Diurnal and Seasonal Variations of Particulate Matter Concentrations in the Urban Forests of Saetgang Ecological Park in Seoul, Korea

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Abstract: Urban forests provide various ecosystem services. Although the function of reducing particulate matter (PM) in the city is known, research into the reduction of PM according to the type and structure of various forests is still needed. It is essential to study the characteristics of PM concentration in urban riparian forests, which are frequently used for outdoor walks in the COVID-19 era. In this study, the diurnal and seasonal changes in PM 10 and PM 2.5 concentrations were analyzed in urban forests with different structures in the riparian forests located in central Seoul. The PM concentration was found to be high regardless of the time of the day in forests with a developed canopy layer. Similar results were found before and after leaf emergence compared with the seasonal PM concentration. The results of this study highlight the need for planned and periodic management of the canopy layer and underground vegetation to prevent the PM trapping effect to ensure the safe use of riparian forests in cities.

Keywords: urban forests; forest structure; particulate matter dynamics; urban forest management; green infrastructure

1. Introduction

In most countries, approximately 90% of the population lives in urban areas for easy access to various infrastructural amenities [1]. However, excessive urbanization can lead to numerous problems, such as environmental pollution. As these problems occur due to complex reasons, it is not easy to find a clear solution. To reduce the problems caused by excessive urbanization, efforts are being undertaken to implement and manage urban forests [2].

Urban forests play an important role in improving the quality of urban environments. They provide urban forest services and contribute to climate control, heat island effect reduction, noise reduction, and energy and carbon reduction [2–6]. Recently, the quality of life of citizens has decreased remarkably as the concentration of yellow dust and particulate matter (PM) has increased, not only in the Korean Peninsula, but also in East Asia. High PM concentrations have notable impacts on air quality, human health, and climate change [7–9]. Therefore, among the various urban forest services, interest in the potential of forests to reduce PM concentrations has increased, and various initiatives have been undertaken to reduce PM concentration using urban forests [10].

Urban forests use the principles of absorption, adsorption, blocking, and deposition to reduce PM concentrations [11–17]. This reduction can be greatly influenced by the number of leaves in individual trees of the forest. PM is absorbed or adsorbed on the leaf surface depending on the development of the leaf as well as its shape and structure [18–21]. In addition, the movement and speed of PM are reduced because of forest canopy development, blocking and depositing PM on the forest floor [13,16]. Based on these results, assorted urban green infrastructures, such as street trees and parks, have been implemented and managed.
The forest structure, or the arrangement of trees and tree density, can affect the wind flow and humidity, thereby affecting the PM concentration level in the forest. Therefore, it is important to understand the environmental characteristics of forests, forest size, and forest structure when implementing and managing urban forests. However, not many studies have been conducted on urban forests that are based on the characteristics of the forest units and field data of PM. In particular, the effects of riparian forests, which are located near pollution sources, on PM concentration levels have not been assessed. Riparian forests can be more effective in reducing PM concentrations as they provide more space for water than roadside trees and green areas. A previous study has highlighted the role of park waters, such as lakes, in reducing PM concentrations [22].

Saetgang Ecological Park, which is located near the Han River, was established as the first ecological park of South Korea in 1997 in an area that had been previously neglected as a wetland by the government. Currently, there are colonies of willows, reeds, and silver grass, as well as wetlands. Saetgang Ecological Park is a representative urban forest in Seoul that not only enriches the biodiversity but also allows many citizens to visit and enjoy nature. However, as the park is located at a lower level than the adjacent road, and because traffic is the main source of PM in the city, it is believed that visitors will be at a health risk due to PM exposure. Research assessing the impact of urban forests characteristics, such as its location, on PM dynamics is lacking.

The aim of this study was to analyze the characteristics of PM dynamics based on the characteristics of urban forests in the Saetgang Ecological Park in Seoul. Based on the measured values of PM and meteorological data in two urban forests with different characteristics, we analyzed the PM dynamics in urban forests and its relationship with environmental factors. The findings of this study can maximize the efficiency of urban forest implementation and management in reducing PM concentrations and can provide information on ecosystem services and environmental taxes in urban forests.

