Changes in particulate matter concentration and meteorological variables after changing forest structure in oak-dominated forests nearby highway tollgate

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ABSTRACT
Oak species are the major dominant tree species of deciduous forests, but the little study was conducted to understand the change of particulate matter concentration after changing the forest structure. This study analyzed the effects of changing forest structure (CFS) on the changes in meteorological factors and air particulate matter (PM) concentration after leaf emergence in oak-dominated forests nearby highway pollutants’ sources. In June 2019, 33% of the total trees were removed from the CFS of oak forests in the vicinity of the tollgate of Misiryeong in Goseong-gun, Gangwon-do, Korea. To understand the changes in leaf emergence between the treatment site (TRS is the site changing forest structure) and control site (CS), we investigated the foliage height profile (FHP, %) at each class of tree height in December 2019 and June 2020. The results showed that FHP (%) was lower in TRS than in CS in both months, and the FHP of the middle canopy class increased after TRS while that of the upper canopy class decreased. The correlation was significant with temperature in March ($p<0.01$) and with wind speed in June ($p<0.01$), indicating that CFS improved the airflow. There was no significant difference in the PM concentration between CS (PM$_{10}$: 37.7 μg/m$^3$, PM$_{2.5}$: 21.1 μg/m$^3$) and TRS (PM$_{10}$: 37.5 μg/m$^3$, PM$_{2.5}$: 20.8 μg/m$^3$) in March; however, the PM concentration in TRS (PM$_{10}$: 65.0 μg/m$^3$, PM$_{2.5}$: 26.2 μg/m$^3$) was lower than that in CS (PM$_{10}$: 73.9 μg/m$^3$, PM$_{2.5}$: 29.1 μg/m$^3$) in June. The rate of PM reduction (%) in TRS was higher in June (PM$_{10}$: 11.3%, PM$_{2.5}$: 10.0%) than in March (PM$_{10}$: 2.3%, PM$_{2.5}$: 4.0%). The low value of PM concentration in June could be related to the leaf emergence. Overall, the results indicated that meteorological factors and PM concentrations had changed in the inner part of the forest after leaf emergence and that the temperature and wind speed were strongly correlated with the PM concentration. These results suggest that CFS can change the forest structure and the airflow in oak-dominated forests, which PM can flow and settle down into the inner forest’s nearby pollutants sources of a tollgate. The results provide basic information for understanding the reduction effect of PM by CFS in oak-dominated deciduous forests nearby highway pollutants source.

1. Introduction
Forests have been found to be effective in absorbing air pollutants and improving air quality (Liu et al. 2016). Particulate matter (PM) reduction by forests depends on the composition and density of tree species at diverse spatial scales. At a leaf scale, the PM adsorption capacity of trees varies depending on the shape and area of the tree crown, leaf and branch density, and leaf microstructure (rough ware, trichomes, and wax layer) (Freer-Smith et al. 2005; Sgrigna et al. 2015). Coniferous trees are more effective in PM$_{10}$ adsorption than deciduous trees (Beckett et al. 2000; Litschike and Kuttler 2008), and especially evergreen coniferous trees having leaves with thick wax layers can adsorb pollutants throughout the year (Gao et al. 2015). Additionally, deciduous trees having leaves with rough surfaces are more effective in PM$_{2.5}$ adsorption than trees having leaves with smooth surfaces (Beckett et al. 2000). PM deposition by vegetation has been observed and studied, but the relative low roles in PM reduction were detected at deciduous forests (Cai et al. 2017), and the PM reduction effects of evergreen pine trees had been studied at the industrialized region of Korea (Yoo et al. 2020, 2021). At a tree scale, leaf area index (LAI), foliage profile (leaf area with height), and tree height could be vegetation structural parameters to alleviate the PM (Zhao et al. 2011). The leaf area index (LAI) and vertical foliage profile (VFP) are two key canopy structure parameters that quantify the distribution of foliage in the horizontal and vertical directions, respectively. Accurate estimation of the LAI and VFP is essential for promoting an understanding of the role of forest canopies in terrestrial ecosystems (Cui et al. 2020). At a stand scale, besides considering the characteristics of trees (e.g. species), the environmental conditions such as meteorological factors (e.g.
temperature, wind speed) and underlying types (forest types, building, street) could be factors to affect PM reduction (Han et al. 2020). Based on the urban forest types (shrubs, coniferous forests, and broad-leaved forests comprising evergreen trees, deciduous trees, and mixed forests), PM concentration is generally lower in summer and particularly, in mixed forests (Gao et al. 2015). Liu et al. (2015) reported that forest structure was the primary reason for the PM$_{2.5}$ concentration difference between different forests. And the deposition velocity onto the forest canopy was higher than which on the wetland and the water surface (Liu et al. 2016). Also, Oak species are the major broadleaf tree species in South Korea. Oak covers 24.2% of the total forest area, which is higher than that of pines (National Geographic Information Institute 2020). Therefore, it is a challenge to know the PM reduction effects in the oak-dominated forests in Korea, the proper management of the secondary oak-dominated forests could be an important task to increase the PM reduction effects in peri-urban forests, in Korea. CFS can promote forest health by increasing the amount of light and providing extra space for the growth of the remaining trees. Also, it can increase the wind speed that can facilitate the entry of PM into the forest; consequently, purified fresh air can be supplied externally. Previous reports indicated that the concentration of PM entering a green area from roads was higher than that from the outside of the road. This indicated that CFS plays a significant role in changing the airflow inside the forest (Chen et al. 2015). Based on the forest organization and management, meteorological factors change in the forest and the changes, in turn, affect the PM reduction ability of forests. Previously, studies on the PM removal amount and efficiency by different tree species have been conducted (Saebø et al. 2012; Cai et al. 2017), however, research on the effect of CFS on PM reduction and variations in meteorological conditions is insufficient. Therefore, this study has assessed the relationship between PM concentration and different meteorological factors by measuring the PM concentration in the treatment site (TRS) subjected to changing forest structure and control site (CS). And we performed research on the effect of changing the forest structure on the PM concentration. This study will provide a basic information for understanding the PM concentration change after leaf emergence in oak-dominated forests.

