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Changes in Air Quality during the COVID-19 Pandemic and Associated Health Benefits in Korea

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Received: 22 October 2020; Accepted: 2 December 2020; Published: 5 December 2020

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Abstract: The COVID-19 pandemic was caused by a highly contagious coronavirus that has triggered worldwide control actions such as social distancing and lockdowns. COVID-19 control actions have resulted in improved air quality locally and around the world in the short-term by limiting human activity. We analyzed the impacts of social distancing and transboundary pollutants on air quality changes using open data and examined the corresponding health benefits focusing on two domestic cities (Seoul and Daegu) in Korea where the spread of coronavirus was severe. During the COVID-19 pandemic, $PM_{2.5}$, PM_{10}, and NO_2 concentrations decreased significantly by 31%, 61%, and 33%, respectively, compared to the previous three years. In particular, the $PM_{2.5}/PM_{10}$ ratio fell 24.5% after the implementation of social distancing, suggesting a decrease in anthropogenic emissions. Moreover, we found that the air quality index (AQI) also improved significantly, with a focus on reducing exposure to sensitive groups. In Seoul and Daegu, improved air quality prevented 250 and 78 premature deaths, and health costs were USD 884 million and USD 278 million, respectively. On the other hand, health loss due to COVID-19 deaths was in sharp contrast to USD 7.1 million and USD 543.6 million. Our findings indicate a significant association between COVID-19 prevalence patterns and health outcomes.

Keywords: COVID-19; air quality; health benefit; $PM_{2.5}$; PM_{10}

1. Introduction

The novel coronavirus (COVID-19) was reported in Wuhan, China at the end of 2019 and spread rapidly around the world, leading the World Health Organization to declare a pandemic in March 2020 [1]. By August, the number of confirmed cases worldwide exceeded 29.5 million, with 9.33 million deaths [2]. South Korea has experienced two coronavirus incidents in the past decade, middle east respiratory syndrome coronavirus (MERS) and COVID-19. Although COVID-19 has a lower fatality rate than MERS or severe acute respiratory syndrome (SARS) [3], the highest reproduction number was estimated to be 3.54 in the early stages of the epidemic in Korea [4], making it more contagious than any other coronavirus. Many countries where COVID-19 has been considered an international concern due to the spread of the virus have taken steps ranging from urging residents to stay at home to social distancing efforts and even lockdowns [5–12].

Starting with the first case on January 20, Korea's spread rate rapidly increased around the metropolitan areas, reporting the second-largest number of confirmed cases in the world until February. Social distancing to prevent the spread of coronavirus began on February 29, and at the end of April, the daily new confirmed cases remained below 10, entering a period of stabilization. However, in August, large-scale cluster infections were confirmed across the country and the second pandemic began, compelling the government to issue stronger social distancing guidelines. The increase in the cumulative number of confirmed cases and social distancing period in Korea are shown in Figure 1.

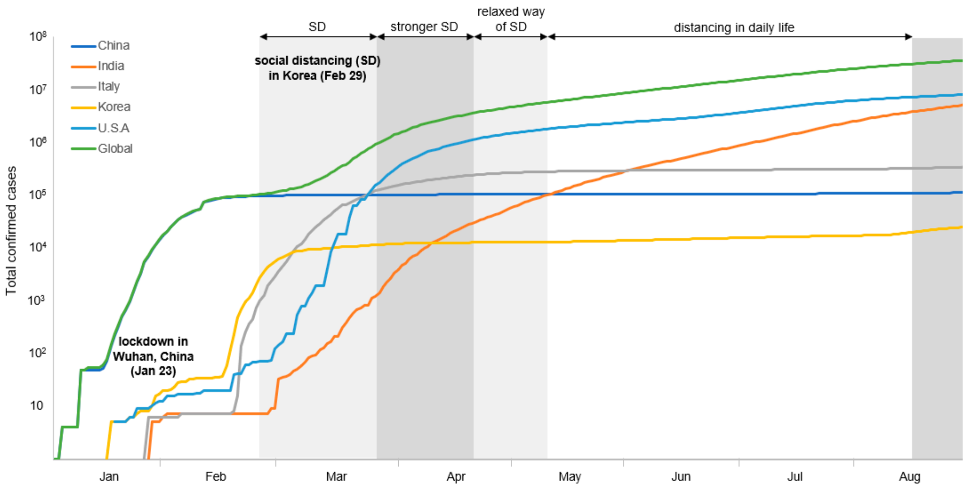

Figure 1. The cumulative number of COVID-19 cases worldwide. The highlighted shadow represents the level of social distancing (SD) in Korea. The data were collected from the WHO Coronavirus Disease (COVID-19) Dashboard [2].

Many recent studies and media have reported that COVID-19 control actions have not only slowed the spread of the virus [13–15], but also brought local and short-term changes in air quality [12,16–21]. Reduced human and industrial activities have decreased air pollutant emissions, and significant improvements in global air quality are being observed in 2020 [22–24]. In particular, in central China where the first COVID-19 confirmed case was reported, a significant decrease in particulate matter (PM) was observed immediately after lockdown. Compared to the same period in the previous three years, from January to March 2020, fine particles ($PM_{2.5}$) and respiratory suspended particles (PM_{10}) decreased by 30.1 to 40.5%, respectively, and the concentration of nitrogen dioxide (NO_2) was significantly reduced by 27.9% [24].

A decrease in air pollutant levels was also reported in Korea, which adopted social distancing, a regulation somewhat weaker than a COVID-19 lockdown [12,25,26]. The reduction in traffic-related emissions due to social distancing and reductions in transboundary pollutants from the neighboring countries lowered the $PM_{2.5}$, PM_{10}, and NO_2 concentrations by 45%, 36%, and 20%, respectively, in March compared to the previous three years [25]. The improved air quality in March was very unusual because, traditionally in Korea, the air quality in spring deteriorates appreciably due to the influence of Asian dust [27].

