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Developing an Adaptive Pathway to Mitigate Air Pollution Risk for Vulnerable Groups in South Korea

Sugyeong Park [1], Sea Jin Kim [2], Hangnan Yu [2,3], Chul-Hee Lim [4], Eunbeen Park [2], Jiwon Kim [2] and Woo-Kyun Lee [2,*]

1 Department of Climatic Environment, Korea University, 145 Anamro, Seongbukgu, Seoul 02841, Korea; synergyeong@gmail.com
2 Department of Environmental Science and Ecological Engineering, Korea University, 145 Anamro, Seongbukgu, Seoul 02841, Korea; bluegulcy@gmail.com (S.J.K.); heyevvin@gmail.com (E.P.); keinesorge2@gmail.com (J.K.); willpower0129@gmail.com (H.Y.)
3 Wetland Research Center of Yanbian University, Yanji 133000, China
4 Institute of Life Science and Natural Resources, Korea University, 145 Anamro, Seongbukgu, Seoul 02841, Korea; limpossible@korea.ac.kr
* Correspondence: leewk@korea.ac.kr

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Abstract: Air pollution is one of the most significant environmental hazards. The elderly, young, and poor are more vulnerable to air pollution. The risk of air pollution was assessed based on the risk framework published by the Intergovernmental Panel on Climate Change (IPCC) in terms of three aspects: hazard, exposure, and vulnerability. This study determined the concentrations of hazardous pollutants using satellite images from 2015 at 1 km^2 spatial resolution. In addition, the study identified vulnerable groups who are exposed to hazardous air pollutants. The study highlighted the degree of vulnerability based on environmental sensitivity and institutional abilities, such as mitigation and social adaption policies, using statistical data. Based on the results, Seoul City and Gyeonggi Province have low air pollution risk owing to good institutional abilities, while the western coastal area has the highest air pollution risk. Three adaption pathway scenarios were assessed in terms of the effect of increases in the budget for social adaptation policies on the level of risk. The study found that the risk can be reduced when the social adaptation budget of 2015 base level is increased by 20% in Gyeonggi Province and by 30% in the western coastal area. In conclusion, this risk assessment can support policy-making to target more vulnerable groups based on scientific evidence and to ensure environmental justice at the national level.

Keywords: disaster risk reduction; air pollution; adaptive pathway; spatial analysis; sustainable development goals

1. Introduction

Air pollution is one of the most significant environmental hazards [1]. Air pollution has the fifth highest mortality risk factor globally and was responsible for approximately 4.9 million deaths in 2017, as a result of chronic obstructive pulmonary disease, which is nearly one out of every 10 people [2].

Air pollution is regarded as an anthropocentric disaster. The negative health effects are predominantly experienced in urban areas, and several urban cities have far exceeded international guidelines [3]. Air pollution has disproportionate impacts on vulnerable groups, such as the elderly, young, and poor [4], who are more sensitive to air pollution, with limited ability to protect themselves from environmental risk [5]. Therefore, these issues should be perceived as a matter of environmental justice, because the risk varies depending on social, economic, and environmental conditions.

In South Korea, levels of fine particle matter ($PM_{2.5}$) in highly populated cities have reached record highs. The national assembly passed a series of bills on safety and disaster management to declare air pollution a "social disaster" in March 2019 [6]. This intervention enabled additional funding for vulnerable groups with the distribution of masks and installation of air purifiers for the elderly, poor, and students, funded by the government. Under the limited budget, it is crucial to be aware of how much and where should be funded. According to the Sustainable Development Report published by the Sustainable Development Solutions Network (SDSN), air pollution in South Korea is considered a "significant challenge" [7]. Air pollution policies should consider both social and environmental aspects in the face of intense economic development in South Korea [8].

The United Nations established the Sustainable Development Goals (SDGs) in 2015, with 17 goals, 169 targets, and 230 indicators to address social inequalities, environmental pollution, and economic development [9]. Of the 17 goals, Goal 3, 7, and 11 are related to the mitigation of air pollution, and the specific indicators are as follows [10]:

- Mortality rate attributed to household and ambient air pollution for the health goal (SDG indicator 3.9.1)
- Proportion of population with primary reliance on clean fuels and technologies for the sustainable energy goal (SDG indicator 7.1.2)
- Annual mean levels of fine particulate matter ($PM_{2.5}$) in cities (population-weighted) for the urban sustainable development goal (SDG indicator 11.6.2)
- Goal 3, 10, and 11 include indicators relating to social adaptation as follows:
- Coverage of essential health services (defined as the average coverage of essential services based on tracer interventions that include reproductive, maternal, newborn and child health, infectious diseases, non-communicable diseases, and service capacity and access, among the general and the most disadvantaged population) (SDG indicator 3.8.1)
- Proportion of people living below 50% of median income, by age, sex, and persons with disabilities (SDG indicator 10.2.1)
- Number of deaths, missing persons, and persons affected by disaster per 100,000 people (SDG indicator 11.5.1)

The objective of this study is to assess the air pollution risk for the vulnerable groups using geographic information system (GIS) techniques based on the risk framework developed by Intergovernmental Panel on Climate Change (IPCC). This study analyzes the relevant data using satellite image and social statistics and presents the threat of air pollution, the level of risk, as well as trends in social adaptation pathways. The objectives of this study were divided into two: (1) to determine the exposure of vulnerable groups to air pollution risks; (2) to investigate the effect of increased social adaptation funding on adaptation pathways. This study is expected to provide evidence-based advice to stakeholders for reducing air pollution risk. Furthermore, the study can provide a means to determine the effectiveness and coherence of air pollution policies based on the risk assessment of vulnerable groups and alignment with the principle of the SDGs—"Leaving no one behind".

2. Study Area and Materials

The study area is South Korea, located at latitude 33°09′–38°45′ N and longitude 124°54′–131°06′ E (Figure 1). It is one of the world's fastest-growing countries and one of the most densely populated and most urbanized countries in the world [11]. The population was estimated to be approximately 51.64 million, with a population density of 530 persons per 1 km^2 in 2018. South Korea covers approximately 100,363 km^2, of which 64% is forests and 19% is agricultural land. In the past three decades, the average annual temperature was 13.2 °C (24.2 °C in the summer and 1.2 °C in the winter) and average annual precipitation was 1237.4 mm (638.7 mm in the summer and 94.1 mm in the winter). The prevailing wind direction is southwesterly in summer and northwesterly in winter.

