A 10-Year Analysis on the Reduction of Particulate Matter at the Green Buffer of the Sihwa Industrial Complex

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Abstract: Green buffer (GB) zones are designed to prevent the spread of air pollutants and odors from industrial complexes (ICs) to residential areas (RAs). We analyzed changes in the concentration of particulate matter (PM) and the number of high PM pollution days for 10 years after the GB was implemented, using the National Atmospheric Environmental Research Stations 2001–2018 dataset. We also performed field measurements of PM10 and PM2.5 from February 2018 to January 2019 to analyze the PM concentrations at human breathing height throughout the GB. Before GB implementation (2001–2006), PM10 in the RA was 9% higher than that in the IC. After GB zone implementation (2013–2018), PM10 in the RA was 11% lower than that in the IC. Furthermore, the PM concentration in the RA (slope = ∆Concentration/∆Time, −2.09) rapidly decreased compared to that in the IC (slope = −1.02) and the western coastal area (WCA) (slope = −1.55) over the 10-year period. At PM concentrations at human breathing height, PM10 and PM2.5 in the RA were lower than those in the IC by 27% and 26%, respectively. After GB implementation, the wind speed was positively correlated but SOx was negatively correlated with the PM reduction rate at a local scale. These results show that there was a reduction of PM during and after GB implementation, implying the need for proper management of GBs and continuous measurement of pollutant sources at the green buffers of industrial complexes.

Keywords: green buffer; PM reduction; vegetation stabilization; Sihwa industrial complex; emission source; tree management

1. Introduction

Large quantities of nitrogen oxides (NOx) and sulfur oxides (SOx) in industrial complexes (ICs) act as particulate matter (PM) precursors and spread to the residential areas (RAs), affecting the health of urban residents [1–3]. Therefore, there is a legal obligation to design a green buffer (GB) zone to reduce the effects of PM emitted from ICs. The GB is a green area implemented to prevent air pollution, noise, and odor from the IC. The GB can be used for managing urban air quality and as a leisure area due to its high accessibility to urban residents and PM-reducing effects [4–7].

The GB zone can reduce PM through the following mechanisms: PM absorption through stomata in leaves [8,9], PM adsorption by the forest structure [10,11], and PM blocking and deposition due to changes in weather conditions inside the forest [12–14]. In addition, the PM reduction effect of the GB can be affected by the season and the forest structure. In summer, the leafy season, the absorption and adsorption of PM through the leaves has been found to actively occur [3], and the PM reduction in the leaf maturity phase has been found to be affected by wind speed [15,16] and high rainfall quantity and duration [17].
The forest structure is related to airflow and PM movement. Excessively dense forests could interfere with smooth airflow, leading to stagnant PM and high PM levels, as has been observed in previous studies [18–20]. In order to increase the PM reduction through the forest, a forest structure with dense vegetation as well as adequate ventilation can be constructed [9,21]. It is important to consider the season and forest structure together to identify the characteristics of PM reduction in a GB zone.

Few studies have been conducted in such forests, with field data at a human-breathing-height level as well as on a regional scale to confirm the PM reduction effect of GB zones. Therefore, this study was conducted on a GB zone created near the Sihwa IC, a major domestic IC, to identify the PM reduction effects at a human detection level and at a regional scale.

The research objectives were (1) to determine the 10-year change in PM concentration after the GB zone was installed in the landscape and (2) to analyze the PM reduction in the GB zone by measuring the PM concentration at a human detection level and on a regional scale. These results can provide information on the ecosystem services and the benefits for environmental taxation of GB zones in industrial complexes.

2. Materials and Methods

2.1. Study Site

The study site, the Sihwa industrial complex (37°20′ N, 126°46′ E), is a medium-sized IC that includes various industries, such as steel and machinery. This is one of the top three ICs in Korea, along with Banwol and Namdong ICs. The major air pollutants in the Sihwa IC are NOx and SOx, which are emitted from the operation of trucks and ships and fossil-fuel combustion from manufacturing industries [22]. As the Sihwa IC is close to the west coast, a strong northwest wind blows inland from the coast.