Meanwhile, in Sao Paulo, a representative megacity in Brazil where the confirmed cases increased rapidly, the concentration of $PM_{2.5}$, PM_{10}, and NO_2 also decreased by 45%, 46%, and 58%, respectively. This improvement in air quality prevented 802 premature deaths and saved about USD 720 million in health costs [11]. Similarly, in Korea, a study focused on Seoul to evaluate the health costs associated with $PM_{2.5}$ decreases, but only the overall change over four months was observed. Thus, detailed evaluations according to short-term changes in air quality were not performed [26]. Also, no research has evaluated only $PM_{2.5}$ but also air pollutants representative of Korea, such as PM_{10} and NO_2.

Moreover, in prior studies, air pollution levels were evaluated and health burden was assessed after COVID-19 control actions in major cities around the world through satellite data analysis, but only a slight difference in CO levels was observed in the Republic of Korea and other pollutants could not be accessed due to the lack of data [28].

Meanwhile, the WHO has reported 7.2 million deaths each year from air pollution, the fifth most serious health-related factor that causes disease [29]. Specifically, in Korea, it was predicted that the number of early deaths by air pollution would increase from 17,000 in 2010 to 30,000 in 2030 and 54,000 in 2060 [30]. Particulate matter (PM) and nitrogen dioxide (NO_2) are well-known air pollutants that cause numerous adverse health effects including cardiovascular diseases in Korea [31,32].

Reductions in air pollution caused a substantial and instant impact on health. In particular, within a few weeks, respiratory and irritation symptoms, cardiovascular diseases, and all-cause mortality were significantly reduced. Health improvements related to air quality led to significant health benefits and contributed to avoidable health risk [33].

The improvements in air quality since COVID-19 have provided an opportunity to evaluate health costs due to air pollutant reductions, including PM [25]. The purpose of our research was to observe the changes in air quality using open data in two representative cities with the rapid spread of COVID-19 in Korea. In addition, the potential health benefit was also investigated by analyzing deaths prevented by social distancing. This study is an applied research that assesses the short-term effect on health and air quality changes due to social measurement during the COVID-19 pandemic.

2. Materials and Methods

To access the health benefits resulting from COVID-19 control actions, the concentration of pollutants, exposure, environmental factors, mortality, and COVID-19 data were comprehensively analyzed as follows.

2.1. Study Site

After the first confirmed case was reported on January 20, local social infections spread widely around Daegu. By February 29, the cumulative confirmed cases accounted for 71% of the nation's confirmed cases (2236/3150), and even though the rate was reduced to 35% on August 31, the city still had the largest number of confirmed cases in Korea (7047/19947) [34].

Seoul is the most densely populated city in the OECD [35], with a population of about 10 million. The spread in Seoul began later than in Daegu, but since mid-August, there have been more than 100 newly confirmed cases per day, with 19% of the confirmed cases reported in Seoul on August 31 (3867/19947) [32]. Therefore, this study focused on the metropolitan city where coronavirus was most prevalent to observe changes in air quality before and after COVID-19 occurrence and evaluate the health benefits.

2.2. Air Pollutant Levels and Meteorological Conditions

The concentrations of $PM_{2.5}$, PM_{10}, and NO_2 were obtained from Air Korea (www.airkorea.or.kr/web) [36], and all data were applied to the Korea Registry of Environment (KMOE)'s Quality Assurance/Quality Control (QA/QC) procedure. There are 25 and 15 The Air Quality Monitoring Stations (AQMS) in Seoul and Daegu, respectively (Figure 2). We obtained the air pollutant levels on an hourly basis and calculated the daily and weekly averages to compare them to the previous three years (2017–2019). In this study, air pollution levels were analyzed for a total of 18 weeks. Observations were made from January 1, 2020, until May 5, when social distancing (SD) was implemented.