South Korea has six metropolitan cities, Incheon, Daejeon, Gwangju, Daegu, Ulsan, and Busan, and nine administrative provinces, viz. Gyeonggi, Gangwon, Chungbuk, Chungnam, Jeonbuk, Jeonnam, Gyeongbuk, Gyeongnam, and Jeju. Seoul, Incheon, and Gyeonggi province are regarded as capital regions, while the rest are non-capital regions.

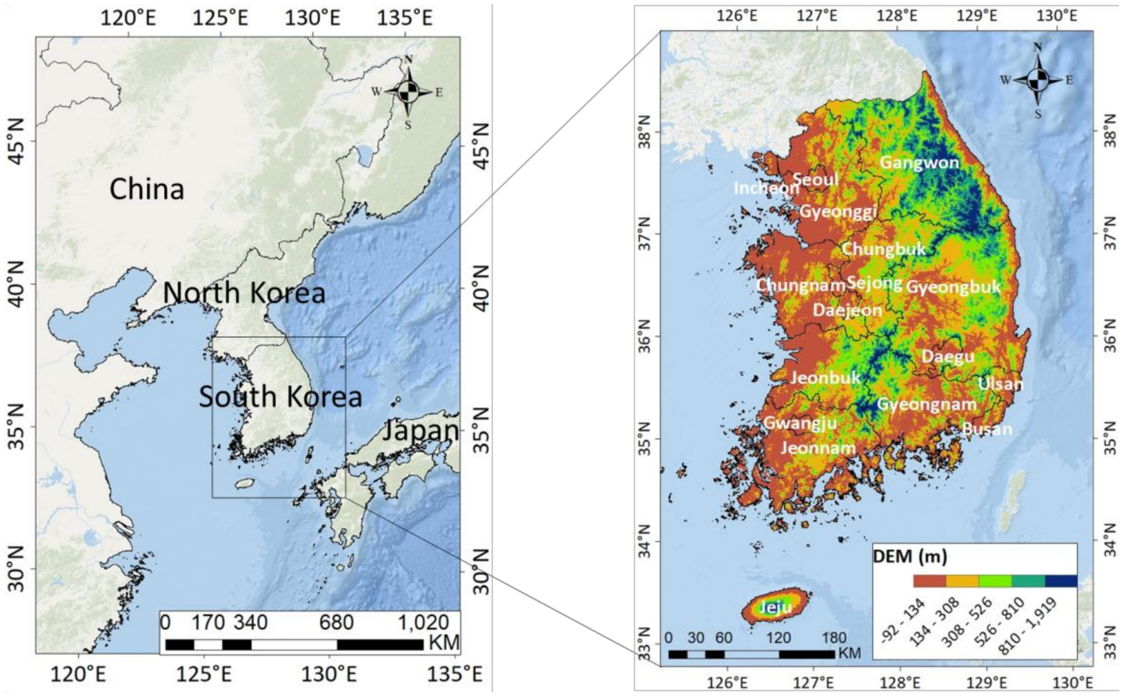


Figure 1. Geographical location of study area and elevation.

An integrated approach is required to mitigate air pollution, with consideration of the mitigation of hazardous pollutants, the people who are adversely affected by hazards, as well as social vulnerability, including the socio-economic context and institutional capability.

According to the IPCC definition [12], "hazards" are defined as the potential occurrence of human-induced physical events that may cause threats. We selected four air pollution indicators that impact on human health: nitrogen dioxide concentration (NO_2), Particle Matter 2.5 concentration ($PM_{2.5}$), ozone (O_3), and sulfur dioxide concentration (SO_2) [13]. "Exposure" is defined as the presence of people in place that could be adversely affected [12]. In this study, we chose three vulnerable groups as exposure indicators based on the scientific evidence of health effects: the elderly who have adverse effects of outdoor pollution due to the weak immune systems [14,15], the young aged between 10 to 19 can be exposed to air pollution due to the frequent outdoor activities [16], and the poor are less prepared for air pollution due to the relative lack of financial capacity against air pollution [16,17]. "Vulnerability" can be defined as sensitivity to harm and lack of capacity to cope and adapt [12]. Sensitivity refers to the degree to which a system is affected adversely. The location of emitting facilities exacerbates the concentration of air pollution, because people who live in or near emitting facilities that emit pollutants are much more sensitive to compared to people who live in a place with few emission sources [18]. The capacity to cope and adapt is understood as the suite of mitigation options to address air pollution, the institutional capacity, and social adaption policies related to vulnerable groups [19]. On this basis of the literature review, we used several data to measure the risk of air pollution as presented in Table 1.

Table 1. Data availability and literature review related to indicators of measuring risk of air pollution (2015).

Components	Categories		Indicators	Definition	Data Source	Reference
Hazards	Pollutants		Nitrogen Dioxide concentration (NO_2)	Ambient air pollution originates from human activities, and PM, O_3, NO_2, and SO_2 have the strongest evidence of health effects	NEO [1]	[20,21]
			Fine Particle Matter 2.5 concentration ($PM_{2.5}$)		SEDAC [2]	[20,21]
			Ozone concentration (O_3)		NEO [1]	[20,21]
			Sulfur dioxide concentration (SO_2)		Air Korea	[20,21]
Exposure	People		Recipients who need support leading a healthy life (%)	Vulnerable groups include the poor, persons aged 10–19, and those over 60	KOSIS [3]	[16,17]
			Young people between 10–19 years old (%)		KOSIS [3]	[15]
			Elderly people over 60 years old (%)		KOSIS [3]	[14,15]
Vulnerability	Sensitive environment		Number of diesel Vehicles (%)	Fuel combustion from vehicles, industrial facilities, and power plants worsen health effects	KOSIS [3]	[22]
			Distance from industrial areas and road		NEINS [4]	[23,24]
			Final energy consumption by fossil fuels (%)		KEEI [5]	[25]
	Adaptive capacity	Mitigation policy	Budget for alleviating air pollution (%)	Government interventions related to electric cars, tree conservation, and renewable energy to mitigate ambient air pollution	LFIOS [6]	[26]
			Tree density (ha)		[27]	[28,29]
			Final energy consumption by renewable energy (%)		KEEI [5]	[26]
		Social adaptation policy	Budget for medical care assistance (%)	Policies can support the vulnerable groups- medical care assistance for poor; school hygiene fund for students; social welfare for elderly	KOSIS [3]	[30]
			Budget for school hygiene management (%)		LEFSIS [7]	[31]
			Budget for social welfare (%)		LFIOS [6]	[32]

[1] NASA Earth Observation (NEO); [2] Socioeconomic Data and Applications Center (SEDAC); [3] Korean Statistical Information Service (KOSIS); [4] National Environment Information Network System (NEINS); [5] Korea Energy Economics Institute (KEEI); [6] Local Finance Integrated Open System (LFIOS); [7] Local Education Financial Statistics Information System (LFFSIS).