The GB zone in Sihwa (37°20′ N, 126°43′ E) was installed to prevent air pollutants from the IC spreading to the RA. This green area was created by reclaiming the mudflat area in 2000. However, the trees were small and planted at low densities, which did not reduce air pollution. Thus, the GB zone was supplemented with additional trees from 2006 to 2012 (Figure 1). At the end of GB implementation, tree height changed from 5~6 m to 8~12 m. Green land capacity (2.02 m³/m²) also increased by 108 % compared to 2006 (0.97 m³/m²). The GB zone is 64.0 ha (length: 3.46 km, width: 0.15–0.25 km, height: 10 m) and consists of diverse trees (Pinus thunbergii and Pinus densiflora) and shrubs [23].
2.2. PM Analysis of Long-Term Monitored Data at a Local Scale

To analyze the long-term changes in PM$_{10}$ concentration before and after the implementation of the GB near the Sihwa IC at a local scale, we used PM data from the national atmospheric environmental research station (NAERS) (Figure 2). We investigated the monthly PM$_{10}$ at NAERS located in the IC and RA (NAERS-IC: 37°20′ N, 126°43′ E; NAERS-RA: 37°20′ N, 126°44′ E, respectively) ($n = 30$ or 31 per month). Since the NAERS began measuring PM$_{2.5}$ in only 2015, this study used the PM$_{10}$ data. To identify PM reduction from the GB, we compared the NAERS data to the monthly PM$_{10}$ of the west coast area (Gwangmyeong, Ansan, Pyeongtaek, Bucheon, Osan, Hwaseong, Siheung; WCA) where the government’s regulations on large PM emission sources are strongly enforced ($n = 30$ or 31 per month). Based on monthly PM data by year ($n = 12$ per year), we analyzed the annual PM$_{10}$ concentration and the trends of PM concentration line slope ($\Delta$Concentration/ $\Delta$Time) over time for yearly data. Also, we calculated the reduction rates of PM (Equation (1)) and the number of high PM pollution days (a daily average PM$_{10}$ concentration $\geq 81$ μg/m$^3$) in the NAERS-IC and NAERS-RA.

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

where $C_{IC}$ is the PM concentration near the IC and $C_{RA}$ is the PM concentration near the RA.
Figure 2. The location of the national atmospheric environmental research station (NAERS) and observed points (OPs) nearby the industrial complex (IC) residential area (RA), and west coast area (WCA), Gyeonggi-do, Korea.

2.3. Correlation Analysis between PM Reduction Rates and Factors at a Regional Scale

The PM reduction rates are affected by the amount of emitted air pollutants, meteorological factors and vegetation vitality. In order to identify the factors in PM reduction rate from the start of GB implementation (After 2006), the correlation between annual PM reduction rate, air pollutant emissions, weather factors and normalized difference vegetation index (NDVI) was analyzed. We used the amount of annual air pollutant emissions in Siheung from the National Air Pollutants Emission Service, based on NAERS measuring data. Nitrogen oxides (NOx) and sulfur oxides (SOx) are mainly produced by Sihwa IC as a result of automotive, metal and plastic manufacturing industries, which burn fossil-fuel. We selected NOx and SOx emissions, as they can represent the characteristics of air pollutant emissions in the Sihwa IC. The amount of emitted NOx and SOx are not only precursors of PM but also can produce secondary PM through chemical reactions in the atmosphere [2,3]. Thus, PM emissions were not considered separately in this study. Since these data are announced every 2 years, we used data up to 2017 for analysis in this study. Annual weather factors (temperature, wind speed, annual precipitation) were measured by the National Weather Service (37°23' N, 126°46' E). The weather station is representative of weather factors in Siheung City and nearby the study site. We thought this station could represent the weather factors for the measuring points. To verify the annual degree of vegetation density of the GB, we utilized NDVI by using USGS Landsat 7 Reflectance Tier 1 among the dataset provided by Google Earth engine (https://developers.google.com/earth-engine/datasets/catalog/LANDSAT_LE07_C01_T1_SR; accessed 3 March 2021). NDVI calculated the median value of satellite images every 2 months from 2006 to 2017 at 13 locations in the GB zone (e.g., NDVI2017.01 = the median NDVI value between 2016.12 and 2017.02). The median value minimizes the effect of ideal value.

