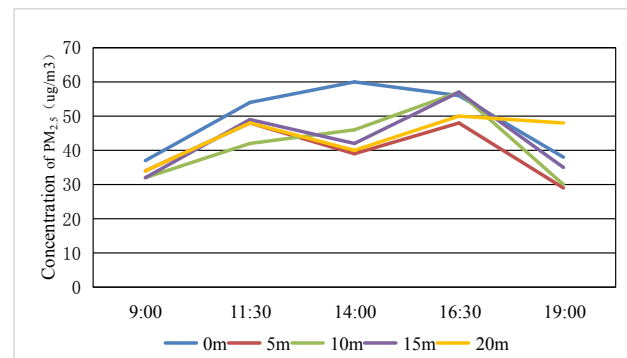


Fig. 7. Diurnal variation in $PM_{2.5}$ concentration in the arbor-shrub-grass community(A2)

3.1.2 Greenbelt with the arbor-grass community

The $PM_{2.5}$ concentration in the greenbelt with the arbor-grass community was the lowest in the morning, as shown in Figs. 8 and 9. Similar to that in the arbor-shrub-grass community, the $PM_{2.5}$ concentration continued to increase in the morning and exhibited declining trend after reaching the peak at about 11:30. The $PM_{2.5}$ was at the minimum concentration at about 14:00 and the $PM_{2.5}$ peak at about 16:30 were not as evident as those in the arbor-shrub-grass community. The small $PM_{2.5}$ peak at about 16:30 may be caused by particulate diffusion in the arbor-grass community, and the unobvious $PM_{2.5}$ valley at about 14:00 may be related to the low canopy density and poor dust-adsorption and dust-detaining capabilities of the arbor-grass community.

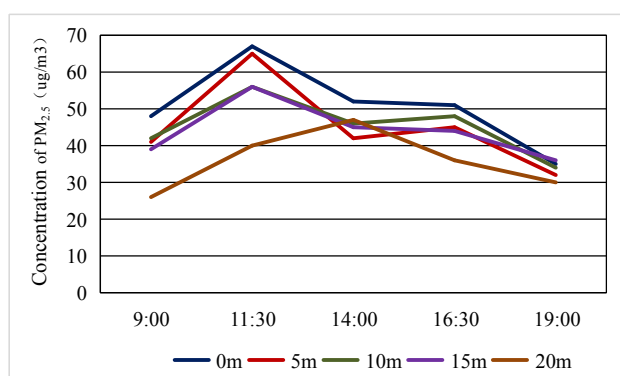


Fig. 8. Daily changes in $PM_{2.5}$ concentration in the arbor-grass community (B1)

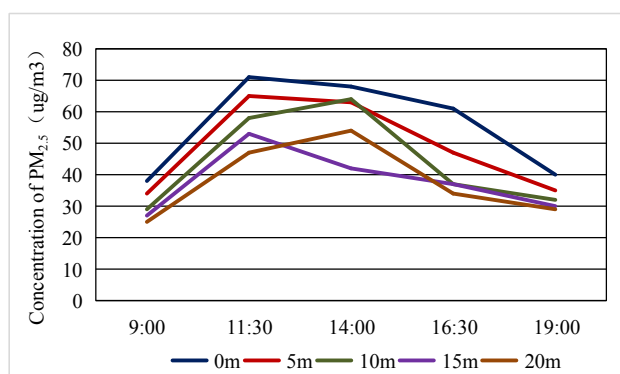


Fig.9. Diurnal variation in $PM_{2.5}$ concentration in the arbor-grass community (B2)

3.2 Effect of greenbelt width on $PM_{2.5}$ concentration

The average $PM_{2.5}$ concentrations of the greenbelt with different plant community structures under different widths were compared (Fig. 10). With the increase in greenbelt width, the $PM_{2.5}$ concentration in the greenbelt decreased gradually. This result indicates that the $PM_{2.5}$ reduction rate is proportional to the greenbelt width when the width is smaller than 15 m. The $PM_{2.5}$ concentrations at 15 and 20 m are very close with a difference of only 3.2%. As shown in Figs. 5 to 8, when the greenbelt width exceeded 20 m, the $PM_{2.5}$ reduction rate was not evident and sometimes became higher than the $PM_{2.5}$ concentration at 0 m (Fig. 7). This result may be due to the fact that with the increase in greenbelt width, the green density increased, and fine particulate matter in the air could not easily drift away with the wind but was retained in the greenbelt. The road greenbelt width should be within 20 m to ensure a high $PM_{2.5}$ reduction effect and save land resources.