3. Methods

3.1. Risk Assessment

The concept of the risk framework was introduced in the fifth assessment report (AR5) of the IPCC Working Group II. It has been widely applied in assessing disaster risk based on physical hazards, exposure, and vulnerability of people [33,34]. Human health is at risk to many extreme events linked to climate change and those with the least resources often have the least ability to adapt [12]. In line with this concept, this study modified the risk framework, which is considered suitable for assessing the risk of air pollution, since air pollution is considered as one of the significant social disasters in South Korea, and it has difference impacts by the health condition. The modified risk assessment framework is shown in Figure 2.

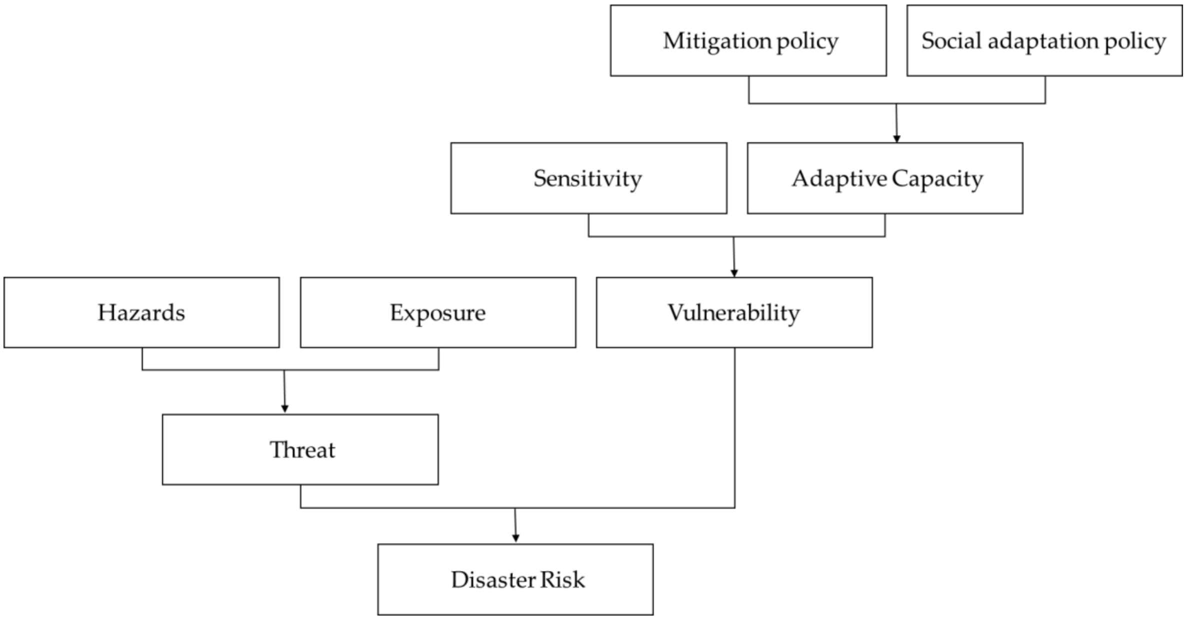


Figure 2. Components of the modified air pollution risk assessment.

The disaster risk was determined through assessing hazards, exposure, and vulnerability as per Equation (1). Before calculating the indicators, each data was normalized with the maximum and minimum value to determine the degree of risk between the regions in the same scale (0–1). The data were processed with GIS techniques. The observational or statistical data were converted into geospatial data through geo-referencing. The statistical data by administrative units were converted into the geospatial data through the geo-referencing of World Geodetic System 1984 (WGS 1984). Both of these non-spatial data were also standardized to the same resolution with spatial data at a scale of 1 km^2. To ensure data consistency, the base year for all data was 2015.

$$Disaster\ risk = Hazard \times Exposure \times Vulnerability \tag{1}$$

where *Hazard* is the sum of normalized concentrations of air pollutants ($PM_{2.5}$, NO_2, O_3, SO_2) in 2015. The $PM_{2.5}$ are available in spatial data, which can be directly used without additional data processing, since $PM_{2.5}$ is provided annually by Socioeconomic Data and Applications Center (SEDAC), while we averaged monthly NO_2 and O_3 spatial data provided by NEO. In terms of SO_2 data, we generated it as the form of spatial data by interpolating the observation data with the geo-referencing of WGS 1984 and the 1 km^2 resolution.

Exposure is the sum of the normalized vulnerable group. Each of the values is the percentage of total population of the elderly, the young and the recipients. The percentages by administrative units were converted into the raster type of geospatial data considering the same geo-referencing and the resolutions. The spatial pattern of vulnerable groups was shown at the scale of administrative units.

In this study, the level of threat is derived by multiplying hazard and exposure indicators, because the degree to which vulnerable groups are exposed to air pollution is a threat of air pollution. To get the Level of Threat, we first added up the Hazards and exposure indicators respectively, and then we multiplied Hazard by Exposure based on the risk assessment framework. The level of threat (*LT*) is defined as per Equation (2), and the *Vulnerability* (*V*) is defined as per Equation (3):

$$LT = \sum_{h=1}^{4}\sum_{e=1}^{3} a_h b_e \text{ , } (a_h \in [0,1],\ b_e \in [0,1]) \tag{2}$$

where:

LT—Level of threat on air pollution,

a_h—the normalized each concentration of air pollutant,

b_e—the normalized each vulnerable group.