The study site is located in the forest near Misiryeyong TG, the source of air pollutants in the west. The CFS in the treatment site (TRS, 38°12′55.91″ N, 128°29′21.73″ E) was conducted in June 2019. To facilitate airflow, from March to June 2019, 33% of the total trees were removed from TRS based on the forest tending procedure of the Korea Forest Service. In order to compare and analyze the PM reduction effect, the control site (CS, 38°12′57.17″ N, 128°29′21.52″ E) was selected about 40 m away from the TRS (Figure 1, Table 1). As a result of the wind rising at the study site, the direction of the main wind was the northwest wind series and it mainly appeared in winter (from October to December) and spring (from January to May) (Figure 1).

Before changing the structure of the forest, the upper (dominant ration; 70.1%) and middle layer (dominant ration; 80.8%) class of these forests was composed of Quercus variabilis Blume and the lower layer class was composed of Quercus variabilis Blume (dominant ration; 42.3%), Quercus mongolica Fisch. ex Ledeb (dominant ration; 44.8%). After changing the structure of the forest, the upper layer class of these forests was composed of Quercus variabilis Blume (dominant ration; 45.5%), Pinus densiflora Siebold & Zucc (dominant ration; 54.5%) and the middle layer class was composed of Quercus variabilis Blume (dominant ration; 91.4%), the lower layer class was composed of Quercus mongolica Fisch. ex Ledeb. (dominant ration; 65.1%) (Table 2). The ratio (%) of dominant species allows us to understand the vertical structure of forests before and after CFS.

### 2.2. Analysis of foliage height profile (FHP, %)

After performing CFS, we investigated the FHP to calculate the vertical distribution of relative coverages in December 2019 and June 2020. To analyze the spatial stand structure changes in TRS and CS, we investigated the foliage height profile (FHP, %) of the two sites. After arbitrarily setting three virtual cylinders (diameter = 20 m) in a 20 × 20 m arbitrary plot, we classified the foliage based on the height ranges of low layer class (0–2 m), middle layer class (4–6 m, 6–8 m), upper layer class (10–12 m, 12–14 m, 14–16 m), and lower layer class (0–2 m, 2–4 m). The FHP of each site was used to calculate the average value of coverage (%) by tree height in each site. Values of 0, 1, 2, 3, 4, and 5 were assigned if the FHP was 0%, 1–20%, 21–40%, 41–60%, 61–80%, and 81–100%, respectively (Figure 2). The FHP was calculated twice, in December 2019 when CFS was conducted and in June 2020 when the following year’s leaf burst timing was complete. PM concentration and meteorological factors were determined in

| Study site | Height above sea level (m) | Aspects | Inclined slope (°) | Average age class | Dominant species |
|-----------|---------------------------|---------|------------------|------------------|-----------------|
| CS (control site) | 198–280 | NE–S | 14–28 | V | Quercus variabilis Blume. |
| TRS (treatment site)* | 244 | SE | 24 | V | Quercus variabilis Blume. |

*TRS (Treatment Site): This site is the CFS (changing forest structure) by removing trees.