2. Materials and Methods

2.1. Study Site

Saetgang Ecological Park is located in the Saetgang river basin, a tributary of the Han River, in Seoul (Figure 1A). As the park has a walking trail of approximately 7.4 km, many citizens actively use the trail. The willow colonies and walking trails of Saetgang Ecological Park are located approximately 10 m lower than the nearby roads (Figure 1B–D). A skybridge located at the same height as the nearby roads in the park designated was as a control site (C), and two points (F1 and F2) with different vegetation structures were set as measurement points (Figure 1B–D).

The main pollutant source of urban forests in the Saetgang Ecological Park is the Olympic-daero (Olympic Expressway). According to the data from the Seoul Metropolitan Government, the average daily traffic volume of Olympic-daero (as of 2020) is 244,824 vehicles (49.3 km/h), accounting for the highest amount of traffic among all Seoul urban highways [23]. North winds from the Han River, located to the north of the urban forests, are likely to be blocked by skyscrapers located in Yeouido’s business district, causing PM to accumulate along the Saetgang River. In addition, the Saetgang Ecological Park is located more than 10 m lower than the Olympic-daero; consequently, various pollutants, including PM from the Olympic-daero, can settle in the park.

Large-scale atmospheric congestion is a problem across East Asia, including in local areas. In the case of the Saetgang Ecological Park, if pollutants are continuously accumulated and the surface is not managed, pollutant re-suspension may occur, and the park can act as a PM trap. The shape and characteristics of the leaves, along with the overall leaf volume and canopy structure, affect the airflow in the forest, further affecting the microclimate and the concentration of airborne particles. Therefore, people visiting the park or other places located on the banks of low rivers or under overpasses in large cities have a high risk of PM exposure. Therefore, largely visited urban forests have an important role in reducing
the PM concentrations. In other words, PM concentration will have a significant impact on people who use urban forest services.

Figure 1. (A) Location of the study area in Yeouido Saetgang Ecological Park in Seoul, Korea. (B) View of Yeouido Saetgang Ecological Park before leaf emergence in March. (C) View of Yeouido Saetgang Ecological Park after leaf emergence in May. (D) Figure of the measuring points.
2.2. Measurement Methods

Sample plots of 0.04 ha and radius 11.3 m were installed at two points on the willow colonies, which form the main vegetation, and the vegetation structure within the cluster were analyzed. The tree, subtree, and shrub layers were identified, and their importance values (IVs) were analyzed by measuring the tree height, diameter at breast height (DBH, cm), crown diameter (m), and crown projection area (m²). The IV of each species was estimated as IV = RA + RD + RF, where RA is the relative abundance calculated as the number of individuals per species per hectare, RD is relative dominance defined as the basal area per species per hectare, and RF is the relative frequency (per ha), estimated as the proportion of plots in which the species occurs at least once. The total area of Saetgang Ecological Park is approximately 758,000 m², and communities of willow-mulberry, hackberry-willow, platanus-willow, elm-willow, erect willow-willow, and reed and pampas grass are present. Two different stand structures of willow-mulberry community (F1 and F2) comprised the study area.

PM_{10} and PM_{2.5} concentrations were measured using a mobile portable PM measuring device Dustmate (Turnkey, UK, ±5% accuracy) that was installed at a height of 1.5 m aboveground at F1 and F2 [24,25]. The PM concentrations were also measured on skybridges, which were at similar heights to the roads (Figure 1D). Dustmate is a portable sensor that can measure outdoor PM_{10} and PM_{2.5} concentrations in real time through the light scattering method. However, in this method, air particles and humidity can interfere with light transmission, and hence, the PM concentrations can be overestimated [17,26]. To eliminate overestimation, the PM concentration data exceeding 80% humidity were excluded. PM monitoring was carried out from March to September 2020, except June, and was measured for 24 h consecutively. The data were used as an average of 5 min. Based on the measured PM data, the hourly, monthly, and seasonal averages were calculated. To confirm the diurnal changes of PM concentrations in the forest, the data were divided into dawn (01:00–06:00), morning (07:00–12:00), afternoon (13:00–18:00), and evening (19:00–24:00) and were then analyzed. Furthermore, to assess the change in PM concentrations due to the emergence of leaves in spring, PM data before April were compared with that after May. In addition, the temperature, wind direction, wind speed, and relative humidity were measured at each measurement point continuously for 24 h using data from the weather station ATMOS 41 (METER Group, USA). Based on the measured meteorological factors, the relationship between PM changes in urban forests was analyzed. The diurnal PM_{10} and PM_{2.5} concentrations at the three study sites were compared with those measured in nearby urban areas, which were located near the study sites. The measurements were conducted at the National Air Quality Monitoring Station (Airkorea; 37° 200’ N, 126° 430’ E). To analyze the seasonal changes in the PM concentration due to the presence or absence of leaves in trees, the PM data obtained during May–September were compared with those obtained during March–April.