The a_h results from the sum of the normalized Hazards indicators: The concentration of air pollutant for NO_2, O_3, $PM_{2.5}$ and SO_2, while b_e comes from the sum of the normalized exposure indices such as recipients of medical benefits (%), the elderly people over 60 years old (%), and young people aged between 10 to 19 (%). To multiply *Hazards* and *Exposure* with the same scale, we normalized these results of *Hazard* and *Exposure* into 0 to 1.

$$V = \sum_{k=1}^{3} S_k \div \sum_{m=1}^{3}\sum_{n=1}^{3} M_m A_n \text{ , } (M_m \in [0,1] \text{ , } A_n \in [0,1]) \tag{3}$$

where:

V—Vulnerability,

S_k—The sum of the normalized Sensitivity,

M_m—The sum of the normalized mitigation policy,

A_n—The sum of the normalized adaptation policy.

Vulnerability is calculated by dividing sensitivity and adaptive capacity. As for Sensitivity indicators, the value of diesel vehicles and final energy consumption by fossil fuel are the percentage of total number of registered vehicles and total energy consumption. As for the distance of road and industries, we buffered 1 km and 2 km distances from industrial areas [23]. Likewise, we also buffered 50 m and 100 m distances from the road [24]. Since the closer people live to industries and the road, the more sensitive to air pollution, we give different weights like a value of 1 in closer areas, while we give a value of 0.5 in farther areas to industrial areas and road.

Adaptive capacity indicators consist of two types: Mitigation policy and Social adaption policy. For Mitigation policy, tree density is directly nominalized and applied in the calculation process, since it is available in spatial data. Meanwhile, the value on budget for alleviating air pollution and final energy consumption by renewable energy is the percentage of total budget and total energy consumption by administrative unit. We normalized the value into 0 to 1 and produced it into raster type by considering the geo-referencing and resolutions. For social adaption policy, the value for medical care assistance is the percentage of medical care expenditure by region to the total, and the school hygiene management is the percentage of the total expenditure by education account. Finally, the value on budget of social welfare is also the percentage of the total budget by administrative unit. All the statistical data were reproduced into raster types with the same geo-referencing and resolutions. To get the value of adaptive capacity, we added up three indicators of mitigation policy and social adaption policy respectively. Following this, the mitigation policy and adaptation policy were added once again. On the basis of calculation, we assess how the proper mitigation policies and social adaption policies attribute to the vulnerability of air pollution via Equation (3), rather than to identify the variety of vulnerability by exposure to difference pollutants. Thus, the risk was calculated by multiplying the level of threat and vulnerability.

3.2. Development of an Adaptive Pathway

Adaptive pathways aim for the development of social adaptation policies, such as funding for medical care assistance, school hygiene management, and social welfare. Social adaptation policies are more flexible than other forms of mitigation policies [35]. Three social adaptation policies were classified using the natural break method with measuring on a 0 to 1 scale, by referring the research case of IPCC [12]: Extreme Low Vulnerability (ELV), Low Vulnerability (LV), Moderate Vulnerability (MV), High Vulnerability (HV), and Extreme High Vulnerability (EHV). The ELV and LV are considered safe areas and are low priority regions for funding, ranging from 0.2 to 0.4; MV are somewhat vulnerable but not urgent areas, ranging from 0.4 to 0.5; HV and EHV are high-risk, priority areas with over 0.5.

We assessed the impact of budget increases in three adaptive pathways to determine the impact on risk. The rate of increase was 10%, 20%, and 30%, which was derived from the difference between the maximum budget and the allocated budget in 2015. In Pathway 1, the budget was increased by 10% in the EHV areas while the budget was maintained in other regions. In Pathway 2, the budget was increased by 10% in HV and 20% in EHV areas. In Pathway 3, the budget was increased by 10%, 20%, and 30% in the MV, HV, and EHV areas, respectively as presented in Table 2.

The adaptive capacity can be shown for each scenario by adding the social adaptation pathways and mitigation policies. Then, the sensitivity indicators can be divided by adaptive capacity to derive the vulnerability. The level of vulnerability differs between the three social adaptation pathways. The integrated risk pathways can be derived by multiplying hazard, exposure, and vulnerability.

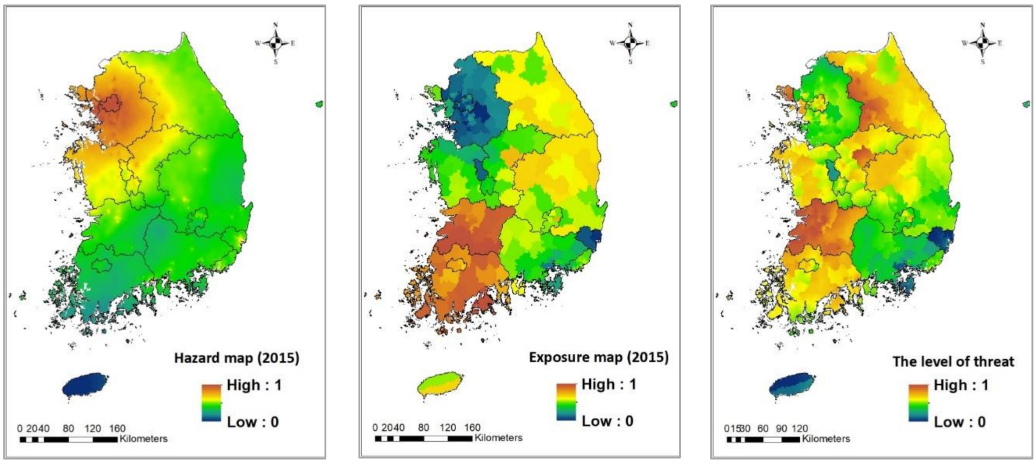
Table 2. Social adaptation pathway by budget increase as of 2015 (%).