As we sought to identify the PM reduction rate as a result of GB implementation, we focused on the period during and after GB implementation. We grouped the annual PM reduction rate, air pollutant emissions, weather factors and NDVI during and after the implementation of GB. We performed Pearson correlation analysis among these grouped data using R version 3.0.2 (R Core Development Team 2019, Vienna, Austria), and statistical significance was set at \( p \)-value < 0.05.
2.4. PM Measurement at Human Breathing Height

To confirm the actual PM reduction effect from the GB, we measured PM using mobile PM measurement equipment. The PM observation points were selected to be two points (OP-IC: 37°20′ N, 126°43′ E; OP-RA: 37°20′ N, 126°44′ E) adjacent to the NAERS (within 500 m) (Figure 2). As the Sihwa Ic has the wind blowing in the northwest direction from the coast to land, the OP-RA located at northern part of the GB zone was the optimum observation point to represent the PM changes through the GB. The distance between the OP-IC and the GB zone is 1 km, and the distance between the OP-RA and the GB zone is 0.76 km. The OP-IC consists of *Pinus strobus* (4.5 trees/100 m²) and *Pseudocydonia sinensis* (0.5 trees/100 m²). The OP-RA is dominated by *Pinus rigida* (8.75 trees/100 m²) and *Pinus densiflora* (0.5 trees/100 m²) [24].

The PM measuring device, Dustmate (Turnkey, UK, ±0.5% accuracy), was installed 1.5 m above the ground, reflecting the height at which humans breathe. The use of Dustmate for analyzing PM concentrations was successfully demonstrated by previous studies [25,26]. Dustmate can measure the real time PM concentration using the light scattering method. However, humidity interferes with the light scattering method, resulting in the overestimation of the PM concentration [27,28]. Thus, we excluded the PM data when humidity values were over 80% to prevent overestimation of PM concentration. From February 2018 to January 2019, we measured PM$_{10}$ and PM$_{2.5}$ concentration for 24 h, once a month. The PM data was measured at intervals of 1 s, and we used the average over a 5 min period for our dataset. We calculated the monthly concentration and PM reduction rate (Equation (1)) for the measured data. It is difficult to represent the monthly PM concentration because PM measurement was carried out during just 1 day. However, we identified days with monthly weather characteristics in advance, and previous studies also showed monthly PM concentrations as a result of measuring PM for a short time [24,29]. So, we can speculate that our measuring data can show the feature of monthly PM.

3. Results

3.1. PM Reduction at a Local Scale

3.1.1. PM Reduction Effect of the GB

From 2001 to 2006, the average PM$_{10}$ concentration in NAERS-RA was 9.4% higher than that in NAERS-IC (Figure 3a). With the start of the implementation of the GB zone in 2006, the difference in PM$_{10}$ concentration between NAERS-IC and NAERS-RA gradually decreased, and the PM in NAERS-IC was higher than that in the NAERS-RA in 2010. After installing the GB (2013–2018), the PM in the NAERS-RA has remained 10.5% lower on average than in the NAERS-IC. The trend line slope ($\Delta$Concentration/$\Delta$Time), which showed PM$_{10}$ concentration gradient over time, was the highest as a value ($-2.09$) of slope in NAERS-RA and the lowest as a value ($-1.02$) of slope in the NAERS-IC (Figure 3a). The concentration changes over time showed a value of slope of $-1.55$ in the western coastal area (WCA) over the 10-year period.