2.3. Analysis

Based on the measured PM and meteorological data, we analyzed the relationship based on the diurnal changes or the presence or absence of leaves. To analyze the diurnal and seasonal changes in PM concentrations in urban forests, data were subjected to one-way analysis of variance (ANOVA), followed by Tukey’s test (p < 0.05) for multiple comparisons using SPSS Statistics Version 25 (IBM Software, New York, NY, USA). All data are presented as mean ± standard error. The correlation between PM concentration and meteorological data was determined using the Spearman rank correlation coefficient. In addition, the OpenAir package in R program was used to understand the situation and variation of PM_{10} and PM_{2.5} levels in the study sites by examining seasonal changes in pollution roses.
3. Results

3.1. Stand Structure Characteristics of Two Willow Forests

The IV of willow and mulberry in F1 were 150.01 and 49.99, respectively and the heights were 12.45 m and 8.23 m, respectively. DBH was 26.50 cm and 9.90 cm, basal area was 0.6 m$^2$ and 0.04 m$^2$, crown diameter was 3.64 m and 3.16 m, and crown projection area was 473.70 m$^2$ and 129.09 m$^2$ for willow and mulberry, respectively. In F2, the IV of willow and mulberry trees were 119.52 and 80.48, and the height was 10.75 m and 7.57 m, respectively. DBH was found to be 14.20 cm and 9.80 cm, basal area was 0.21 m$^2$ and 0.07 m$^2$, crown diameter was 2.53 m and 2.81 m, and crown projection area was 249.70 m$^2$ and 193.30 m$^2$ for willow and mulberry, respectively. The densities of the *Salix koreensis* and *Morus alba* in F1 and F2 were 3.5 trees/100 m$^2$ and 4.75 trees/100 m$^2$, respectively (Table 1).

Table 1. Stand structure characteristics of two willow forest (F1 and F2) in the Yeouido Saetgang Ecological Park.

| Species            | F1          | F2          |
|--------------------|-------------|-------------|
|                     | *Salix koreensis* | *Morus alba* | Total | *Salix koreensis* | *Morus alba* | Total |
| Importance value (IV) | 150.01 | 49.99 | - | 119.52 | 80.48 | - |
| DBH (cm)            | *26.50 ± 8.05* | 9.90 ± 4.75 | **21.76 ± 10.52** | *14.20 ± 4.57* | 9.80 ± 6.43 | **12.58 ± 5.59** |
| Height (m)          | 12.45 ± 3.14 | 8.23 ± 3.18 | 11.24 ± 3.62 | 10.75 ± 2.60 | 7.57 ± 1.81 | 9.68 ± 2.69 |
| Crown depth (m)     | 7.41 ± 2.75 | 6.80 ± 3.27 | 7.24 ± 2.79 | 6.07 ± 2.00 | 6.19 ± 2.12 | 6.11 ± 1.99 |
| Clear length (m)    | 5.04 ± 1.29 | 1.43 ± 0.10 | 4.01 ± 2.01 | 4.78 ± 1.33 | 1.50 ± 0.63 | 3.57 ± 1.96 |
| Basal area (m$^2$)  | *0.6* | 0.04 | **0.63** | *0.21* | 0.07 | **0.28** |
| Crown diameter (m)  | *3.64 ± 1.44* | 3.16 ± 0.61 | **3.50 ± 1.25** | *2.53 ± 0.50* | 2.81 ± 1.01 | **2.63 ± 0.72** |
| Stem volume (m$^3$) | *8.03* | 0.37 | **8.40** | *2.36* | 0.62 | **2.98** |
| Crown projection area (m$^2$) | *473.70* | 129.09 | **602.76** | *249.70* | 193.30 | **442.99** |
| Crown volume (m$^3$) | 681.67 | 166.10 | 847.77 | 455.40 | 246.90 | 702.26 |
| Forestland area (m$^2$) | 400 | 400 | 400 | 400 | 400 | 400 |

Significant differences between forest sites (F1 and F2) at $p < 0.05$ (two-sample $t$-test) are denoted by * and **, respectively. Values are shown as the mean ± standard deviation.