Class	No action	Pathway 1	Pathway 2	Pathway 3
Extreme Low Vulnerability (ELV)	0	0	0	0
Low Vulnerability (LV)	0	0	0	0
Moderate Vulnerability (MV)	0	0	0	10
High Vulnerability (HV)	0	0	10	20
Extreme High Vulnerability (EHV)	0	10	20	30

4. Result

4.1. Result of Risk Assessment

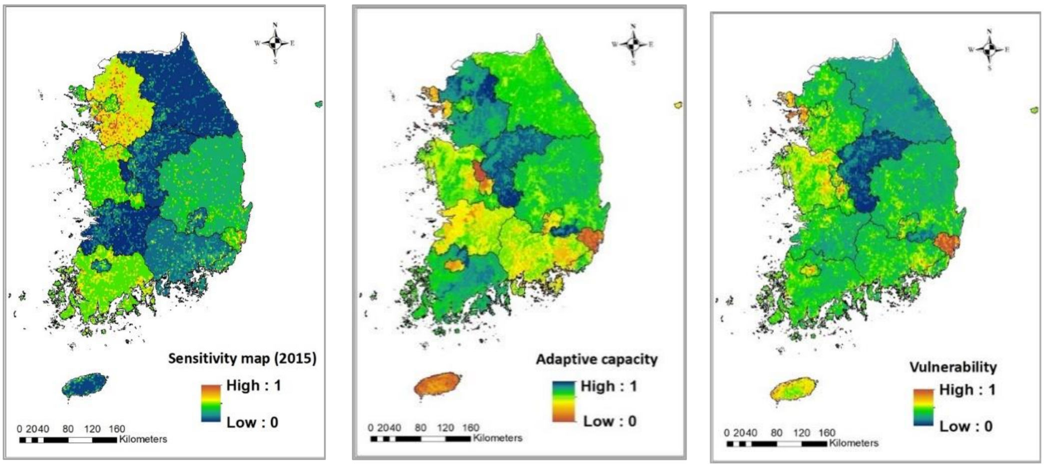
The results of the mapping of indicators are shown in Figure 3a–c. The results indicate that the hazards (Figure 3a) are centralized in Seoul City and Gyeonggi metropolitan areas, accounting for almost 50% of the Korean population, where there is a high level of pollution. Although there are extensive physical hazards in Seoul city and Gyeonggi Province, there is little threat from air pollution (Figure 3c). In contrast, there are no significant air pollution hazards in Jeonbuk and Jeonnam Province, but air pollution levels could pose a severe threat to those who live in these regions (Figure 3c). The level of threat varies across the regions due to the spatial distribution of vulnerable groups. In 2015, the productive population aged 15 to 64 represented 75.9% of the total Seoul population. There were relatively few vulnerable groups, such as the elderly and poor, in Seoul City and Gyeonggi Province, despite the high population in these areas, compared to Jeonnam and Jeonbuk Province (Figure 3b). In contrast, Jeonbuk and Jeonnam Province account for around 3% of the Korean population, yet have a higher number of beneficiaries, including the elderly (38.4%) and poor (10.2%). A high spatial inconsistency exists between the observed hazards and the locations of vulnerable groups. As the population becomes more concentrated, institutions and infrastructure are also concentrated in urban areas, with less development in rural areas. Since 1960, this has resulted in regional disparity in terms of growth in urban areas and rural areas [36,37].



(a) **(b)** **(c)**

Figure 3. Result of indicators: **(a)** Hazard map, **(b)** Exposure map, **(c)** Level of threat.

The results of mapping the indicators for estimating vulnerability are shown inFigure 4a–c. The results for sensitivity (Figure 4a) show greater sensitivity around highly-populated cities, especially in the capital regions. This is attributed to the high number of emission facilities, which are located in Seoul and the Gyeonggi Province, while the vulnerability for the capital regions is not as high (Figure 4c). In contrast, rural areas emerge as more vulnerable, in particular Jeonbuk, Chungnam Province, and Ulsan City (Figure 4c), although these areas have lower sensitivity (Figure 4a). Vulnerability shows a different spatial pattern compared with sensitivity, relating to the degree of adaptive capacity (Figure 4b).



(a) **(b)** **(c)**

Figure 4. Results of indicator of vulnerability: **(a)** Sensitivity map, **(b)** Adaptive capacity map, and **(c)** Vulnerability map.

The results of the risk assessment show an obvious contrast between the western coastal areas, including urban areas, and the eastern coastal region (Figure 5). The western coastal areas show spatial clusters of HV and EHV, especially at Incheon (97.6%), Seoul City (79.4%), Chungnam (55%), and Jeonbuk Province (90.5%). In contrast, the northern parts of the eastern coastal region, including Gyeonggi (58.3%), Chungbuk (92.3%), and parts of Gyeongnam (96.8%), are less at risk of air pollution with ELV and LV (Table 3).

Seoul, Incheon City, Jeonbuk, and Chungnam Province have a high threat (Figure 3c) and high risk (Figure 5), showing similar spatial patterns. However, at Gangwon and Chungbuk Province, the risk was relatively low, compared to the high level of threat. The results of the vulnerability (Figure 4c) indicate the highly vulnerable areas in metropolitan areas, such as Incheon, Gwangju and Ulsan cities, and Chungnam Province, while the results of risk assessment (Figure 5) indicate the severe high-risk areas in the metropolitan areas of Seoul, Incheon, Jeonbuk, and Chungnam Province.

Table 3. Area of risk by administrative unit.

Class Area	ELR [1]		LR [2]		MR [3]		HR [4]		HER [5]	
	Km^2	%	Km^2	%	Km^2	%	Km^2	%	Km^2	%
Seoul	0	0	29	6.2	67.8	14.4	251.7	53.6	121	25.8
Busan	145.2	28.8	271	53.8	72.6	14.4	14.5	2.9	0	0
Incheon	0	0	4.8	1.2	4.8	1.2	19.4	4.8	372.7	92.8
Daegu	135.5	20.1	300	44.6	198.4	29.5	38.7	5.8	0	0
Gwangju	0	0	38.7	10.4	140.4	37.7	150	40.3	43.6	11.7
Daejeon	33.9	8.3	121	29.8	183.9	45.2	62.9	15.5	4.8	1.2
Ulsan	513	66.7	198.4	25.8	38.7	5.0	19.4	2.5	0	0
Sejong	251.7	68.4	106.5	28.9	9.7	2.6	0	0	0	0
Gyeonggi	1655.3	21.9	2754	36.4	2265.1	30	730.8	9.7	154.9	2.0
Gangwon	1185.8	9.4	6655	52.8	3523.5	27.9	1181	9.4	62.9	0.5
Chungbuk	3867.16	67.8	1398.8	24.5	396.9	7.0	38.7	0.7	0	0.0
Chungnam	48.4	0.8	493.7	8.6	2032.8	35.5	2671.7	46.6	484	8.4
Jeonbuk	0	0	62.9	1.1	498.5	8.5	3160.5	53.7	2163.5	36.8
Jeonnam	4.84	0.1	934.1	12.8	3707.4	50.9	2526.5	34.7	106.5	1.5
Gyeongbuk	2860.44	19.9	7318	50.9	3605.8	25.1	537.2	3.7	43.6	0.3
Gyeongnam	4617.36	62.1	2579.7	34.7	232.3	3.1	9.7	0.1	0	0.0
Jeju	445.28	36.4	614.7	50.2	150	12.3	14.5	1.2	0	0.0

[1] Extreme Low Risk (ELR) with 0 to 0.2; [2] Low Risk (LR) with 0.2 to 0.4; [3] Moderate Risk (MR) with 0.4 to 0.5; [4] High Risk (HR) with 0.5 to 0.6; [5] Extreme High Risk (EHR) with 0.6 to 1.