The PM$_{10}$ reduction rate in the GB zone also showed a similar tendency to the changes in PM$_{10}$ concentration (Figure 3b). The PM reduction rate was the lowest, at $-21.3\%$, in 2005, just before the start of the GB installation. After 2006, the reduction rate began to increase slowly, and a positive reduction rate was first observed in 2010, at 14.1%. PM$_{10}$ reduction in the GB zone has continued to show positive values, with the highest PM$_{10}$ reduction effect observed in 2016. The reduction rate in 2018 was 6.2%, although it was lower than before. The average annual deviation of PM reduction rate was ±17.6 before the implementation of GB. The variability of PM reduction rate decreased since 2010 (±2.8) and showed stable value after the implementation of GB (±5.7).
Figure 3. (a) The average annual PM$_{10}$ concentration ($\mu$g/m$^3$) in the NAERS-RA (National atmospheric environmental research station nearby residential area), NAERS-IC (National atmospheric environmental research station nearby industrial complex) and WCA (west coast area); (b) PM$_{10}$ reduction rate (%) of green buffer (GB).

The number of high PM pollution days was calculated by focusing on the period during (2006–2012) and after (2013–2018) implementation of the GB. In this period, changes in the PM$_{10}$ concentration and reduction rates began to appear (Figure 4). During the implementation of the GB, the number of high PM pollution days in the NAERS-RA (68 days) was observed to be, on average, 20 days more than that for the NAERS-IC (48 days). The average number of high PM pollution days in the IC was five days higher than in the RA after 2010. After the GB was installed, the NAERS-IC and NAERS-RA had 58 days and 38 days, respectively, showing an inverted form. In particular, the difference in the number of high PM pollution days between the NAERSs was the largest, with an average of 31 days, two years after GB implementation. After this time, the NAERS-IC had many high PM pollution days, but the difference between the NAERSs decreased more than before.
3.1.2. The Characteristics of PM Reduction Rate During and After GB Implementation

Table 1 shows the correlation coefficients between the PM reduction rate, air pollutant emission, meteorological factors and NDVI. During the implementation of GB, the PM reduction rate showed correlation with SO\(_x\), meteorological factors and NDVI, except for NO\(_x\). The PM reduction rate was positively correlated with wind speed and annual precipitation. Although NDVI showed low correlation with the PM reduction rate, there was also a positive correlation. SO\(_x\) and temperature were negatively correlated with PM reduction rate. After the implementation of GB, only SO\(_x\) and wind speed had negative and positive correlation with the PM reduction rate, respectively.

Table 1. Correlation coefficients between PM reduction rate, air pollutant emissions, weather factors and NDVI.

| Correlation Coefficient | PM\(_{10}\) Reduction Rate During GB Implementation (2006–2012) | PM\(_{10}\) Reduction Rate After GB Implementation (2013–2017) |
|-------------------------|-------------------------------------------------|-------------------------------------------------|
| NO\(_x\)                | -0.08                                          | 0.096                                          |
| SO\(_x\)                | -0.85 **                                       | -0.80 **                                       |
| Temperature             | -0.97 ****                                     | 0.39                                           |
| Wind Speed              | 0.88 ***                                       | 0.94 ***                                       |
| Annual Precipitation    | 0.86 **                                        | -0.49                                          |
| NDVI                    | 0.69 *                                         | 0.56                                           |

\(p < 0.1, ** p < 0.05, *** p < 0.01, **** p < 0.001.\)

3.2. The Effect of PM Reduction of the GB Zone at Human Breathing Height

From February 2018 to January 2019, PM\(_{10}\) and PM\(_{2.5}\) concentrations were high in March (average 123.1 μg/m\(^3\)) and May (average 179.4 μg/m\(^3\)), and March (average 84.3 μg/m\(^3\)) and June (average 65.1 μg/m\(^3\)), respectively (Figure 5a,b). Except for PM\(_{10}\) in February, the average PM\(_{10}\) and PM\(_{2.5}\) in the OP-IC was 41.2% and 35.4% higher than in the OP-RA, respectively.