3.2. Diurnal Changes of PM Concentration

During the day, both PM$_{10}$ and PM$_{2.5}$ concentrations showed the highest values in the evening (19:00–24:00) and dawn (01:00–06:00), and lower overall values in the morning and afternoon. For PM$_{10}$ and PM$_{2.5}$ concentrations, F1 was approximately 25% and 20% higher than that of F2, respectively. The daily average of PM$_{10}$ concentration was the highest at 39.3 µg/m$^3$ in F1 and the lowest at 31.57 µg/m$^3$ in F2. Among the study sites, the PM concentration in C was 34.92 µg/m$^3$, and the value of the urban area was 32.60 µg/m$^3$. The daily average concentration of PM$_{2.5}$ was 18.26 µg/m$^3$ and 15.45 µg/m$^3$ in F1 and F2, respectively. F1 was higher and F2 was lower than 17.71 µg/m$^3$ in the urban area (Figure 2A,B).
Figure 2. Diurnal changes in PM concentration (µg/m³) in the Yeouido Saetgang Ecological Park. (A) Hourly PM$_{10}$ concentration at the measuring points. (B) Hourly PM$_{2.5}$ concentration at the measuring points. The same letter indicates no significant difference between measurements ($p < 0.05$, one-way analysis, ANOVA, and then Tukey’s test for multiple comparisons). Values are shown as means ± standard deviation. C; control, F1 and F2; urban forest site 1 and 2, respectively; Urban; Urban area.

3.3. Seasonal Changes in the PM Concentration

The PM$_{10}$ concentration before leaf development was approximately 22% higher than those after the leaf development in both C and urban areas. However, the PM$_{10}$ concentrations were 68% and 65% higher in F1 and F2, respectively. Urban forest area had a larger difference in seasonal PM$_{10}$ concentrations than urban areas (Figure 3A). In the case of PM$_{2.5}$, the concentrations after leaf development were approximately 4%–5% higher than those before leaf development in the C area and urban areas, whereas they were approximately 28% and 55% lower in F1 and F2, respectively (Figure 3B).

Figure 3. Cont.
different in these sites (Figure 4, Table 3). In addition, after leaf development, the ratio of PM$_{10}$ and PM$_{2.5}$ concentrations were lower than before leaf development due to seasonal variations in the wind speed and the wind direction. For pollution roses of PM$_{2.5}$, the frequency was similar to those for pollution roses of PM$_{10}$, whereas the concentrations were remarkably lower (Figure 4, Table 3).

Table 2. Meteorological conditions at two willow forests in Yeouido Saetgang Ecological Park during the study period.

| Region | BL | AL |
|--------|----|----|
|        | WS (m/s) | Temp (°C) | RH (%) | WS (m/s) | Temp (°C) | RH (%) |
| C      | 2.01 ± 0.96 | 10.26 ± 5.87 | 46.17 ± 15.19 | 1.19 | 20.84 | 57.09 |
| F1     | 0.90 ± 0.39 | 10.25 ± 5.82 | 50.82 ± 0.46 | 0.46 | 21.43 ± 4.78 | 65.89 |
| F2     | 0.98 ± 0.45 | 9.85 ± 5.37 | 50.21 ± 0.52 | 0.52 | 21.43 ± 5.03 | 63.22 |
| U      | 2.94 ± 1.20 | 10.27 ± 5.37 | 51.01 ± 17.72 | 1.65 ± 0.92 | 21.55 ± 4.44 | 62.57 ± 14.06 |

Values are shown as mean ± standard deviation. BL; Before leaf emergence (March–April), AL; After leaf emergence (May–September), C; control, F1 and F2; urban forest sites 1 and 2, respectively, Urban; Urban area, WS; wind speed, Temp; temperature, RH; relative humidity.