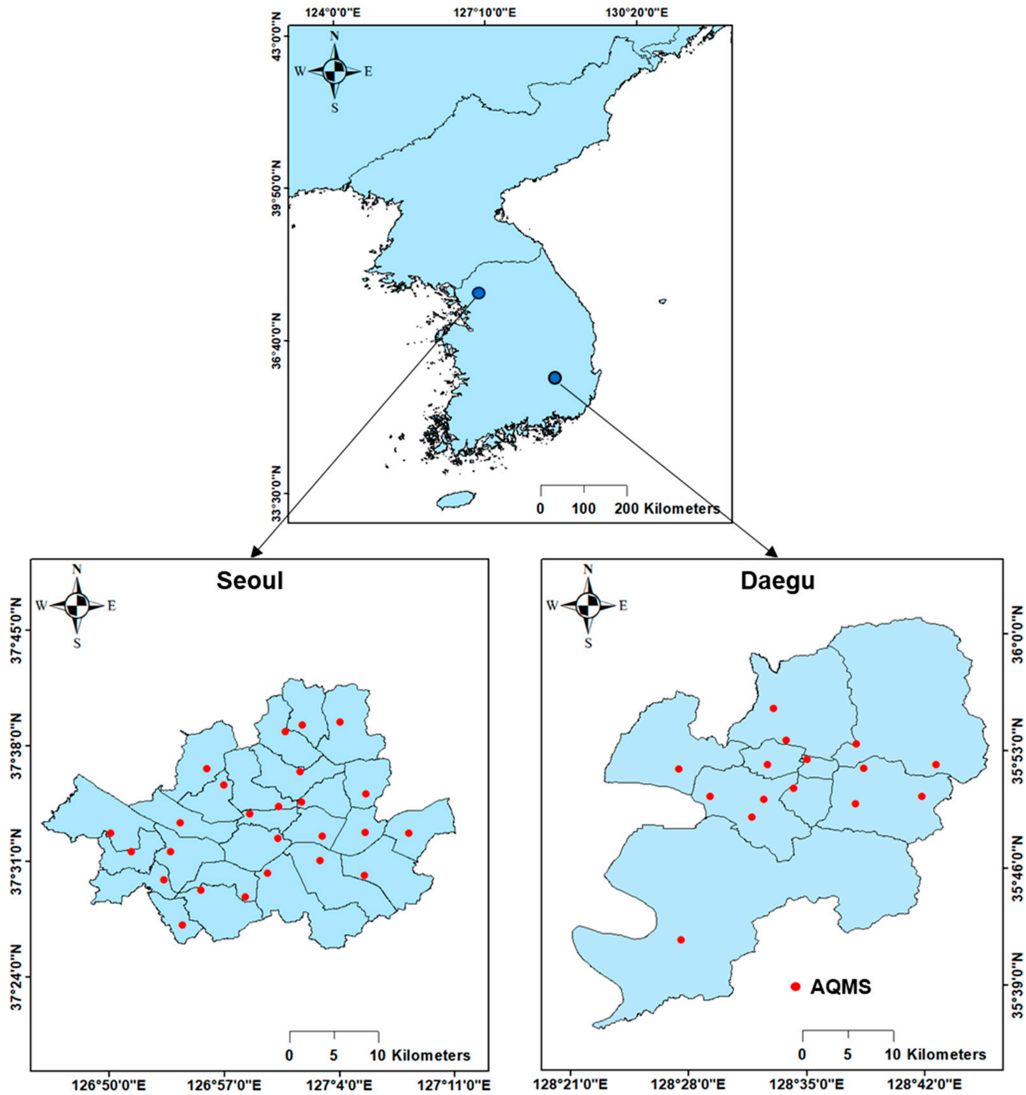

Figure 2. Location of Seoul (left) and Daegu (right) in Korea. Red dots indicate the location of the air quality monitoring stations (AQMS).

In addition, we evaluated the AQI to efficiently access air quality related to health concerns. The AQI is widely used as a tool to easily communicate how polluted the air currently is and the level of health effects on the public. The AQI was classified into six categories and expressed in colors representing different levels of health concern. The AQI of the air pollutants was calculated as interpolation Equation (1) [37]:

$$I = \frac{I_{high} - I_{low}}{C_{high} - C_{low}} * (C - C_{low}) + I_{low} \quad (1)$$

where

I: Air Quality Index
C: pollutant concentration
C_{low}: the concentration breakpoint $\leq C$
C_{high}: the concentration breakpoint $\geq C$
I_{low}: the index breakpoint corresponding to C_{low}
I_{high}: the index breakpoint corresponding to C_{high}

Meteorological conditions including precipitation, wind speed, temperature, and humidity were analyzed through open data available on the Korea Meteorological Administration website [38]. As shown in Table S1, no significant differences were observed between the previous three years and 2020 in meteorological conditions.

To analyze the wind speed and direction of Northeast Asia including Korea, 'ERA5 monthly averaged data on single levels' provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) [39] was used to investigate speed and wind direction in the East Asian region from January to March 2020. Using this data, we made a wind map in meters per second by using ArcGIS 10.6 at a height of 100 m above the surface of the Earth.

2.3. COVID-19 and Mortality Data

The cumulative number of COVID-19 cases around the world was expressed by modifying the statistical data of the WHO Coronavirus Disease Dashboard [2]. Daily confirmed cases and death statistics related to COVID-19 were obtained through the Korea Disease Control and Prevention Agency (KCDA) [32].

In Korea, mortality data is published to the public through Statistics Korea (KOSTAT) [40], and since it is usually accessible after 1.5 years, the mortality rate in 2020 was estimated based on statistical data from 2016 to 2018. To evaluate all-cause mortality, we used non-accidental (A00-R00) mortality based on the International Classification of Disease [41].

2.4. Assessment of Health Benefits Related to Air Quality

The attributable fraction (AF) method was adopted to evaluate avoided deaths due to $PM_{2.5}$, PM_{10}, and NO_2 during the COVID-19 pandemic. Concentration-response (C-R) functions are widely used to evaluate the relationship between air pollution and health outcomes [42–44]. In this study, log-linear C-R functions were used as follows:

$$Avoidable\ (preventable)\ deaths = \left(1 - exp^{-\beta \times \Delta x}\right) \times number\ of\ deaths \quad (2)$$

where β represents C-R coefficients, Δx is the decrease in the level of air pollutants, and the number of deaths was based on mortality over the same period in past years (2016–2018).

In this study, the C-R coefficients of each air pollutant adopted values derived from well-designed previous studies (Table 1). In addition, we used AirQ+ software tool that was developed by WHO to quantify the health impacts of air pollution.

Table 1. The concentration-response (C-R) coefficients for $PM_{2.5}$-, PM_{10}-, and NO_2-induced mortality.

Air Pollutants	Estimated C-R Regression Coefficients	Epidemiological References
$PM_{2.5}$	0.00405	[11,45]
PM_{10}	0.0008	[46]
NO_2	0.00135	[47]

Finally, we evaluated health outcomes to investigate the cost of mortality at the society level. The value of statistical life (VSL) represents how much individuals are willing to pay (WTP) to reduce the risk of death [48], and has been widely used in studies dealing with air quality and health [49–53]. The economic cost of a mortality impact was calculated through VSL and multiplied by premature deaths (COVID-19) or avoided deaths. In our study, we evaluated economic outcomes related to health by adopting USD 3.53 million proposed by the OECD as a representative VSL in Korea [54].