**Table 1.** Location of the study site in Wonam-ri, Toseong-Myeon, Goseong-gun, Gangwon-do in the Republic of Korea.
TRS and CS in both March and June 2020, to include the leaf emergence time.

2.3. Measure of PM concentration and weather factors according to CFS

A light scattering-type PM measuring device (Turnkey, UK, ± 5% accuracy), with high mobility, is capable of real-time measurements (TSP, PM$_{10}$, PM$_{2.5}$). The use of Dustmate for measuring PM concentrations was successfully demonstrated by previous studies (Chen et al. 2015; Wu et al. 2018). We excluded the PM data when humidity values were over 80% to prevent the overestimation of PM concentration (Yoo et al. 2020). To consider the average breathing rate of people, we installed the device at a height of 1.5 m. PM concentration was measured for 24 h at intervals of 1 s; subsequently, the average values of the acquired data were calculated every 5 min. Further, we measured meteorological factors (temperature, °C; relative humidity, RH, %; wind speed, m/s) for 24 h using portable equipment.

Table 2. The stand structure of treatment site after CFS.

| Study site (TRS) | Dominant species (Dominant ratio, %) | Number of trees (trees/ha) | Average Diameter at Breast Height (DBH) (cm) | Average height (m) | Breast cross-sectional area (m$^2$/ha) | Volume (m$^3$/ha) |
|------------------|--------------------------------------|----------------------------|---------------------------------------------|-------------------|---------------------------------------|-----------------|
| Before CFS       |                                      |                            |                                             |                   |                                       |                 |
| Upper layer class| Quercus variabilis Blume (70.1)      | 525                        | 20.9 ± 4.7                                  | 12.6 ± 0.7        | 18.8                                   | 117.8           |
|                  | Larix kaempferi (Lamb.) Carrière (17.9) |                            |                                             |                   |                                       |                 |
|                  | Pinus densiflora Siebold & Zucc. (7.9) |                            |                                             |                   |                                       |                 |
|                  | Quercus mongolica Fisch. ex Ledeb. (4.1) |                            |                                             |                   |                                       |                 |
| Middle layer class| Quercus variabilis Blume. (80.8) | 1,000                      | 15.4 ± 3.0                                  | 10.4 ± 1.2        | 19.23                                  | 102.9           |
|                  | Larix kaempferi (Lamb.) Carrière (8.5) |                            |                                             |                   |                                       |                 |
|                  | Quercus mongolica Fisch. ex Ledeb. (6.7) |                            |                                             |                   |                                       |                 |
|                  | Quercus serrata Murray (4.0)         |                            |                                             |                   |                                       |                 |
| Low layer class  | Quercus variabilis Blume. (42.3)     | 375                        | 4.6 ± 2.0                                   | 3.3 ± 1.5         | –                                      | –               |
|                  | Quercus mongolica Fisch. ex Ledeb. (44.8) |                            |                                             |                   |                                       |                 |
|                  | Quercus serrata Murray (12.9)        |                            |                                             |                   |                                       |                 |
| After CFS        |                                      |                            |                                             |                   |                                       |                 |
| Upper layer class| Quercus variabilis Blume (45.5)      | 275                        | 21.6 ± 8.4                                  | 12.6 ± 0.6        | 11.44                                  | 71.9            |
|                  | Pinus densiflora Siebold & Zucc. (54.5) |                            |                                             |                   |                                       |                 |
| Middle layer class| Quercus variabilis Blume. (91.4)   | 650                        | 15.3 ± 3.0                                  | 10.5 ± 1.1        | 12.4                                   | 65.7            |
|                  | Larix kaempferi (Lamb.) Carrière (3.3) |                            |                                             |                   |                                       |                 |
|                  | Pinus densiflora Siebold & Zucc. (5.3) |                            |                                             |                   |                                       |                 |
| Low layer class  | Quercus variabilis Blume. (26.3)     | 700                        | 4.4 ± 1.8                                   | 4.1 ± 1.3         | –                                      | –               |
|                  | Styrax japonicus Siebold & Zucc. (2.6) |                            |                                             |                   |                                       |                 |
|                  | Fraxinus rhynchophylla Hance (2.5)    |                            |                                             |                   |                                       |                 |
|                  | Quercus Mongolica Fisch. ex Ledeb. (65.1) |                            |                                             |                   |                                       |                 |
|                  | Abies holophylla Maxim. (3.5)        |                            |                                             |                   |                                       |                 |