To investigate the relationship between wind and PM, we analyzed the seasonal changes in pollution roses using measured data from the monitoring stations. We examined the pollution roses and analyzed the effects of weather patterns on contamination formation. In the C area and urban areas, which had similar heights, the wind speed was faster, and the wind direction was different to that in F1 and F2, which were located in the lower areas (Table 2). Therefore, the ratios of PM$_{10}$ and PM$_{2.5}$ concentrations were also different in these sites (Figure 4, Table 3). In addition, after leaf development, the ratio of PM$_{10}$ and PM$_{2.5}$ concentrations were lower than before leaf development due to seasonal variations in the wind speed and the wind direction. For pollution roses of PM$_{2.5}$, the frequency was similar to those for pollution roses of PM$_{10}$, whereas the concentrations were remarkably lower (Figure 4, Table 3).
Table 3. Average of PM$_{10}$, PM$_{2.5}$, WD, and WS as seasonal changes in Yeouido Saetgang Ecological Park.

| Region | PM$_{10}$ (µg/m$^3$) | PM$_{2.5}$ (µg/m$^3$) | WD ($^\circ$) | WS (m/s) |
|--------|----------------------|----------------------|----------------|----------|
| **C**  | 35.78 ± 12.07        | 17.11 ± 7.31         | 181.76         | 2.01 ± 0.96 |
|        | 29.28 ± 12.30        | 18.25 ± 11.13        |                |          |
| **F1** | 45.62 ± 20.51        | 18.88 ± 10.84        | 186.67         | 0.90 ± 0.39 |
|        | 26.90 ± 15.47        | 15.02 ± 11.11        |                | 0.45 ± 0.14 |
| **F2** | 51.01 ± 17.72        | 1.65 ± 0.92          | 21.55          | 1.15 ± 0.30 |
|        | 62.57 ± 14.06        | 21.55 ± 4.44         |                |          |

Figure 4. Seasonal changes in pollution roses of PM$_{10}$ and PM$_{2.5}$ in Yeouido Saetgang Ecological Park. BL: Before leaf development (March–April), AL: After leaf development (May–September), WD: Wind direction, WS: Wind speed.
3.4. Correlation between PM Concentration and Meteorological Factors

The PM concentrations in urban forests are affected by meteorological factors. Therefore, in this study, a correlation analysis was carried out considering meteorological factors as factors that affect PM concentrations in urban forests. Table 4 shows the correlation coefficients between PM\textsubscript{10}, PM\textsubscript{2.5}, and four meteorological factors (wind direction, WD; wind speed, WS; temperature, TEMP; and relative humidity, RH) at three locations in the measurement area. All three points showed a high correlation with WS between PM\textsubscript{10} and PM\textsubscript{2.5} before leaf development. In other words, WS was a major factor that affected PM concentrations before leaf development. However, post leaf development, both PM\textsubscript{10} and PM\textsubscript{2.5} concentrations showed a lower correlation with WS than before leaf development.

| Region | Particulate Matter (PM) | Correlation Coefficient ($r$) | Significance p-Value |
|--------|-------------------------|-------------------------------|---------------------|
|        |                         | r-WD  | r-WS  | r-Temp | r-RH | p-WD  | p-WS  | p-Temp | p-RH |
| C      | BL                      | -0.501 | -0.683 | 0.341  | 0.272 | 0.0000 | 0.0000 | 0.0051 | 0.0271 |
|        | AL                      | 0.503  | -0.224 | 0.081  | 0.498 | 0.0236 | 0.3420 | 0.7336 | 0.0256 |
| F1     | BL                      | -0.492 | -0.646 | 0.401  | 0.177 | 0.0001 | 0.0000 | 0.0022 | 0.1906 |
|        | AL                      | 0.353  | -0.092 | 0.648  | 0.398 | 0.0066 | 0.4931 | 0.0000 | 0.0020 |
| F2     | BL                      | -0.202 | -0.536 | 0.499  | 0.355 | 0.1153 | 0.0000 | 0.0000 | 0.0047 |
|        | AL                      | -0.219 | -0.424 | -0.063 | 0.337 | 0.1432 | 0.0033 | 0.6764 | 0.0219 |