3. Results and Discussion

3.1. Comparision of Air Pollutant Levels

The time-series of $PM_{2.5}$, PM_{10} and NO_2 concentrations in Seoul and Daegu for the control period (2017–2019) and COVID-19 period in 2020 are shown in Figures 3–5, respectively. The concentration of $PM_{2.5}$ during the observation was significantly lower than that of the control period, with an average reduction of 30.7 μg/m^3. For $PM_{2.5}$, it was reduced by 44.2 μg/m^3 and 42.6 μg/m^3 in Seoul and Daegu, immediately after implementing SD (week 8) respectively (Figure 3). Significant reductions in $PM_{2.5}$ were also observed even before SD (weeks 1–7) due to changes in transboundary $PM_{2.5}$ concentrations [25]. Especially in China, the plant operations temporarily stopped in early January due to the New Year holiday, reducing industrial emissions. Also at the end of January, strict COVID-19 lockdown measures centered on Hubei Province were implemented, which curbed $PM_{2.5}$ man-made emissions due to traffic volume and industrial development [24]. The impact lasted until March, leading to a decrease in $PM_{2.5}$ concentrations in South Korea. Korea also showed a sharp drop in traffic after SD was implemented and a huge reduction in $PM_{2.5}$ concentrations in the early SD period as a result of decreased anthropogenic emissions as human activity decreased [12]. Since March 22nd, SD efforts were further strengthened (week 14) and another significant $PM_{2.5}$ decrease was observed. In particular, Seoul showed its greatest reduction during the observation period, with a decrease of nearly 80% from 57.1 μg/m^3 to 11.6 μg/m^3. $PM_{2.5}$ concentration changes were immediately apparent in the first SD efforts and two weeks after the implementation of strict SD (week 16), probably related to reductions in regional atmospheric congestion.

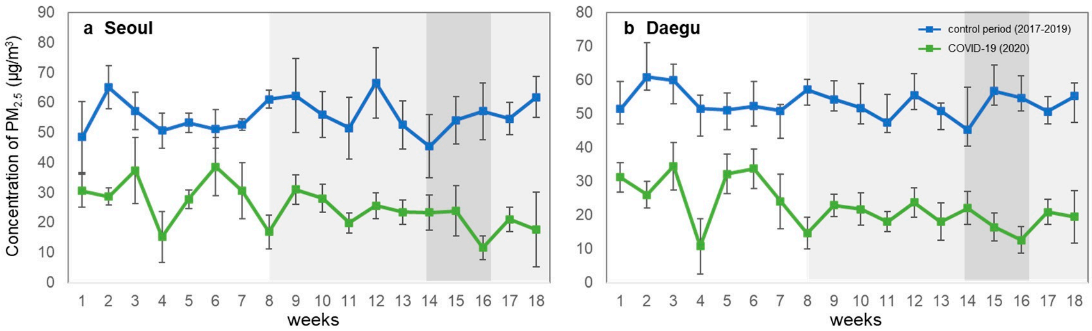

Figure 3. Comparison of average $PM_{2.5}$ concentrations by week between 2020 and the previous three years in (**a**) Seoul and (**b**) Daegu. Highlighted shadow represents the level of social distancing. The error bar means standard deviation.

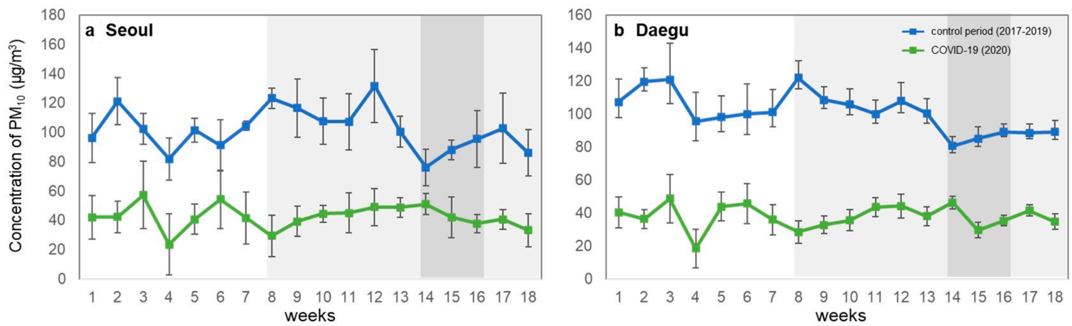

Figure 4. Comparison of average PM_{10} concentrations by week between 2020 and the previous three years in (**a**) Seoul and (**b**) Daegu. Highlighted shadow represents the level of social distancing. The error bar means standard deviation.

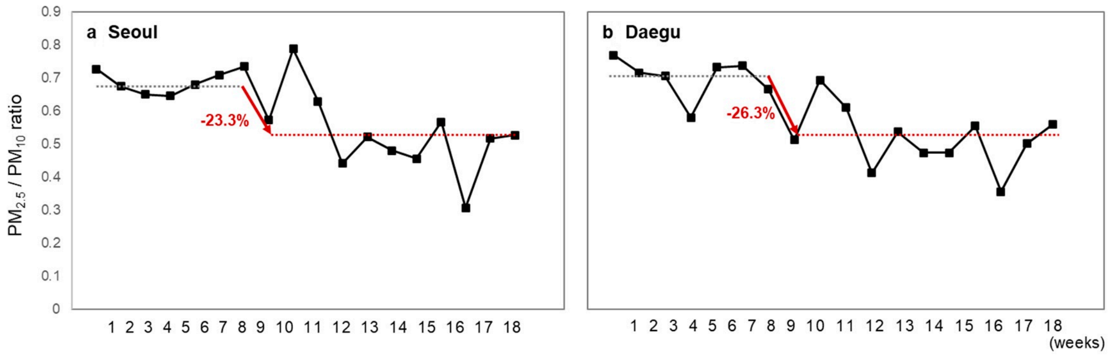

Figure 5. Changes in weekly $PM_{2.5}/PM_{10}$ ratios in (**a**) Seoul and (**b**) Daegu. The black dotted line represents the average ratio before SD, and the red dotted line represents the average ratio after SD. The reduction in the $PM_{2.5}/PM_{10}$ ratio is highlighted.

