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Communication

New Prospects to Systematically Improve the Particulate Matter Removal Efficiency of Urban Green Spaces at Multi-Scales

Rui Zhang [1,2] and Keming Ma [1,2,*]

1 State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
2 College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China
* Correspondence: mkm@rcees.ac.cn; Tel.: +86-10-62849104

Abstract: Previous studies on the removal of airborne particulate matter (PM) by plants have mostly focused on the individual scale, hence there is a lack of systematic understanding of how to improve the PM removal effect of green spaces (GS) at multi-scales. We provide new insights into an integrated model, which integrates the utilization efficiency of vertical space and time into the multi-cycle PM removal model developed in our previous study. By analyzing the variabilities of the influencing factors at different scales, directions to improve this function at multiple scales can be proposed. According to the planning of urban GS, five scales were divided. At the species scale, plants should not only have the characteristics to match the local climate, but also a high utilization efficiency of time and space. At the community scale, increasing the hierarchy and structural complexity can help improve the utilization of vertical space. At the patch and landscape scales, the factor affecting the PM removal efficiency of GS lie in precipitation frequency, and large/small green patches with low/high landscape fragmentation in climates with low/high precipitation frequency are recommended. At the urban scale, it is necessary to increase the degree of temporal and spatial distribution matching between PM and GS. These findings can improve urban GS planning to contribute to the removal of airborne PM.

Keywords: multi-scale integration; PM removal model; systematic analysis; spatio-temporal utilization efficiency

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1. Introduction

Airborne particulate matter (PM) is a general term for all kinds of solid and liquid PM existing in the atmosphere. By 2015, PM pollution has become the fifth leading cause of human death [1]. It is found that there is no absolutely safe threshold for the harm of PM pollution to human body [2], therefore, no matter whether in developing countries with more serious pollution or in developed countries with relatively cleaner air, the residents, especially urban residents, cannot avoid the harm of PM to their health [3]. PM pollution has always been the focus of public concern.

Plants can effectively filter PM in the air [4]. Improving the PM removal capacity of GS requires comprehensive efforts at multi-scales [5]. First, it is necessary to clarify the influencing mechanism and optimize the multi-scale impacts of GS on PM removal. However, previous studies have often focused on the individual scale such as species selection [6–8], the effects of plant community type and structure on PM diffusion [9–11], the influence of GS landscape patterns on PM concentration [12–14], and estimation of the PM removal amount of GS in a city [15–17]. Looking for a direction to improve the PM removal efficiency of GS from a single scale often overlooks the impact on other scales. In contrast, integration across spatial scales can provide information that cannot be obtained by multiple single-scale studies [18]. However, there is still a lack of systematic understanding on how to improve the PM removal effect of GS at multi-scales.

From the perspective of the influencing mechanism of PM removal by plants, clarifying the influencing factors at each scale and changing the variation direction of these factors by regulating GS construction is a new analytical pathway for multi-scale integration. According to i-Tree model, the factors affecting PM removal efficiency per unit leaf area can be fundamentally analyzed from PM concentration, deposition velocity, resuspension rate, and wash-off coefficient [19,20]. The annual washing times of leaves, determined by the climate and leaf period, affect the utilization efficiency of time. Leaf area index (LAI) determines the total leaf area per unit land area, which represents the utilization efficiency of land space. The distribution of GS in horizontal space may lead to the variation of meteorological factors and PM concentration [13,21]. At the urban scale, there is an uneven distribution of PM and GS, both in time and space [17]. Herewith, we built a PM removal model under ideal conditions based on a multi-cycle PM removal model [22], and integrated the above-mentioned factors. Therefore, the aim of this communication is to expand the analysis of the variability of influencing factors at multi-scales and extrapolate the methods to improve the PM removal efficiency of urban GS at multi-scales.

2. Methods

Based on the multi-cycle PM removal model developed in our precious study [23], the annual PM removal amount per unit land area under ideal conditions was calculated as the product of the wash-off amount each time, annual washing times, and LAI, as presented in Equations (1)–(3):

$$Q_{ann-land} = \frac{3600 C_w V_d C (1 - rr) \left(e^{Trr/(1-rr)} - 1 \right)}{rr \left(C_w + e^{Trr/(1-rr)} - 1 \right)} \times \frac{t_l}{T} \times LAI \quad (1)$$

$$V_d = aV^b \quad (2)$$

$$rr = cV^d \quad (3)$$

where $Q_{ann\text{-}land}$ is the annual PM removal amount per unit land area; t_l is the leaf life span/annual duration (h) when the plant is a deciduous/evergreen species; T is the time interval between two precipitation events (h); C_w is the wash-off coefficient of precipitation on the leaf PM; V_d is the deposition velocity of PM ($m \cdot s^{-1}$); C is the PM concentration in the air ($g \cdot m^{-3}$); rr is the hourly PM resuspension rate; LAI is leaf area index; V is the wind speed ($m \cdot s^{-1}$); and a, b, c, and d represent the species attributes, which are calculated by fitting experimental data with the corresponding equations [24,25].