Source: Korea Forest Service.
It is difficult to represent the monthly PM concentration because PM measurement was carried out for just 1 day. However, we identified days with monthly weather characteristics in advance and previous studies also showed monthly PM concentration by measuring PM for a short time (Gao et al., 2020; Yoo et al. 2020). So, we can speculate that our measuring data can show the feature of monthly PM. We measured PM concentration and weather factors for 24 h at the same time with one device for each study site (CS, TRS). The reduction rate (%) of PM concentration was calculated as follows (Equation 1):

\[
\text{PM reduction rate} \% = \left( \frac{C_{\text{con}} - C}{C_{\text{con}}} \right) \times 100 \% 
\]

where \( C \) is the PM concentration of TRS (\( \mu g/m^3 \)) and \( C_{\text{con}} \) is the PM concentration of CS (\( \mu g/m^3 \)).

### 2.4. Statistical analysis

Simple linear regression and Pearson’s correlation were used to analyze the relationship between meteorological factors and PM concentration. To determine whether the PM concentration differed significantly between CS and TRS and between June and March, a one-way analysis of variance was used. The significance of differences between the calculated mean values was tested using Duncan’s honest significance difference test. Results were considered significant at *\( p < 0.05 \) and **\( p < 0.01 \) and R statistical free software v.3.0.2 (R Core Development Team 2019, http://cran.seoul.go.kr/) for all statistical analysis.

### 3. Results and discussion

#### 3.1. Changes in FHP by CFS and leaf emergence

The FHP in December 2019, six months after conducting CFS, was higher in CS than in TRS (Figure 3). At a vertical height, there was no significant difference in the FHP between CS and TRS from 4 to 8 meters in the tree height, but there was a significant difference from the tree heights from 8 to 18 meters. In the oak-dominated forests, the small portion of pine trees (Pinus densiflora) was attributed to the increase of FHP from 12 to 14 meters in the tree height, the FHP in CS was approximately 40% higher than in TRS. When the leaf emergence was complete in June of the following year, FHP was higher in CS than in TRS (at 12–14 m tree height), and it was 35% and 30% higher in CS than in TRS at the tree heights from 4 to 6 meters and 6 to 8 meters, respectively. In particular, as oak trees were mainly distributed over a tree height of 8–10 m, CS recorded higher FHP than TRS (by more than 50%).

The survey site was characterized majorly by trees of more than 8 m in height and by the sparse
distribution of low vegetation and shrubs. The FHP in CS for each canopy layer was higher than that in TRS, and the FHP of CS and TRS differed by more than 50% or more from the 8 to 10 meters heights in June 2020, after the leaf emergence of *Quercus variabilis* Blume was finished.

The results indicated that CFS reduced the density of the upper canopy class. The canopy growth of the low and middle canopy classes increased with the increase in the amount of light, thereby increasing the FHP after leaf emergence. As CFS can change the meteorological factors of wind speed and relative humidity of the forests stands. Therefore, CFS can reduce the PM deposition rate in the crown layer and allow PM to remain in the crown layer for long periods (Vesala et al. 2005). However, in a viewpoint of leaf emergence, leaves and twigs can increase the adsorption ability of PM in June than March. In the leaf emergence scale, the adsorption ability can affect the PM reduction effects, but in an oak-stand scale, the CFS can change the meteorological factors of wind speed and relative humidity affecting the deposition ability in the forests. This study could not divide the effect of leaf emergence and CFS on the function of adsorption and deposition in a field condition. However, the CFS procedure can initiate the PM difference between CS and TRS sites in this experiment, further field study could be needed to divide the compounding effects of leaf emergence and CFS.