4. Discussion

4.1. PM Concentration Variations in Urban Forests/PM Concentration Temporal Differences

Periodic PM pollution events in urban areas are more likely to occur in the winter–spring seasons in the Northern Hemisphere due to increased air temperature and more frequent atmospheric inversions due to global climate change [27,28]. Moreover, spring–summer seasons may also increase the PM concentrations due to stationary air masses, intense secondary aerosol formation, and increased occurrences of forest fires [28–35]. In Korea, the PM concentrations are lower in summer than in other seasons because of active mixing by turbulent flow, such as rains and typhoons [36]. At the national level, a period of high PM concentrations due to large air currents appears as a seasonal feature; however, as the emissions of roads and automobiles, which are major pollutants in cities, are relatively...
constant throughout the year, the seasonal characteristics of PM in urban forests can be identified. In urban forests, the presence or absence of leaves according to the season plays a significant role in the increase or decrease in PM concentrations in the forest. Thus, the PM data before and after leaf development were analyzed.

The PM concentrations in urban forests were analyzed using the data for March–April (i.e., before willow leaf development) and May–September (i.e., after willow leaf development). The PM$_{10}$ concentrations in urban forests were higher than those in urban areas near road pollutants, but were lower after leaf development. The PM$_{2.5}$ concentrations were similar in urban forests and urban areas before leaf development, but were lower in urban forests after leaf development. For both PM$_{10}$ and PM$_{2.5}$, the difference in concentrations before and after leaf development was high in urban forests, and was lower in F2, where the canopy layer was more developed (Figure 3). These results are consistent with the previously published research findings that PM is adsorbed or adsorbed on the leaf surface and was blocked through the canopy layer, and the level of PM reduction increases as the canopy layer develops [13,16,20].

According to the results of diurnal changes in PM concentration, the concentrations of PM$_{10}$ and PM$_{2.5}$ were high at evening (19:00–24:00) and dawn (01:00–06:00) when the atmosphere was relatively stable. In addition, the PM concentration in the city may increase due to the increase in vehicular movement and atmospheric stability in urban areas during commuting hours [17,37]. Regarding the diurnal PM dynamics, the PM concentration may decrease due to dispersion of air as temperature and wind speeds gradually increase after noon (12:00) and humidity decreases. In other words, the difference in PM concentrations in the forest during the day is due to temperature and wind speed.

PM concentrations may increase with increased humidity in urban areas. As the atmospheric humidity increases, the amount of solar radiation decreases; thus, the heat from solar radiation is absorbed by the air, reducing the atmospheric temperature close to the Earth’s surface. As a result, the air layer close to the Earth’s surface is cooler than the upper layer, reducing the upgoing air currents and increasing the air pollutant concentrations on the surface. Additionally, during the night, as the temperature decreases, a temperature inversion occurs, which acts as a cap and inhibits the diffusion of PM [38,39].

### 4.2. Differences in PM Concentration between Two Different Forests

In the present study, significant differences in DBH, basal area, crown diameter, crown projection area, and stem volume were observed in the trees of urban forests F1 and F2. The development of the canopy layers is different in the two forests; F1 has a more developed canopy than F2 (Table 1). The WS and airflow in a forest are affected by the degree of canopy development or the difference in forest stand density [20,39,40]. Owing to these differences in the canopy layer, the wind speed within F1 was thought to be relatively lower than that in F2 and the concentrations of PM$_{10}$ and PM$_{2.5}$ were higher in F1 than in F2 regardless of the time of the day (Figure 2). This difference in PM concentrations is because the PM from the source settles downward by diffusion or gravity according to the airflow, as well as forest canopy as the study sites are located in the urban forest. PM is absorbed and adsorbed by the forest canopy, and the difference in airflow and turbulence occurs due to the density difference (canopy sparsity) of the forest, which may cause the difference in the PM concentrations in forests [20]. Similar differences for F1 and F2 were also found when seasonal comparisons between concentrations were analyzed before and after leaf development.

The wind speed at the road pollutant source point was more than twice as high as that at F1 and F2. PM may enter the urban forests F1 and F2 along with the wind blowing along the riverbank at the same height as the forest or with the wind blowing from the higher road level, which is the main pollution source. PM concentration is believed to be heavily affected by the wind blowing into the forest, and the pollution rose measured in C, F1, and F2 shows that the PM concentration and wind direction are different at each location (Figure 4, Table 3). These results showed further differences after leaf development.
According to the wind profile in forests in a previous study, wind speed is relatively high around the stem and decreases in the canopy layer. The characteristics of understory vegetation may also affect the airflow in forests. In addition, depending on the canopy sparsity of the forest and the difference in the density of the forest, the turbulence that occurs inside the forest also differs [20,40–42]. It is known that more turbulence occurs due to the increase in the space inside the forest due to the low density of the forest, and it is known that the decrease in wind speed is less in sparse forests than in dense forests [22,40–43]. F1 has less airflow in the forest due to the “umbrella effect” caused by the developed canopy; thus, it is expected that lower airflow and turbulence will occur in F1 rather than in F2. However, PM introduced into the forest is believed to be trapped inside the forest due to low airflow, turbulence, due reduced outflow, and thus maintains a high PM concentration in the forest.