The changes in PM_{10} concentrations were similar to those of $PM_{2.5}$, as shown in Figure 4. Immediately after the implementation of SD measures, PM_{10} concentrations were reduced by 59.5 μg/m^3 and 63.3 μg/m^3 in Seoul and Daegu, respectively. As described earlier, this was interpreted as the result of reductions in transboundary PM from the neighboring countries and decreases in PM due to SD. In particular, after the implementation of SD, PM_{10} concentrations in both cities were reduced by 76% compared to the control period. The effect of the enhanced SD is weak compared to that observed in $PM_{2.5}$ but still led to a continued decrease in PM_{10} concentrations.

We estimated the contribution of particles to the atmospheric PM by their size using the $PM_{2.5}/PM_{10}$ ratio (Figure 5). The ratio is widely used to identify the source of PM. A high ratio indicates a high contribution of $PM_{2.5}$, which represents artificial emission generation, and a low ratio represents the contribution of coarse particulates from natural sources such as Asian dust or wildfires [55,56]. Before and after SD, the $PM_{2.5}/PM_{10}$ ratio decreased significantly, which was related to reductions in anthropogenic $PM_{2.5}$ due to the restriction of human activities. Interestingly, notable changes in the $PM_{2.5}/PM_{10}$ ratio were also observed in the first two weeks following COVID-19 control actions. This delayed effect was mainly seen around 15 to 16 weeks when the wind speed was relatively slow (1.0–2.2 m/s) and the atmosphere was relatively stagnant.

The change in NO_2 concentrations was minute compared to PM but was significantly reduced compared to the control period as shown in Figure 6. The sharp decline in traffic since SD has led to a decrease in traffic-related NO_2 in both cities. Particularly in week 8, the average reduction was 38.7 μg/m^3 and a delayed reduction effect was shown two weeks after the implementation of enhanced SD (week 16). The average NO_2 concentration before SD was lower than that of the control period, but higher concentrations were partially observed, resulting in a relatively weaker effect of reduced transboundary pollutants compared to PM. According to a Korea-China-Japan cooperative study (Long-range Transboundary Air Pollutants in North East Asia: LTP), Chinese sources contributed about 40% of Korea's NOx, while the transboundary concentration of PM was up to 80% [57]. This supports our findings that the effects of transboundary NO_2 before SD were weaker than those of PM.

Even before the implementation of SD in Korea, Korea's air pollution levels were affected by the neighboring countries, which had already implemented COVID-19 control actions, resulting in significant reductions in concentrations along with the limiting effect of domestic sources due to SD.

In general, due to the nature of the Northeast Asian environment, which is dominated by western winds, South Korea is significantly affected by air pollutants from neighboring countries including China and North Korea [58]. According to KMOE, atmospheric PM in Korea from winter to spring is affected 28% to 82% from neighboring countries [59]. The Northeast Asia cooperative study also reported that the transboundary $PM_{2.5}$ from China was 32%, and the effect increased to 70% in the period of high concentration. NOx concentrations were also shown to have a transboundary effect of about 40% [55]. These previous research results support that air quality improvements before week

8, which were not related to social distancing in Korea, were related to strong COVID-19 lockdown measures in China.

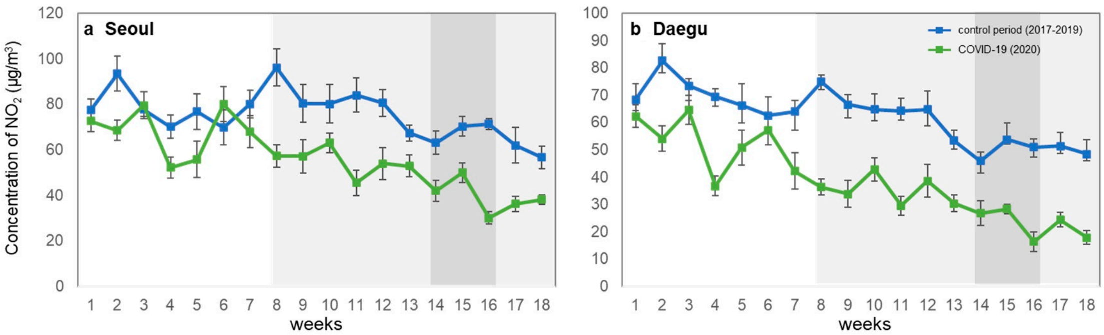

Figure 6. Comparison of average NO_2 concentrations by week between 2020 and the previous three years in (**a**) Seoul and (**b**) Daegu. Highlighted shadow represents the level of social distancing. The error bar means standard deviation.

The average wind speed and direction during the observation period are shown in Figure 7. As expected, the western wind was quite dominant in January and affected measurements in February and March. The results of wind direction and wind speed analysis during the pre- and post-SD periods support the impact of improved air quality in neighboring countries across the borders, especially in Northeast Asia.