### 3.2. Correlation between meteorological factors and PM concentration

We measured temperature, RH, and wind speed along with the PM concentration in TRS and CS. The corresponding results are shown in Figure 4. In March, there was no significant difference in temperature between TRS and CS. RH was the highest in CS (68.9%) and TRS (68.0%) at 10:00 h, and the lowest (20.0% and 19.6%, respectively) at 12:00 h. Further, the temperature was the highest at 07:00 h. (CS: 15°C, TRS: 15.1°C) and the lowest at 00:00 h (CS: 4.8°C, TRS: 5.0°C), and the wind speed was the highest at 07:00 h (CS: 4.4 m/s, TRS: 4.8 m/s). In June, RH in CS and TRS was the highest at 87.8% and 87.3% at 12:00 h, respectively, and the lowest at 48.2% and 46.7%, respectively, at 10:00 h. Further, the temperature was the highest at 11:00 h (CS: 25.5°C, TRS: 27.0°C) and the lowest at 00:00 h (CS: 14.9°C, TRS: 14.8°C), and the wind speed was higher in TRS after 4:00 and 19:00 h than in CS, with the maximum wind speeds observed at 22:00 h (CS: 1.2 m/s, TRS: 2.0 m/s).

To analyze the correlation between PM concentration and meteorological factors in the forest sites and to conduct simple linear regression, temperature, RH, and wind speed were measured every 5 min for 24 h in March and June. In both CS and TRS in March, the R² value between the PM$_{10}$, PM$_{2.5}$, and the temperature was 0.5 or higher, and that between PM$_{10}$, PM$_{2.5}$, and wind speed was 0.4 or higher in June (Figure 5). Further, the PM concentration was positively correlated with temperature in March and with wind speed in June.

When the forest density is high, the air becomes turbulent, and when the forest density is low, air enters the forest and filters pollutants (Bernatzky 1983). As CFS controlled the forest density, RH was high in March and June with CS having high forest density. In June, when the leaf emergence of oak forests was complete, wind speed differed between CS and TRS. Further, during these months, temperature and wind speed were higher in TRS than in CS. Inside the forest, wind speed is related to the deposition speed of PM (Spitsyna and Skripalshchikova 1991). Also, low wind speed, temperature, and vertical turbulence, an increase
combine to cause slow particle diffusion and, hence, an increase in the concentration of PM (Sun et al. 2013). And during summer, the high relative humidity and lush vegetations accelerate dry deposition, and consequently, PM concentration reaches their lowest levels (Zhai et al. 2019). At a forest stand level, the CFS can change the meteorological factors of wind speed and relative humidity, and pollutants could settle

Figure 4. Meteorological conditions in different months for CS and TRS in March (a, b) and June (c, d).

Figure 5. Simple linear regression of PM concentration and meteorological factors. (a–c) CS–March, (d–f) TRS–March, (g–i) CS–June, and (j–l) TRS–June.
differed. In TRS, PM10 was not significantly correlated with TSP and PM2.5, which have large-sized particles, whereas the concentration of PM2.5 was high in June, whereas the concentration of PM2.5 and PM10 was almost similar in March and June. These results indicate the importance of meteorological and ground conditions should be considered to increase the dispersion and the deposition ability of PM in forests (Janhall 2015).

To analyze the correlation between PM concentration and meteorological factors by season and treatment site, we calculated and analyzed the average value of these variables measured every 5 min for 24 h. In March, the correlation of PM10 and PM2.5 in CS and TRS both with temperature and RH was significant (p < 0.01 and p < 0.05, respectively) (Table 4). In June, the correlation of PM10 and PM2.5 with wind speed was significantly high in CS (p < 0.01), whereas that with temperature and RH was not significantly differed. In TRS, PM10 was not significantly correlated with meteorological factors, whereas it was significantly correlated with wind speed (p < 0.01), similar to that observed in CS. Previous studies have demonstrated that diurnal variations in PM2.5 and PM10 are influenced by wind speed, temperature, and relative humidity (Peng et al. 2011; Zhai et al. 2019).