The model had been tested in our previous study and the interaction between the influencing factors had also been discussed [23]. The factors selected in the model are consistent with i-Tree model [20], which can be divided into two categories: biological and environmental. Biological factors include plant leaf attributes (a, b, c, d) that affect the wash-off coefficient (C_w), deposition velocity (V_d), and resuspension rate (rr) of PM as well as individual attributes that affect the utilization efficiency of vertical space (LAI) and time (t_l). Environmental factors include PM concentration (C), wind speed (V), and precipitation interval (T). Among these factors, LAI can be controlled by adjusting the species selection and community structure. C_w varies with species and is affected by precipitation patterns [26,27]. V_d and rr vary with species and are affected by V [24,25], while t_l varies with species and may also be affected by climate. V and C have strong variability in nature, but the optical porosity, patch size, and distribution pattern of GS can also affect the exposed V and C of plants [21,28]. These six factors are relatively controllable, while T is determined by climate and is uncontrollable. Changing the controllable factors by adjusting the GS construction, to improve the PM removal efficiency of GS, is therefore our train of analysis.

In order to master the promotion direction of PM removal by GS at multi-scales, it is necessary to clarify the scale classification. Three scales were proposed in previous studies, that is single tree, stand, and regional [5,29]. However, considering that the planning of urban GS involves species selection, community construction, green patch building, and GS distribution in urban areas, the method to promote PM removal efficiency by GS will be analyzed at five scales: species, community, patch, landscape, and urban (Figure 1).