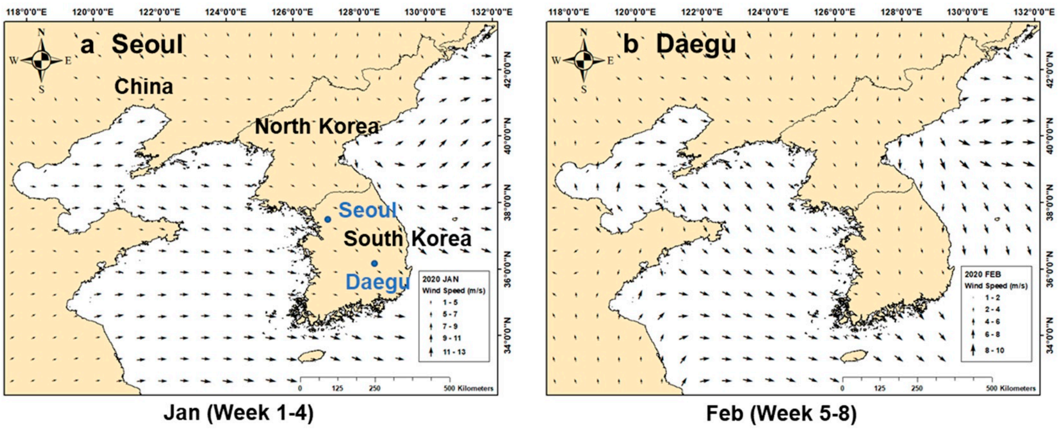

Figure 7. Map of wind speed and direction analysis in the Northeast Asia region in January and February. ((**a**): Seoul and (**b**): Daegu)

3.2. Distribution of Air Quality Index (AQI)

The daily AQI based on the concentrations of $PM_{2.5}$ and PM_{10} in Seoul and Daegu is shown in the Figure 8. NO_2 could only be calculated from an AQI above 200, but no day exceeded 200 in this study. The AQI results, shown in contrasting colors between the COVID-19 pandemic period and the control period showed a dramatic improvement in air quality. Interestingly, the AQI for $PM_{2.5}$ has not been classified as unhealthy (red) since the COVID-19 outbreak in either city. During the control period, the values unhealthy for the sensitive group (SG) accounted for the majority, with 91.2% and 92.8% in Seoul and Daegu, respectively, whereas in 2020, the proportions were moderate at 68.3% and 65.9%, respectively.

The AQI for PM_{10} also showed a significant reduction. In both cities, it was moderate during the control period at 86.4–98.4%, while good at 75.4–86.5% in 2020.

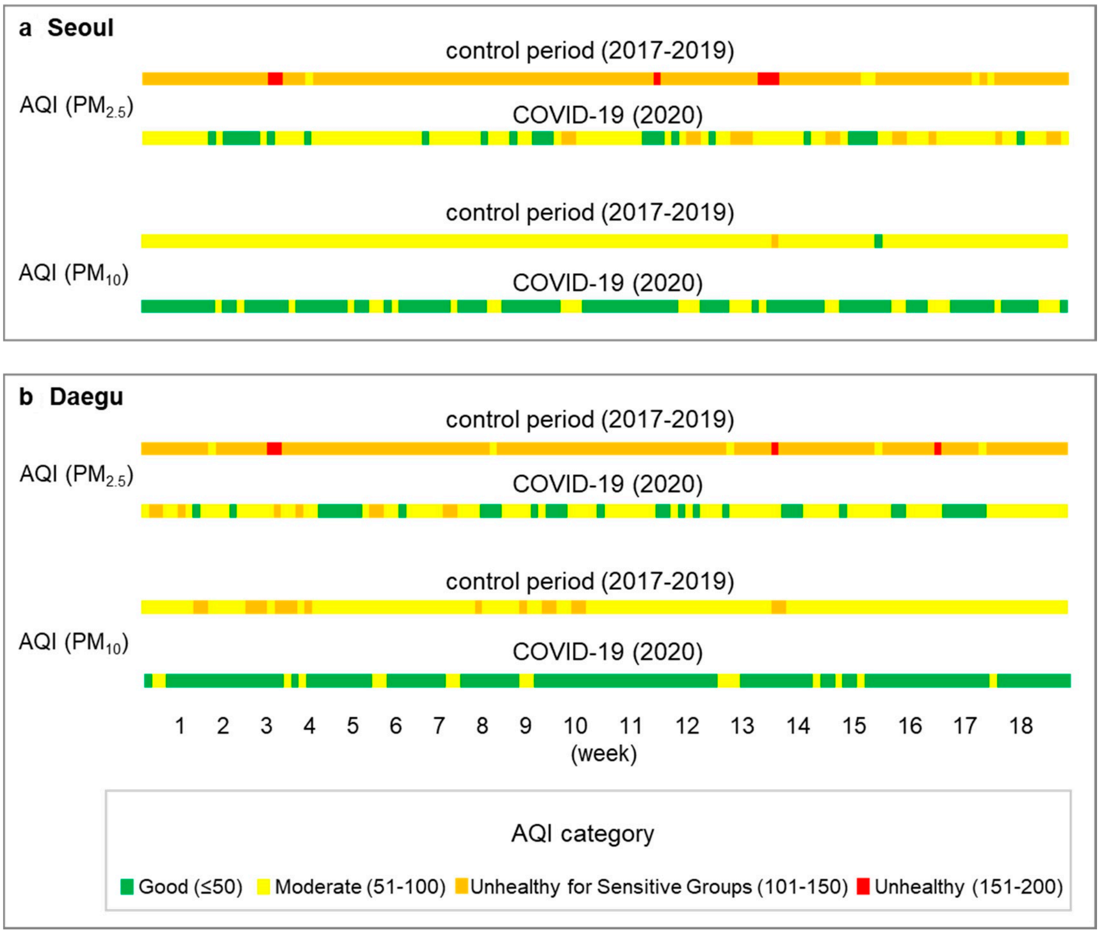

Figure 8. Comparison of daily AQI distribution of $PM_{2.5}$ and PM_{10}. Each AQI color indicates a different level of health concern. ((**a**): Seoul and (**b**): Daegu)

The AQI analysis showed a significant improvement in air quality centered on PM. In particular, it was rare that air quality deteriorated to the level of unhealthy for the SG, and significant health benefits would have been seen in at-risk groups (e.g., the elderly, children, and people with lung disease) due to the effects of air quality improvements in 2020.