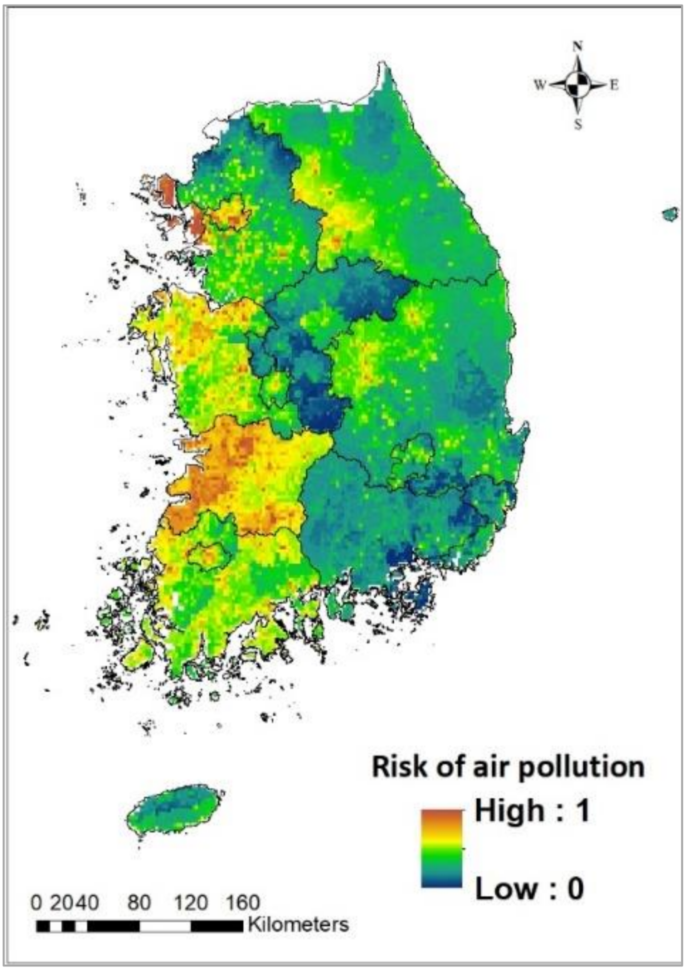


Figure 5. Results of air pollution risk assessment.

The results have been proven by previous research [38]. The long-terms effects of air pollutants on human health are assessed using a cohort database provided by the National Health Insurance Service. The respiratory diseases are considered as the long-term health effects of air pollutants, whereupon the new hospital admissions of respiratory diseases are measured to assess the health risk. The research shows the number of hospital admissions and the fraction of hospital admissions by province level. Since 2007, 11,956 patients have been hospitalized at least once due to respiratory disease caused by air pollution, and the incidence of hospital admissions was 17,875 during the study period. On national average, the fraction of hospital admissions is 0.46, but the fraction of Jeonbuk area is 10% higher than the national average. Although the population of Jeonbuk only takes 3.5% of the nation, and the degree of air pollution is also not much more severe than capital cities, many respiratory patients are hospitalized in Jeonbuk. This is similar with the result of this study.

4.2. Social Adaptation Pathways

The budgets for medical assistance, school hygiene management, and social welfare were increased by 10%, 20%, and 30% in MV, HV, and EHV areas by scenarios. The results of the risk assessment for this social adaptation pathway are shown in Table 4. The level of risk in the western coastal area gradually increased as the budget for social adaptation policies was increased. The risk in the EHV area decreased by 1.46% from no action in 2015 (3.79%) to Pathway 3 (2.33%), and the risk in the HV area also reduced by 5.51% from no action in 2015 (19.93%) to Pathway 3 (14.42%).

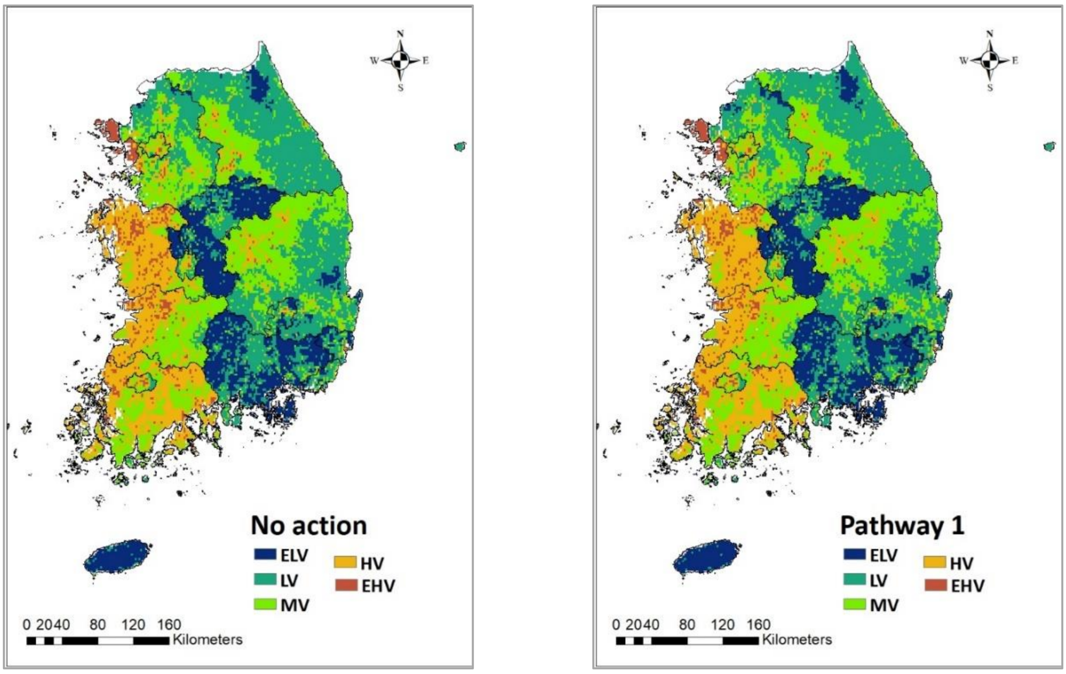
In contrast, the ELV and LV areas are increased by 10.98% and 0.92%, respectively. There is no significant difference between no action and Pathway 1 when raising the budget by only 10% in the