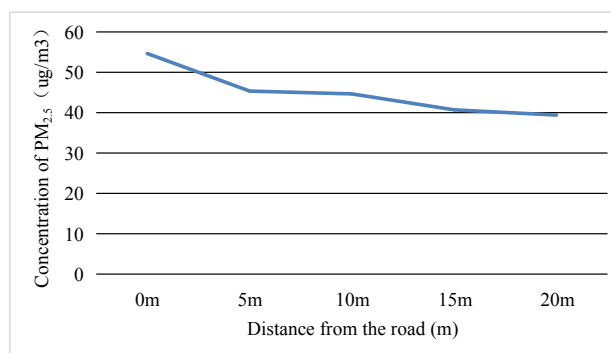


Fig. 10. Effect of greenbelt width on $PM_{2.5}$ concentration

3.3 Effect of different plant community structures on $PM_{2.5}$ reduction rate

Different plant community structures possess different $PM_{2.5}$ reduction capabilities. The mean $PM_{2.5}$ reduction rates in four sample plots at five time points when the greenbelt widths were 0, 5, 10, 15, and 20 m were calculated. Combined with road greenbelt width, the influences of plant community structure on $PM_{2.5}$ reduction rate were analyzed (Fig.11).

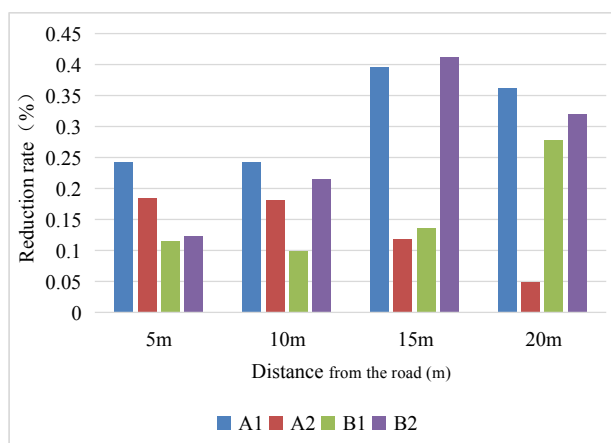


Fig. 11. Influences of plant community structures on $PM_{2.5}$ reduction rate

(1) When the greenbelt was narrow (0 m to 5 m), the capabilities of greenbelts with different plant community structures to reduce $PM_{2.5}$ concentration were in the order $A1 > A2 > B2 > B1$. A1 and A2 achieved the highest $PM_{2.5}$ reduction rate. The $PM_{2.5}$ reduction rate of A1 reached 24.3%, which was 112.5% higher than that of B1. Therefore, an arbor-shrub-grass community should be adopted when the road greenbelt is relatively narrow.

(2) When the greenbelt width increased to 10 m, the $PM_{2.5}$ reduction rates of arbor-grass and arbor-shrub-grass communities were similar. The $PM_{2.5}$ reduction rates of A1 and A2 changed slightly. The $PM_{2.5}$ reduction rate of B1 decreased to some extent, and the $PM_{2.5}$ reduction rate of B2 increased significantly and showed a difference of 11.5% with that of A1. When the greenbelt width was 15 m, the $PM_{2.5}$ reduction rates of all sample plots, except for A2, increased significantly, especially B2. The $PM_{2.5}$ reduction rate of B2 was 4.2% higher than that of A1. This finding indicates that the $PM_{2.5}$ reduction rate of road greenbelts is proportional to the greenbelt width. However, at this greenbelt width, the arbor-grass community was relatively open and easily facilitated $PM_{2.5}$ diffusion, as manifested by the evident $PM_{2.5}$ reduction rate. The 15 m wide greenbelt with the arbor-shrub-grass community is in the center of the

community, which has dense plants, high humidity, and poor ventilation. While the road traffic continues generating pollutants, the airborne particulates were suspended and concentrated in the community center and became difficult to be diffused, resulting in a low $PM_{2.5}$ reduction rate. The cover plants is relatively higher in A2, so fine particulate matter could not easily diffuse.