The PM reduction rate in the GB zone was also similar the PM concentration (Figure 5c). Except for February and August, a PM reduction effect was observed in the GB. The average reduction rate of PM\(_{10}\) and PM\(_{2.5}\) was 26.2% and 23.4%, respectively, which showed PM\(_{10}\) reduction rate had a 12.0% higher value than that of PM\(_{2.5}\).
4. Discussion

4.1. The Effect of PM Reduction of the GB Zone at a Local Scale

4.1.1. PM Reduction Effect of the GB

Before the GB implementation, the RA had higher PM$_{10}$ concentration than the IC, which was affected by PM generated from the IC (Figure 3a). However, during and after the implementation of GB, the PM values in the RA were lower than those in the IC. This result showed that the GB zone had a PM reduction effect [30,31]. As the PM from the IC passed through the GB, trees could absorb PM via leaf stomata [32–34] and remove PM by blocking and deposition onto the leaves and branches [35,36].

In addition, the trend line slope of PM concentration over time in NAERS-RA had the highest value, showing a rapid decrease of PM concentration (Figure 3a). NAERS-IC showed a relative flat decrease, and the WCA showed an intermediate slope. This indicates that the WCA has been well managed under the regulations for air quality in Seoul metropolitan areas, but the IC seems to be little affected by such environmental policy. The steep decrease in the RA can be attributed to the indirect effects of GB blocking the pollutants from the IC. Therefore, the PM reduction in the GB was as effective as the regulations for large PM emission sources [37,38]. However, low levels of PM were still observed in the Sihwa IC where the PM was generated. Thus, steady management is required for emission sources as well as areas affected by the PM.

The effect of PM reduction in the GB zone was not observed immediately after implementation of the GB, but it has increased over time (Figures 3 and 4). This means that trees need a period of stability after planting. As the growth and stabilization of the trees progressed, active PM absorption, adsorption, blocking and deposition through trees slowly emerged [11,39,40]. The physiological stabilization of trees ensures that the PM reduction in the GB zone can be maintained continuously. But at some point, PM reduction is less than before. This indicates that proper management of tree shape and density is needed to maintain PM reduction through trees. Thus, the GB zone should not only be
dense for offering large absorption, adsorption and deposition area, but also be porous to allow active atmospheric diffusion [9,41]. It is important to manage the GB zone depending on the purpose of its establishment and PM levels.

4.1.2. The Characteristics of PM Reduction Rate during and after GB Implementation

The factors affecting PM reduction rate were different for the periods during and after the implementation of GB (Table 1). During the GB implementation, PM reduction rate was positively correlated with wind speed and annual precipitation. Wind speed is related to atmospheric diffusion. High wind speed influences active air currents and rapid dispersion of PM in the atmosphere, resulting in low PM concentration [24,42,43]. Annual precipitation can be related with the wet deposition of PM. This could also inhibit surface dust transport [43,44]. NDVI showed a low value but a positive correlation with PM reduction rate. This indicates that high vegetation vitality could affect the active PM reduction effect through GB [3,9]. SOx and temperature showed a negative correlation with PM reduction rate, which might be related to the process of the secondary PM formation. SOx is precursor of PM [45,46], and high temperature causes a photochemical reaction between SOx and other gaseous contaminants, producing secondary PM [47,48]. However, trees can accumulate PM on leaves up to their PM-retaining capacity. Precipitation and strong winds are needed to begin a new cycle of PM accumulation [49]. Thus, when PM accumulation by a tree reaches a saturation point, PM accumulation can be limited, which results in low PM reduction rate. In addition, low temperature can increase the deposition of PM and reduce PM through trees [13,14].

After the GB implementation, only wind speed and SOx had positive and negative correlation with PM reduction rate, respectively (Table 1). These results imply that the vegetation vitality as well as atmospheric diffusion through structural tree management are important after tree stabilization. A large quantity of trees can reduce wind velocity and suppress air currents and the PM deposition on trees, resulting in reducing the PM reduction effect of the GB zone [16,50]. A large-sized plantation forest and a GB zone of high porosity can affect the wind field at the local scale [9,51,52]. Therefore, it is crucial to maintain the PM reduction effect of the GB through proper management of tree density, forest structure and PM emission sources.