EHV area. In other words, the risk of air pollution cannot be expected to reduce when increasing the budget by only 10%. In Pathway 2, parts of Gyeonggi Province improved immediately from HV to MV, when increasing the budget for social adaptation policies by 10%. However, the western coastal areas are still at risk, even with a 20% increase in the budget in the EHV areas. In Pathway 3, the risk in the western coastal area was reduced only after increasing the budget by 30% in the EHV areas, as shown in Figure 6.

Table 4. Area of risk phases according to the pathways in South Korea.

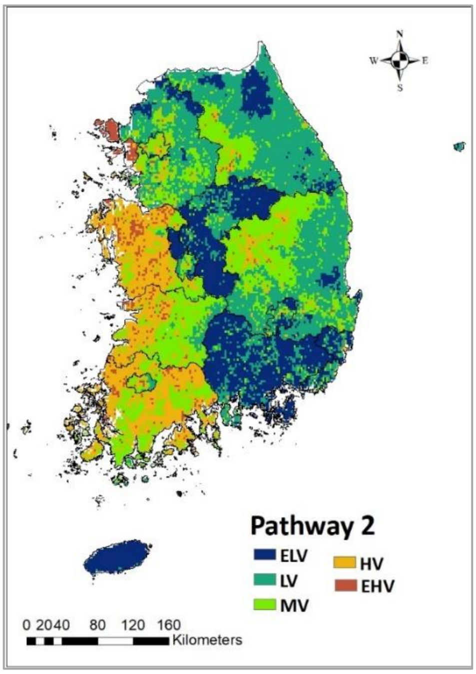
	No action		Pathway 1		Pathway 2		Pathway 3	
Class Area	Km^2	%	Km^2	%	Km^2	%	Km^2	%
ELV [1]	15308.92	15.95	15797.76	16.46	20177.96	21.02	25845.6	26.93
LV [2]	31063.12	32.36	31721.36	33.05	31992.4	33.33	31944	33.28
MV [3]	26852.32	27.97	26286.04	27.38	23624.04	24.61	22113.96	23.04
HV [4]	19127.68	19.93	18687.24	19.47	17172.32	17.89	13842.4	14.42
EHV [5]	3634.84	3.79	3499.32	3.64	3020.16	3.15	2240.92	2.33
SUM	95986.88	100100100	95991.72	100	95986.88	100	95986.88	100

[1] Extreme Low Vulnerability (ELV); [2] Low Vulnerability (LV); [3] Moderate Vulnerability (MV); [4] High Vulnerability (HV); [5] Extreme High Vulnerability (EHV).

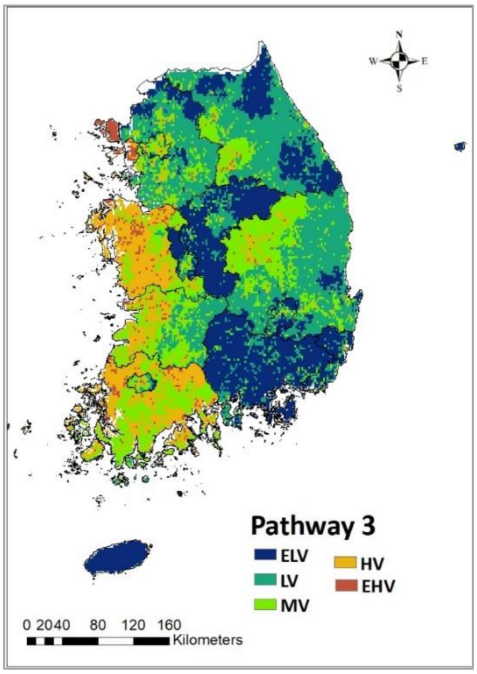


(a) (b)

Figure 6. *Cont.*



(c)



(d)

Figure 6. Risk assessment results for social adaptation pathways: **(a)** No increase in budget; **(b)** Pathway 1 with 10% increase in budget in EHV; **(c)** Pathway2 with a 10% and 20% increase in budget in HV and EHV areas; **(d)** Pathway 3 with a 10%, 20%, and 30%.

5. Discussion

The capital areas, including Seoul, Incheon City, and Gyeonggi Province, are hazardous, due to air pollution. Although these regions have a high adaptive capacity to combat the threat of air pollution, the vulnerability does not decrease because the sensitivity is very high. In fact, in 2015, the budget for medical care assistance in the capital areas was approximately 1.4 million USD, the largest in the country, accounting for approximately 29.4% of the total national medical care assistance budget. However, these areas also had the highest proportion of diesel cars (36.4%) and an extensive road network. To reduce the risk of air pollution, capital areas can support mitigation policies through the strict control of emission levels, rather than increasing social welfare budgets, such as medical care assistance.

The government of South Korea has established environmental regulations for the mitigation of air pollution. Article 16 of the Clean Air Conservation Act requires metropolitan cities to set permissible emission levels [39]. This regulation can play a key role in stimulating the development of clean technology and clean fuels [40]. Also, the government published the implementation plan for renewable energy, Renewable Energy 2030, in 2017, which includes a target to make up 20% of total renewable energy supply by 2030. Furthermore, as part of the Korean Sustainable Development Goals (K-SDGs) published by the Ministry of Environment: Commission on Sustainable Development in 2018, the country set a goal for expanding the number of eco-friendly cars from 90,000 units to 8.8 million units by 2030 [41]. In addition, the government is aiming to increase the urban park area per capita from 9.6 m^3 in 2017 to 11.6 m^3 in 2030. However, the annual average of particulate matter in Seoul (25μg/m^3) exceeds World Health Organization guideline limits (10 μg/m^3) in 2017 [42]. Thus, these interventions should be implemented and reviewed, particularly in capital areas where there is a more urgent need to reduce the level of pollutant emissions [43].