In previous studies, a decrease in the AQI level of 14.9–32.2% was observed in central China where the COVID-19 lockdown was implemented [24]. In addition, significant improvement in air quality was also found in cities that implemented measures to prevent the spread of coronavirus [11], although not lockdowns, consistent with our study. These improvements in AQI have been observed worldwide, including the United States [44,60], Italy [61], and India [8,23] experiencing COVID-19.

3.3. Corresponding Health Outcomes

Based on the results of the concentration compared to the control period, the relative risks (RRs) and attributable factors (AFs) for each pollutant from January 2020 were calculated and are shown in Tables S2 and S3. In Seoul, the RR was 1.05–1.20 for $PM_{2.5}$, 1.02–1.08 for PM_{10}, and 0.99–1.06 for NO_2. In Daegu, the RR was 1.08–1.19 for $PM_{2.5}$, 1.03–1.08 for PM_{10}, and 1.01–1.05 for NO_2. In week 8, when the largest reduction in air pollutants was observed, the RR was the highest, and the AF values derived from the RRs were in the order of $PM_{2.5}$ (0.12) > PM_{10} (0.05) > NO_2 (0.03) in both cities. Noticeably, compared to the AFs observed in Sao Paulo, Brazil [11], a megacity similar to Seoul, the $PM_{2.5}$ and PM_{10} had greater AFs in Seoul, whereas NO_2 had greater AFs in Sao Paulo. This difference seems to have occurred because the main indicator of air quality is NO_2 in Sao Paulo whereas, in Korea, $PM_{2.5}$ is the contributory pollutant.

Based on the AF values, we assessed the preventable deaths and monetary values in each city (Table 2). The analysis showed many more preventable deaths due to reduced air pollution in Seoul, which has a large population. The decrease in PM_{10} and NO_2 saved the lives of at least 55 people, and especially $PM_{2.5}$ prevented about 250 premature deaths. The effects in Daegu were not as appreciable as those in Seoul, but due to a significant drop in $PM_{2.5}$, the number of avoidable deaths was estimated to reach about 78. The number of deaths from COVID-19 differed greatly from two in Seoul to 154 in Daegu during the investigation period.

Table 2. Assessment of weekly avoided deaths due to reductions in $PM_{2.5}$, PM_{10}, and NO_2.

	Estimated Avoided Deaths					
Location	**Seoul**			**Daegu**		
Weeks	**$PM_{2.5}$**	**PM_{10}**	**NO_2**	**$PM_{2.5}$**	**PM_{10}**	**NO_2**
1	8.2	5.0	0.8	3.3	2.2	0.3
2	16.6	7.4	4.0	5.2	2.5	1.5
3	9.5	4.3	−0.3	3.5	2.0	0.4
4	16.9	5.8	3.0	5.7	2.3	1.6
5	11.5	5.6	3.3	2.7	1.5	0.8
6	6.0	3.5	−1.7	2.7	1.6	0.3
7	10.2	5.9	2.0	3.6	1.8	1.0
8	19.7	8.7	6.1	5.1	2.3	1.6
9	13.5	6.8	3.5	4.4	2.2	1.6
10	11.9	5.5	2.5	4.2	2.0	1.1
11	13.3	5.4	5.6	3.9	1.5	1.6
12	16.1	6.7	3.7	4.2	1.7	1.2
13	12.2	4.4	2.1	4.5	1.8	1.1
14	9.4	2.2	3.1	3.1	0.9	0.9
15	12.5	3.9	2.9	5.0	1.4	1.1
16	18.4	4.9	5.9	5.1	1.4	1.5
17	13.6	5.2	3.7	3.9	1.3	1.2
18	18.0	4.5	2.7	4.7	1.5	1.4

Health benefits based on the VSL approach were USD 884 million and USD 278 million in Seoul and Daegu, respectively (Figure 9). Interestingly, Seoul had two COVID-19 deaths, with economic losses of USD 7.1 million, while Daegu had 154 deaths and USD 543.6 million in health costs, showing sharply contrasting results. In Seoul, despite its dense population, social distancing was effective, whereas Daegu saw the rapid spread of secondary, tertiary, and other infections from cluster infection cases at the early stages of COVID-19. The results suggest that the initial spread rate of infectious diseases can have a significant effect on subsequent health outcomes.

The number of prevented deaths related to reductions in transboundary $PM_{2.5}$ before SD was 78 and 26 in Seoul and Daegu, respectively. After 8 weeks, since the effects of reductions in transboundary $PM_{2.5}$ were synergistic with the SD effect, it could not be evaluated separately, but the COVID-19 control actions of the neighboring countries probably continued to affect Korea. Thus, the premature deaths avoided before the 8th week of SD suggests that changes in air pollution in the neighboring countries could affect not only air quality but also health outcomes in other countries.