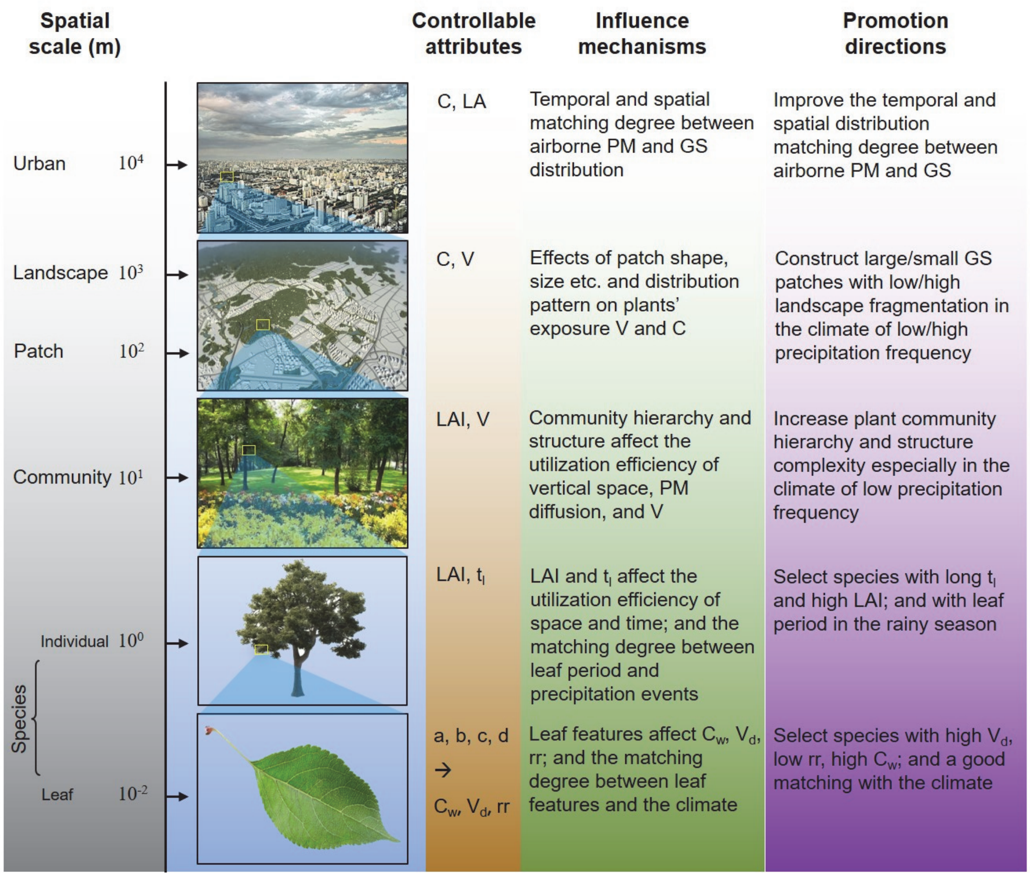

Figure 1. Controllable attributes, influence mechanisms, and promotion directions of particulate matter (PM) removal by green space (GS) at each scale. C_w, wash-off coefficient of precipitation on leaf PM; V_d, deposition velocity of PM; C, PM concentration in the air; rr, hourly PM resuspension rate; LA, leaf area; LAI, leaf area index; V, wind speed; a, b, c, and d, species attributes that affect C_w, V_d, and rr.

3. Results and Discussions

The controllable attributes, influence mechanisms, and promotion directions of GS to remove PM at each scale are summarized in Figure 1.

3.1. Species Scale

Species selection involves all the biological and related factors in the model (C_w, V_d, rr, LAI, and t_l). Among these five factors, C_w, V_d, and rr affect the PM removal efficiency per unit leaf area, while LAI and t_l affect the utilization efficiency in space and time, respectively. This means that the selection of plant species needs to be considered not only at the leaf scale, but also at the individual scale.

At the leaf scale, a high C_w and V_d and a low rr have positive effects on PM removal efficiency. Among these three factors, the influence of C_w requires special attention. Although many studies evaluated the PM capture ability to select species [30,31], the resilience of plants to remove PM is often inconsistent with the ability to capture PM [32,33]. The relative magnitudes of the PM removal efficiencies of different species at the leaf scale are also affected by V and T [23]. This explains the conversion of the relative magnitudes of the PM removal efficiency of different species in different seasons found in the field experiments to a certain extent [34]. The influence of climate on species selection is not only limited to the leaf scale but also exists at the individual scale.

At the individual scale, t_l and LAI were linearly and positively correlated with $Q_{ann\text{-}land}$. Under the same climate, the difference in t_l was mainly reflected in the difference between deciduous and evergreen plants. For deciduous plants, the leaf period in a year is the leaf life span, and when leaves fall off, the LAI changes to zero. For evergreen plants, the leaf period in a year is one year, and the LAI may not change as much as that of deciduous plants, but it will also change with seasons [35]. This is the main reason for seasonal variation in this function [36]. Under different climates, on the one hand, temperature and precipitation have direct impacts on leaf life span [37], on the other, due to the uneven distribution of precipitation, the ability of plants to remove PM may vary greatly with climate. For instance, in a temperate continental monsoon climate, the precipitation frequency is higher in the leaf-on season than that in the leaf-off season, which is conducive to PM removal by plants. However, in the Mediterranean, precipitation is concentrated in winter, during which the PM removal effect is greatly reduced. In addition to the influence of climatic factors, LAI could also be affected by many other factors such as height, crown shape, leaf type, and leaf area density. A high LAI indicates a high utilization efficiency of the vertical space. It is worth noting that for the use of small land patches scattered on impervious surfaces, plants with large crowns can expand the utilization efficiency of the horizontal space. For example, street trees with large crowns can cover impervious roads, thereby improving the utilization efficiency of the horizontal space.

The relative magnitudes of the PM removal efficiency of different species are not invariable. Establishing the relationship between species attributes and meteorological factors, and simulating the annual PM removal amount under different climates may thus be a universal method for species selection.

3.2. Community Scale

LAI, C, and V can be affected by the characteristics of the plant community. When excluding the factors derived from the species that constitute the community, structural attributes are the key factors affecting these three attributes. This is the overall utilization efficiency of the plant community in vertical space and impact of community structure characteristics on C and V.

For a plant community, the plants used to build GS can include different life and growth forms. The collocation of different species in vertical space can increase the community hierarchy and make more efficient use of the vertical space. The higher the hierarchy and complexity of the community structure, the higher is the average LAI.

The impact of plant community structure on C is mainly reflected in its indirect effects on the diffusion of PM through its direct influence on environmental factors [10,38]. However, its influence on PM diffusion has no explicit effect on the relative C inside and outside the community. The C inside the community may be higher or lower than the C outside [39]. The plant community may play a buffering role in changes in C [38]. Therefore, changes in C could be ignored at the community scale.