4.2. The Effect of PM Reduction of the GB Zone at Human Breathing Height

Overall, PM10 concentration was high in March and May, and PM2.5 concentration was high in March and June (Figure 5a,b). The high PM concentration in March can be attributed to the increase in fuel use and the influence of external PM. In May, Asian dust was present at the measurement times, resulting in a high PM10 [53–55]. Unlike previous studies [47,56], high levels of PM2.5 concentration were observed in June. This was related to the high value of relative humidity at the monitoring points. Although we excluded PM data when the relative humidity exceeded 80%, the high humidity in June seems to have led to an overestimation of PM from the measuring device [57–59]. Except for PM10 concentration in February, the average PM values were higher at OP-IC than at OP-RA. In February, PM10 and PM2.5 concentrations at the measuring time (21–22 February 2018) were 39 μg/m³ and 19 μg/m³, respectively, slightly exceeding the standard for fine PM quality (a daily average PM10 concentration ≤ 30 μg/m³ and PM2.5 concentration ≤ 15 μg/m³). At low PM concentrations, PM reduction through the GB zone was not significantly affected. However, we considered not only the effect of GB but also the distance effect on PM reduction according to the distance from air pollutant emitters. PM10 and PM2.5, which have a long atmospheric lifetime, decreased [60]; thus, we can speculate that the influence of the GB on PM reduction was greater than that of distance [24].

The PM reduction rate of the GB was also shown as common in PM concentration (Figure 5c). A PM reduction effect in the GB was observed, except for February and August, when PM concentrations were low. In particular, the average PM10 reduction rate was higher than that for PM2.5. This related to the characteristics of PM10. PM10 contains
larger sized classes of particles than PM$_{2.5}$ and has a short atmospheric lifetime. This could influence the active absorption, adsorption and deposition through trees [60].

5. Conclusions

This study showed that the GB zone was effective in reducing PM generated in the IC. On a local scale, PM concentration and the number of high pollution days of PM were higher in the IC than the RA after the implementation of the GB zone. The trend slope line of PM concentration in the RA rapidly decreased over time, which can be attributed to the indirect blocking effects of the GB by PM absorption, adsorption and deposition through trees. The effect of the PM reduction gradually increased over time, as the physiological stabilization of the trees took place. In addition, the PM reduction rate was positively and negatively related to wind speed and SO$_x$, respectively. This means that both proper management of tree density and high PM emissions are needed to improve PM reduction. At human breathing height, except for the months where the PM was low, the PM concentration in the IC was also higher than the RA. Our results showed that proper management of tree density and PM emission sources are required to maintain the PM reduction effect of GB zone. In addition, the ecosystem services and benefits for environmental taxation of the GB zone could be evaluated through this customized method for local and human breathing height levels.

However, this study was conducted only in the one region (Sihwa) in Korea. In addition, the study on the exposure state of humans was measured on a 24 h basis, which is not comparable to monthly PM characteristics. Thus, the generalization on the PM reduction caused by the GB zone could be limited and might not apply all over the country. In future studies, it is necessary to measure the monthly PM by continuous PM measurement for human breathing height. The overall PM reduction characteristics of the GB zone will need to be determined by comparing the local and human levels.

Author Contributions: Analyzing data and writing the paper, S.-Y.Y.; searching and analyzing preceding research data, S.C.; managing the research project and measuring the field data, N.K.; analyzing the PM data, T.K.; designing the study site and contributing to the discussion of the PM results, C.-R.P.; calculating and analyzing NDVI changes, W.-H.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Publicly available datasets were analyzed in this study. This data can be found here (The national atmospheric environmental research station: St. 131232 Sihwa Industrial Complex, St. 131231 Jeongwang-dong, www.airkorea.or.kr; The national weather service: St. 565 Siheung, data.kma.go.kr).

Acknowledgments: This research was funded by the National Institute of Forest Science of Korea, Grant number NIFOS FE0000201801. We acknowledge the critical comments from anonymous reviewers and the editor.

Conflicts of Interest: The authors declare no conflict of interest.

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