PM concentrations are generally high during January–March and low from June–August (Gehrig and Buchmann 2003; Wu et al. 2007; Xu et al. 2007; Gao et al. 2015; Han et al. 2017). But this study, the average overall PM concentration was lower in March than in June. But the differences in the individual PM2.5 and PM10 concentrations were significant in March, with PM10 concentration being 20 μg/m³ or more. The concentration of total suspended particulates (TSP) and PM10, which have large-sized particles, was high in June, whereas the concentration of PM2.5 and PM10 was almost similar in March and June. These results indicate the importance of meteorological data in the interpretation of PM reduction in forests areas. Slinn (1982) reported that the diameter size of fine dust particles affects the PM deposition speed and is an essential factor in depositing PM of less than 10 μm size because the deposition of this PM generally decreases until reaching a minimum size of 0.3 μm. This is because as the diameter of the PM decreases, the acceleration of PM (to deposit) due to gravity decreases (Lee and Ramamurthi 1993). In addition, PM deposition on the plant surface is affected by factors, such as RH, wind speed, turbulence, and the PM shape and diameter, all of which affect the plant purification or PM deposition rate (Litschke and Kuttler 2008). The particle dry deposition velocity (Vd) mainly depends on the particle size and meteorological conditions (Zhang et al. 2001). In addition, for the vegetation underlying layer, Vd is not only dependent on meteorological factors, but also on the species, leaf area index (LAI), canopy height and other vegetation characteristic values (Han et al. 2020). Therefore, in this study, it was judged that forest density control by CFS reduced the PM concentration by affecting the PM deposition speed and adsorption by trees and changing the meteorological variables.

### 3.3. Changes in PM concentration and reduction rate (%)

PM concentration was measured every 5 min for 24 h to analyze the average PM concentration by particle size (Figure 6). In March, in CS and TRS, the maximum TSP concentrations were 153.8 μg/m³ and 152.4 μg/m³, respectively, and the average PM10 concentrations were CS 37.4 μg/m³ and TRS 37.3 μg/m³, respectively, and PM2.5 concentrations were CS 21.0 μg/m³ and TRS 20.7 μg/m³ respectively.
In June, in CS and TRS, the maximum TPS concentrations were 117.0 \( \mu \text{g/m}^3 \) and 128.8 \( \mu \text{g/m}^3 \), respectively, maximum PM10 concentrations were 21.6 \( \mu \text{g/m}^3 \) and 20.4 \( \mu \text{g/m}^3 \), respectively, but the average PM10 (49.7 \( \mu \text{g/m}^3 \) and 47.5 \( \mu \text{g/m}^3 \), respectively) and PM2.5 concentrations were low. The average PM concentration was lower in March than in June, but the difference by particle size was significant. In particular, the variation in PM10 concentration in March (up to 20 \( \mu \text{g/m}^3 \) or more) was more significant than that in June (10 \( \mu \text{g/m}^3 \)).

To analyze the effect of TRS on PM reduction, we measured PM10 and PM2.5 concentrations for 24 h, and the average concentrations were compared (Figure 7). Overall, PM concentration was higher in June than in March. In addition, there was no significant difference in the PM concentration between TRS and CS in March (CS: PM10, 37.7 ± 4.67 \( \mu \text{g/m}^3 \) and PM2.5, 21.1 ± 3.19 \( \mu \text{g/m}^3 \); TRS: PM10, 37.5 ± 4.78 \( \mu \text{g/m}^3 \) and PM2.5, 20.83 ± 3.19 \( \mu \text{g/m}^3 \)), but PM10 and PM2.5 concentrations in June were lower in TRS than in CS (CS: PM10, 73.9 ± 5.41 \( \mu \text{g/m}^3 \) and PM2.5, 29.1 ± 2.07 \( \mu \text{g/m}^3 \); TRS: PM10, 65.0 ± 4.41 \( \mu \text{g/m}^3 \) and PM2.5, 26.2 ± 1.82 \( \mu \text{g/m}^3 \)). Furthermore, the PM reduction rate in TRS was higher in June (PM10: 11.3%, PM2.5: 10.0%) than in March (PM10: 2.3%, PM2.5: 4.0%).

PM concentration is seasonally affected by the stagnation of air pollutants caused by seasonal differences in atmospheric-mixed height and the occurrence of a temperature inversion layer (Park et al. 2002; Han et al. 2017). In addition, PM concentration is greatly affected by local pollutants and yellow dust, and cross-boundary pollutants. In this study, PM concentration was higher in June than in March. However, the maximum and minimum deviations by fine dust particle size were more elevated in March (Figure 5), thus, showing seasonal characteristics. However, these results need to be further supplemented through long-term monitoring for a more accurate analysis. The PM reduction rate in both TRS and CS was high in June. This could be attributed to the leaf burst timing, which was complete in June, in the research site dominated by oak forests, which are broad-leaved trees. Oak has large leaves and a high crown density, and the forest density increases in June when the leaf burst timing is completed. Changes in TSP and PM10 concentrations of these forests differ from those of herbaceous plants and trees (Chen et al. 2017), and PM reduction by trees is highly related to tree growth and metabolism, forest density, wind speed, and deposition by rainfall (Gao et al. 2015).