Subduction of the plant community on V indicates that the more complex the plant community structure, and the higher the leaf area density, the more is the subduction [28,40]. According to the interaction effect of V and T on PM removal by plants, reducing V in the long T area is more conducive to the PM removal function of plants [23]. Therefore, it is recommended to build plant communities with more complex structures. Unmanned aerial system remote sensing is an effective method for greenery structure monitoring [41]. In short T areas, an appropriately high V may be conducive to PM removal. However, when increasing the ventilation within the plant community, its negative impact on LAI should be considered.

3.3. Patch and Landscape Scale

The influence of plant communities on V and C cannot be independent of scale in the horizontal space [11,21]. The expansion of plant communities in horizontal spaces forms green patches. Furthermore, the combination of multiple green patches in space forms the GS landscape. Green patches have an edge effect on PM removal by affecting V and C [42,43], therefore, the green patch itself and the GS landscape composed of multiple patches affect the PM removal efficiency of plants.

The effect of the GS landscape pattern on V is intuitive. The larger the green patch, the lower the degree of landscape fragmentation, the lower the overall permeability, and the greater the reduction in V [21]. According to the interaction effects of V and T on PM removal by plants, building large patches in climates with long T is conducive to PM removal by plants [23]. Previous studies often focus on the relationship between green patches and C [44,45], while the removal of PM is a process of PM deposit on leaves, they are not meaningful for reference. There is an urgent need for experimental studies at the patch scale. Similarly, for planning the GS landscape, it is suitable to reduce the degree of fragmentation in long T areas.

Research on the relationship between GS and PM at the landscape scale mostly focuses on the influence of patch size, morphological characteristics, and distribution pattern on C [46]. In general, the larger the green patch and the more complex the shape, the more effective the reduction in C [13]. In addition, C often shows a positive relationship with the fragmentation degree of the GS landscape [12]. From the model, C is linearly and positively correlated with $Q_{ann\text{-}land}$, and to achieve a higher PM removal efficiency, it is appropriate to achieve higher C in the GS. Although small patches and fragmented GS landscapes are not conducive to the reduction in C, they may be conducive to full contact between plants and PM.

Ultimately, the goal is to achieve a reduction in population exposure to C. At small time and space scales, the effects of PM deposition and diffusion on C may be inconsistent [47,48]. Therefore, the choice of green patch size needs to weigh in the deposition and diffusion effects on PM. In densely populated areas, it is necessary to fully understand the influence of plants on PM diffusion to achieve a lower C. For GS away from populated areas, more attention needs to be paid to the PM deposition effects.

3.4. Urban Scale

Compared with the uncertainty and instability of the variation at small scales, C and GS often have clearer and more stable spatial distribution patterns at urban scales. C and the leaf area affect the PM removal amount in the form of their product (Equation (1)). Therefore, to improve the PM removal amount of GS in the entire urban area, more GS should be arranged in areas with higher C. The distribution of PM and GS often varies in time and space [41,49], and always has a great mismatch [22], which often leads to differences in air quality improvement rates [41,50]. The spatial distribution of PM in urban GS can be easily measured from satellite remote sensing and land use information [51,52], therefore, the matching degree between GS and PM in space distribution is easy to perceive. However, both C and LAI change with season, and the time matching between them has got little attention. Moreover, at the urban scale, the demand of residents for this service also varies with time and space, and to achieve more ecological benefits, it is necessary to consider the balance between service supply and the demand [22].

4. Conclusions and Prospects

By integrating the environmental and biological factors that affect the PM removal efficiency of GS, the coordination and unity of this effect at multi-scales was realized. It is of great practical significance to systematically recognize the PM removal effect of urban GS at multi-scales. Suggestions to improve this service on multi-scales are proposed as follows. Species selection should consider not only the matching degree between leaf characteristics and climate, but also the utilization efficiency of time and space. The construction of a plant community with a multi-hierarchy and complex structure is helpful for increasing the utilization efficiency of vertical space and improving the PM removal efficiency of leaves in long T climates. At the patch and landscape scales, GS affects the PM removal efficiency mainly by changing V and C, and the construction direction is affected by T. In the long/short T area, the construction of large/small green patches and GSs with low/high degrees of fragmentation may help plants remove PM. At the urban scale, improving the degree of matching between GS and PM, both in space and time, is the promotion direction. The research focus on the patch and smaller scales should be to improve the PM removal efficiency of GS, while at landscape and larger scales should be on how to achieve more ecological benefits.

It should be noted that, the interaction between airborne particles and plants varies greatly with particle size at the leaf [30] or community [39] scales. Therefore, to maximize this service, the particle size composition in the local air should be considered, while trade-offs between the removal of particles of different sizes are required. In addition, the model needs more experiments to verify at each scale.

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