As for non-capital areas, such as Gangwon, Gyeongbuk, Chongnam, and Jeonbuk Province, there should be an emphasis on social welfare policies for decreasing the risk of vulnerable groups, such as the elderly, poor, and students. These areas require a different mitigation approach to the risk of air pollution. First, Gangwon and Gyeongbuk Province are less hazardous due to the topography, where the altitude increases from west to east. It is difficult for air pollution to pass the mountain range from west to east. Despite the favorable topography, there are vulnerable groups spread out across these regions. Thus, it is necessary for local government to invest in social welfare policies. For example, the budget of medical assistance in Gangwon (3.7%) and Gyeongbuk (7.4%) does not exceed that of Seoul (14.7%) alone in 2015. Secondly, the risk in Chungnam and Jeonbuk is very high. The physical hazards and sensitivity to harm are not high as the capital areas, yet the threat and the risk are very high because the vulnerable groups are clustered and the adaptive capacity is lower than the capital areas. In 2015, the proportion of the total budget spend on social welfare was 24.6% in Chungnam and 27.6% in Jeonbuk, which is far below that of the Seoul metropolitan area (39.5%) and lower than the national average (31.3%). The government pays attention to these regions due to the level of risk associated with lack of adaptive capacity. Policymakers should recognize the importance of social adaption policies in these areas to protect socially vulnerable people like the elderly and those who need medical support.

We examined the importance of the mitigation policies for capital areas and the social adaptation polices for non-capital areas. Mitigation policies are mentioned such as technology development for electric vehicles, renewable energy and afforestation. Meanwhile social adaptation policies refer that it is ability to address unpredictable circumstances by carrying out precautionary thinking in this study [34,35]. Scenarios for various social adaptation pathways were developed to examine the results of implementation. Social adaptation pathways include the provision of suitable policies and budgets in vulnerable areas.

The assessment of the pathway scenarios indicate that the western coastal areas are paid less attentions to in the budget allocation; for example, with a 20% increase in social adaptation policy budget in northern Gyeonggi Province, there was a shift from EHV to MV, but other regions do not exhibit such a distinctive transition. The EHV areas in the western coastal areas were improved only when the budget was increased by 30%. The divergence is related to differences in budget allocation between capital regions and non-capital regions. Given that budget allocation is strongly related to political will, it is clear that the western coastal areas were relatively less supported [44]. The government has focused on supporting Seoul City and Gyeonggi Province, whilst not fully supporting the other regions [45]. Without adequate government support, disaster risk cannot be managed or reduced [44]. To accommodate future risks, the disaster fund should be increased by at least 30% to alleviate risk and to meet permissible emissions levels in western coastal areas such as Chungnam and Jeonbuk.

Mitigation policies and/or social adaptation policies should be implemented in high-risk regions depending on the context. In 2018, the government of South Korea published the K-SDGs to address mitigation of air pollution and to ensure environmental justice in line with the principle of leaving no one behind [41]. First, Goal 3, 7, and 11 mention mitigation targets for air pollution. Target 3.7 aims to reduce the number of deaths from disasters with a focus on protecting the vulnerable groups. Target 11.7 aims to reduce the adverse environmental impact of cities, including air quality and waste management. Target 7.2 aims to increase the generation of clean energy, and Target 7.4 is aimed at minimizing air pollution from the transportation sector. Second, Goal 3, 10, and 11 relate to social adaptation policies to address air pollution with detailed targets and indicators. Target 3.9 aims at achieving universal health coverage by expanding public health services. Target 10.2 aims to promote equitable social, economic, and political inclusion, irrespective of age, sex, disability, or social status with specific indicators for the poverty rate of the elderly. Target 11.5 aims to reduce the number of deaths and economic losses from disasters as well as to devise and implement integrated risk management solutions for urban disasters in order to decrease disaster-related deaths. Thus, by 2030, mitigation targets should be focused on the capital regions, such as Seoul, Incheon City and Gyeonggi Province, while social adaption targets must be implemented in non-capital areas, such as Gangwon, Gyeongbuk, Chungnam, and Jeonbuk.

6. Conclusions

Air pollution is an environmental problem with socio-economic impacts. Air pollution has emerged as a serious issue, and its risk to vulnerable groups, such as the poor, youth, and elderly, requires urgent attention. This study quantified the level of risk of vulnerable groups exposed to air pollution and evaluated the effect of increasing the budget for social adaptation policies on risk levels. To assess the integrated risk of air pollution, we used the modified risk framework, using three main indicators: hazards, exposure, and vulnerability.

Hazard and sensitivity are higher around capital regions in highly populated areas, but the health threats and social vulnerability are higher in non-capital regions. Specifically, the western coastal areas, including Seoul, Incheon City, and Chungnam and Jeonbuk Province revealed spatial clusters, while the eastern region, including the northern parts of Gyeonggi, Chungbuk, and parts of Gyeongnam have lower risk of air pollution. With an increase in the budget of social adaptation policies, the risk in western coastal areas gradually decreased. In the western coastal areas, which includes EHV areas, the risk was reduced after increasing the budget by 30%; in Gyeonggi province, the risk was reduced only when the social adaptation budget was increased by 20%. The variation in effects across the regions is related to the unbalanced budget allocation between capital regions and non-capital regions.

There are three main conclusions from this study. First, mitigation policies should be supported in capital regions, such as Seoul, Incheon City, and Gyeonggi Province to reduce emissions. Second, there should be greater emphasis on social welfare policies for reducing the risk of vulnerable groups in non-capital regions, such as Gangwon, Gyeongbuk, Chongnam, and Jeonbuk Province. Thirdly, appropriate policies and budget should be implemented in risky areas in priority order.

Based on the principle of leaving no one behind, the results of the air pollution risk assessment should guide government policy and decision-making. The mitigation targets (Target 3.7, 11.7, 7.2, and 7.4) should focus on capital regions. In parallel with this, the social adaption targets (Targets 3.9, 10.2, and 11.5) should be implemented in non-capital regions.

This study attempted to determine the risk of air pollution for vulnerable groups and highlights the spatial effects of policies; however, the study could not consider the different conditions to exposure to air pollution. These limitations notwithstanding, the study is expected to support the mitigation of the risk of air pollution for vulnerable groups in South Korea by setting appropriate goals of policies and providing direction in terms of policy implementation.

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