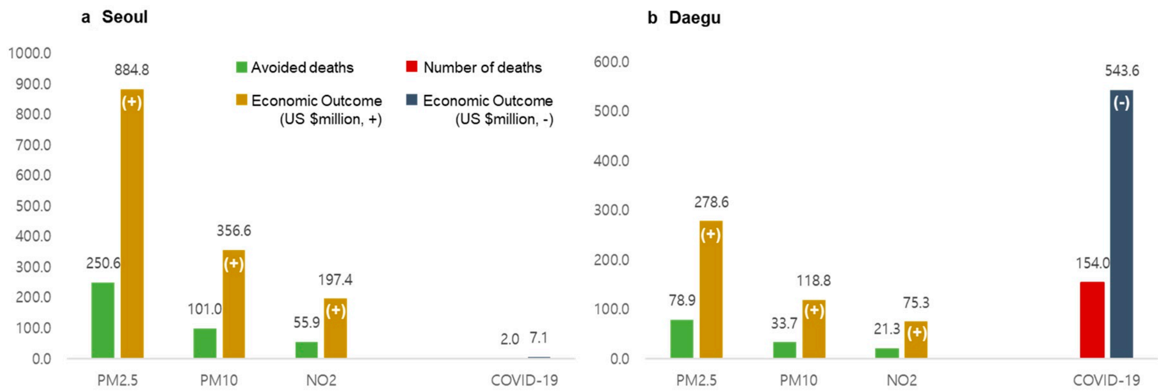

Figure 9. Avoided deaths from $PM_{2.5}$, PM_{10}, and NO_2 reductions over 18 weeks, and associated economic outcomes (+). The economic outcome from COVID-19 deaths was evaluated as (-). ((**a**): Seoul and (**b**): Daegu)

4. Conclusions

We investigated the impact of COVID-19 control actions on air quality and the resulting health benefits. Dramatic air quality improvements were observed in both cities. In the case of $PM_{2.5}$, it was reduced by 30.6–30.8% and PM_{10} was significantly reduced by 59.5–63.3%. NO_2 also decreased by 26.1–39.6%, supporting the positive effects of human activities.

The $PM_{2.5}/PM_{10}$ ratio significantly decreased from 0.69–0.70 before SD to 0.52–0.53 after SD. This proves that while the effect of improving air quality before SD was due to reductions in transboundary pollutants, the reductions in anthropogenic emissions in Korea after SD also affected the results.

The AQI of $PM_{2.5}$ and PM_{10} showed air quality improvement more clearly. South Korea generally experiences severe air pollution from winter to spring, but it was never rated as unhealthy in 2020. In addition, the number of days assessed as unhealthy for sensitive groups was considerably reduced, and it is thought that there would be a significant health effect on at-risk groups. However, the $PM_{2.5}/PM_{10}$ ratio still exceeded 0.5 and the AQI distribution often exceeded 100, confirming that $PM_{2.5}$ was still a contributory pollutant to Korean air quality.

We were able to assess the deaths prevented from reduced air pollutant levels. $PM_{2.5}$ was still a key pollutant in the health benefit evaluation, and there were 250 and 78 preventable deaths in Seoul and Daegu, respectively. The resulting health benefits were estimated at USD 884 million and USD 278 million, respectively. This was a conservative approach and could be evaluated as a greater health benefit when the effects of PM_{10} and NO_2 are considered together.

The number of deaths caused by COVID-19 showed a large difference, with two and 154 in Seoul and Daegu, and USD 7.1 million and USD 543.6 million in economic losses, respectively, showing a prime example of the remarkable health effects from the initial spread of coronavirus.

Several limitations exist in this study. First, the evaluation of air pollutant levels reflecting meteorological conditions was not performed. Precipitation, wind speed, and temperature can affect atmospheric diffusion, and more accurate concentration comparisons are needed in consideration of meteorological conditions. Second, since 2020 mortality data were not available, the past average mortality rate was used. Differences in mortality rates due to COVID-19 may occur, and the mortality statistics for 2020 can be used to access health benefits in more detail.

Nevertheless, we confirmed that COVID-19 control actions caused changes in air quality and contributed to preventing deaths from air pollution. Moreover, the results implied that changes in air quality in the neighboring countries caused effects across borders. Meanwhile, we assessed health benefits due to improved air quality, but it was evaluated that the global disease burden caused by COVID-19 is even greater.

The results of this study indicate the direction we should take to lead a sustainable and healthy life in preparation for the post-COVID-era and emphasize the necessity of national and global efforts.

Supplementary Materials: The following are available online at http://www.mdpi.com/2076-3417/10/23/8720/s1: Table S1: Meteorological conditions during COVID-19 pandemic and control periods, Table S2: Relative risks (RRs) and attributable factors (AFs) for $PM_{2.5}$, PM_{10}, and NO_2 (Seoul), and Table S3: Relative risks (RRs) and attributable factors (AFs) for $PM_{2.5}$, PM_{10}, and NO_2 (Daegu).

Author Contributions: Conceptualization, J.H.S. and J.R.S.; methodology, J.H.S., J.S.K., J.Y. and H.Y.; software, H.W.J. and M.R.; validation, J.W.K., S.Y. and J.Y.; formal analysis, J.H.S., J.W.K., S.Y., J.S.K. and H.Y.; investigation, J.H.S., H.W.J. and J.S.C.; data curation, N.N.J., J.Y. and J.S.C.; writing—original draft preparation, J.H.S. and J.R.S.; writing-review and editing, J.H.S. and J.R.S.; visualization, J.H.S. and M.R. All authors read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors acknowledge the free use of the Air Korea data. The authors thank G. Byun and D. A. Huh for their insightful comments in writing the manuscript.

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

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