The ecosystem services provided by forests are diverse [2,44,45]. Similarly, in cities where approximately 90% of the population of a country lives, the ecosystem services of urban forests are also diverse, and their value is increasing. Urban forests aim for the active use of forests by people, and therefore, appropriate forest implementation and management should be followed. Efforts are needed to develop a suitable urban forest model for each city and to maximize the function and effectiveness of urban forests. In this study, we found that urban forest density and canopy management are necessary to reduce the risk of PM exposure for people visiting urban forests that are located at a relatively lower level in the city. It is possible to control the concentration of PM in the forest by managing the canopy layer, controlling the density of the forest. Nonetheless, it is essential to manage urban forests, such as ecological parks, that are actively used by people. However, as the functions and effects of urban forests are very diverse, it is necessary to establish distinct management methods for different forests by using case studies rather than adopting the same management techniques in all urban forests. For people to safely use and enjoy urban forest services, research into changes in PM concentrations for diverse forest types and structures should be conducted through field measurements. Riparian forests, such as those in the Saetgang Park, require planned and periodic management to prevent PM trapping, and a management strategy for riparian forests is required to consider the aspect of water quantity control.

According to Sebastiani et al. (2021), urban green infrastructure (UGI) in the metropolis of Naples (Southern Italy) removes approximately 1148 Mg of PM$_{10}$ annually as an air quality improvement effect, for an annual monetary value of 36 million euros [46]. In addition, the total annual air quality improvement of the peri-urban vegetation of the national park in the Mexico City megalopolis was approximately 0.02% for CO, 1% for O$_3$, and 2% for PM$_{10}$, of the total annual concentrations for the three pollutants [47]. Thus, the benefits and challenges provided by each tree species should be given prior attention, and biological and economic value of their ecosystem services, which can support local managers and policymakers responsible for developing urban planning strategies, should be evaluated to ensure sustainable development and human well-being in metropolitan cities.

5. Conclusions

This study focused on the PM reduction function of urban forests, which is a key ecosystem service. Based on the actual PM concentration measurement, we analyzed the effect of reducing PM according to the forest structure. Particularly, we focused on the PM concentration characteristics of urban riparian forests, which are often used for outdoor walks in the COVID-19 era.

Diurnal and seasonal changes of PM$_{10}$ and PM$_{2.5}$ concentrations were analyzed for urban forests with different riparian forest structures located in Seoul. The PM concentration was found to be high regardless of the time of the day in the forests with a developed canopy layer. Similar results were found before and after leaf emergence compared with the seasonal PM concentration. Furthermore, the development of the canopy layer in riparian forests located lower than the road level causes pollution by trapping PM in the
inner forest. The reduction effect of PM in urban forests is affected by the wind direction, wind speed, vehicular traffic volume, tree characteristics, monthly mixing height, and large-scale airflow. Therefore, if an appropriate forest structure and a corresponding model is developed and implemented according to the forest location and various meteorological conditions, the PM concentration reduction function, one of the most important urban forest ecosystem services, is expected to be effectively expressed.

Moreover, UGI, green space, and green corridors, and their respective diversities, are important resources that should be preserved and increased to improve the environmental conditions and ameliorate the air quality in urban areas [48,49]. In particular, this study represents the important role of vegetation in improving the air quality in highly populated metropolitan areas, and emphasizes biodiversity conservation and the importance of green infrastructure provided by urban forests [49,50]. For the safe use of riparian forests, located in the urban area and used as a recreational site for many people, planned management of the canopy layer and underground vegetation is required to prevent PM trapping in the forests. In the future, research into strategies to maximize the effect of reducing PM concentrations through long-term monitoring in various urban forest types should be conducted.

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