The growth of trees, that is, an increase in the leaf area, is an important factor in absorbing fine dust. The results of this study showed a higher PM reduction rate between CS and TRS in June than in March. This could be possible because of the blocking effect of leaves and canopy. Jin et al. (2014) reported a PM reduction rate of 50–60% by reducing the canopy density and stated that proper pruning, which reduces the canopy density and area, facilitates airflow in the

![Figure 6. PM concentrations (\( \mu \text{g/m}^3 \)) were measured for 24 h for four particle size classes. Values are given as mean ± standard error in (a) March and (b) June.](image1)

![Figure 7. Average PM concentration (left, \( \mu \text{g/m}^3 \)) and PM reduction rate (right, %) in the oak forests in (a) March and (b) June.](image2)
forest and lowers air pollution. Tree species and their structure and leaf shapes are key factors responsible for the deposition and resuspension of dust (Litschike and Kuttler 2008).

In CS (control site) like the pollutants trap, it seems that PM could not escape due to its dense forest structure (Figure 3) and continuous input of pollutants nearby traffic roads. Therefore, the increase in PM concentration could be related to air stagnation at a small spatial scale. However, in TRS (Treatment site) like pollutants filter, it seems that PM could be absorbed and deposited with the micro-structure of leaf, twigs, branches and trunks in structurally changed filters of oak forests. Leaf growth in June could explain the filter effects rather than the trap effect in March. However, the long-term monitoring including resuspension of PM could ascertain the filter effect of forests. These results could indicate the possibility of forests as a filter than trap with a proper application of CFS at a small spatial scale.

4. Conclusions

This study was conducted to understand the correlation between PM reduction and meteorological factors in oak forests through CFS. We measured the PM concentrations and meteorological factors in March (spring) and June (summer) to understand the seasonal effects of broad-leaved trees according to the leaf burst timing. The research results for each study are summarized as follows.

1. FPH (%) by CFS: After performing CFS, in both December 2019 and June 2020, the FHP (%) in CS for each canopy layer was higher than that in TRS; moreover, the FHP (%) of CS and TRS differed by more than 50% or more (8–10 m tree height) in June 2020. We knew that the forest density of the upper and middle canopy layers in CS was higher than that of the TRS.

2. PM concentration and meteorological factors: RH was higher and wind speed was lower in June than in March. In both March and June, the wind speed in TRS was slightly higher than that in CS, indicating that airflow increased as the forest density was reduced after CFS. The correlation between PM concentration and RH and temperature in March and between PM concentration and wind speed in June was significant ($p < 0.01$, $p < 0.01$, respectively). Although the average overall PM concentration did not significantly differ between CS and TRS in March, it was lower in TRS than in CS June. The average concentration of PM$_{10}$ was higher in June (35 μg/m$^3$) than in March (27 μg/m$^3$). The PM reduction rate was also higher in June (PM$_{10}$: 11.3%, PM$_{2.5}$: 10.0%) than in March (PM$_{10}$: 2.3%, PM$_{2.5}$: 4.0%).

Through the changing forest structure (CFS), we improved the airflow by increasing space and providing light inside the forest. So, changing the structure of the forest prevents air stagnation inside the forest and improves the growth of the middle and lower vegetation. Particularly, changes in wind speed were related to the PM deposition rate; the higher the deposition speed, the lower the resuspension rate (Witherspoon and Taylor 1969; Sehmel 1980; Nicholson 1988); therefore, density control through CFS in broad-leaved forests was considered a significant factor in reducing PM concentration. This study will provide basic information for understanding the PM concentration change after leaf emergence in oak-dominated forests. However, this study was conducted for a short period of time and measured PM concentration in the horizontal direction. Thus, it is difficult to completely confirm the changes in PM concentration due to CFS. In future studies, long-term monitoring is needed to identify the changes in the characteristics of PM reduction in CFS. And the measurement of vertical PM concentration including resuspension would be necessary to observe PM for each canopy layer and calculate the deposition rate of PM.

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Author contributions

Sumin Choi: study designing, running simulations and optimizations, result analysis, manuscript writing. Sin-Yee Yoo: study designing, data collection, PM data analysis; Jaeho Yeo: data collection, PM data analysis; Chan-ryul Park: manuscript writing and revision.

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