(3) When the greenbelt width exceeded 20 m, the greenbelt was far from the dust sources, and fine particulate matter were retained in community center. Therefore, $PM_{2.5}$ concentration decreased with the increase in the horizontal distance. The reduction rate was lower than that when the greenbelt width was 15 m. In addition, the arbor-shrub-grass community had a high canopy density. A1 achieved the highest $PM_{2.5}$ reduction rate (36.2%), followed by two arbor-grass community structures (32.7% and 27.9%) and A2 (4.9%). The different $PM_{2.5}$ reduction rates of A1 and A2 may be due to different plant species, especially lower shrub species. The lower shrub species of A1 included *Nandina domestica*, *Camellia sasanqua*, and *Rhododendron simsii*. The shrub layer of A2 was lower than that of A1, thus leaving a large, blank space under the arborous canopy that was beneficial for $PM_{2.5}$ diffusion. Furthermore, given that *Rhododendron simsii* leaves have hairy surfaces, their ability to adsorb fine particulate matter is enhanced, thus causing different $PM_{2.5}$ concentrations in the two greenbelts. Although B1 and B2 are both of the arbor-grass community, the tree species are different. The arborous layer of B1 is composed of dungarunga *Osmanthus fragrans*, and the arborous layer of B2 is megaphanerophyte *Cinnamomum camphora*. Given that *Osmanthus fragrans* is short, fine particulate matter could not be easily diffused in the greenbelt. Therefore, the $PM_{2.5}$ reduction rate of B2 was always higher than that of B1, especially in center of the greenbelt (15 m). Evidently, plant species influence the $PM_{2.5}$ reduction rate of greenbelts, except for the plant community structure. This finding demonstrates that the arbor-shrub-grass community can be adopted for greenbelts with a width of over 20 m, but the center could use the arbor-grass community. The arbor-grass community is less dense than the arbor-shrub-grass community and favorable for $PM_{2.5}$ diffusion.

4 Conclusions

Road greenbelts can help reduce the concentration of airborne pollutants such as $PM_{2.5}$. However, $PM_{2.5}$ reduction rates is significantly sensitive to the biological structure of vegetation community (e.g. plant species and planting density, condition of canopy), and greenbelt widths. To determine the optimal plant community structure and greenbelt width, $PM_{2.5}$ concentrations were tested in four

greenbelts with arbor-shrub-grass and arbor-grass communities of different greenbelt width in Suzhou Industrial Park. The daily variation law of $PM_{2.5}$ concentration and the effects of plant community structure and greenbelt width on $PM_{2.5}$ reduction rate were analyzed.

Based on the results, the following conclusion remarks can be drawn:

(1) The $PM_{2.5}$ reduction rate is related to traffic volume and $PM_{2.5}$ accumulation rate.

(2) The $PM_{2.5}$ reduction rate of road greenbelts is proportional to greenbelt width if it is within 15 m. However, when a greenbelt is too wide, e.g. exceeding 20 m, the ability to remove $PM_{2.5}$ will decline. Therefore the width of greenbelt should be controlled to within 20 m to ensure good $PM_{2.5}$ reduction and save land resources.

(3) If the greenbelt width varies, the same plant community structure will exhibit different $PM_{2.5}$ reduction rates. Plant community structures should be in accordance with the $PM_{2.5}$ reduction rate by considering the greenbelt width. The best plant community structure is difficult to determine. Hence, the arbor-shrub-grass community should be adopted when the road greenbelt is narrow in Suzhou. When the greenbelt width ranges between 6 and 20 m, the arbor-grass community should be used. When greenbelt width is over 20 m, arbor-shrub-grass and arbor-grass communities should be adopted in the center, which is minimally dense and favorable for $PM_{2.5}$ diffusion.

This study has made contributions to a thorough understanding on the effects of plant community structures on $PM_{2.5}$. It provides data for scientific and reasonable road greenbelt planning in Suzhou and references for similar studies in other regions. However, the concentration of airborne $PM_{2.5}$ can also be influenced by other environmental and meteorological factors, which were not addressed in this study. Ongoing research activities include investigating the concentration of $PM_{2.5}$ as being affected by the plant communities during different seasons and pollution. This will help establish the $PM_{2.5}$ reduction principle of plant communities and serve urban green space planning.

Acknowledgement

This work was financially supported by the Ministry of Housing and Urban-Rural Development, project number 2014-K6-006.

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