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Air quality co-benefits from climate mitigation for human health in South Korea

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ABSTRACT

Climate change mitigation efforts to reduce greenhouse gas (GHG) emissions have associated costs, but there are also potential benefits from improved air quality, such as public health improvements and the associated cost savings. A multidisciplinary modeling approach can better assess the co-benefits from climate mitigation for human health and provide a justifiable basis for establishment of adequate climate change mitigation policies and public health actions. An integrated research framework was adopted by combining a computable general equilibrium model, an air quality model, and a health impact assessment model, to explore the long-term economic impacts of climate change mitigation in South Korea through 2050. Mitigation costs were further compared with health-related economic benefits under different socioeconomic and climate change mitigation scenarios. Achieving ambitious targets (i.e., stabilization of the radiative forcing level at 3.4 W/m^2) would cost 1.3–8.5 billion USD in 2050, depending on varying carbon prices from different integrated assessment models. By contrast, achieving these same targets would reduce costs by 23 billion USD from the valuation of avoided premature mortality, 0.14 billion USD from health expenditures, and 0.38 billion USD from reduced lost work hours, demonstrating that health benefits alone noticeably offset the costs of cutting GHG emissions in South Korea.

1. Introduction

A global commitment to respond to climate change threats was made at the 21st conference of the United Nations Framework Convention on Climate Change (UNFCC) in Paris in 2015 with the goal of limiting “global average temperature rise in this century to well below 2 °C above pre-industrial levels and to pursue efforts to limit it below 1.5 °C” (UNFCCC, 2015). According to this Paris Agreement, each country should determine its own plans and submit them as nationally determined contributions (NDCs). However, policymakers often hesitate to propose ambitious mitigation targets because these efforts have associated economic costs. Nevertheless, there are measurable co-benefits in terms of air pollution reduction and human health improvement, which could result in substantial economic benefits and offset a considerable fraction of the mitigation costs (Fig. A1) (Balbus et al., 2014; Gao et al., 2017; Xie et al., 2018).

A rapidly growing body of literature investigating health co-benefits from climate mitigation focuses on the global implications (Markandya

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et al., 2018; Scovronick et al., 2019; Vandyck et al., 2018). Although these studies provide regional details, results for South Korea as a separate region have not been available, except in a study by Vandyck et al. (2018). Through decades of rapid development and reconstruction after the Korean War (1950–1953), South Korea has become one of the top 20 global economies, with a Gross Domestic Product (GDP) of 1.4 trillion USD (UNSTATS, 2017). Concurrently, South Korea has faced challenging environmental problems, particularly with respect to air quality issues. South Korea ranked seventh among the largest producers of carbon dioxide (CO_2) emissions worldwide in 2014 (UNFCCC, 2017) and placed 173 out of 180 countries in terms of air quality, according to the 2016 Environmental Performance Index (EPI, 2016). Classified as a Group 1 carcinogen by the World Health Organization and known to trigger a variety of illnesses (Loomis et al., 2013), outdoor air pollution is predicted to be responsible for the premature deaths of 1109 per million Koreans by 2060 if no mitigation efforts are made (OECD, 2016). Furthermore, pressure is mounting to mitigate CO_2 emissions in contribution to international efforts.

Thus, it is important to analyze air quality-related health co-benefits that could be realized under recent international pledges to mitigate climate change, which could help shape climate change mitigation policies in South Korea. A few studies have examined the economic impacts of air pollution in South Korea, but these have been focused on the policy implications associated with air pollution and do not consider the economic benefits of climate change mitigation (Leem et al., 2015). Other mitigation assessment studies in South Korea focus on sectors other than health or are limited in scope to a single city (Chae, 2010; Leem et al., 2015; Winchester and Reilly, 2019). To fill this research gap, we conducted an integrated study by combining an air quality model, economic model, and health assessment model to evaluate the health co-benefits of climate change mitigation under different scenarios in South Korea.

2. Materials and methods

2.1. Study framework

This study adopted an interdisciplinary multi-modeling approach combining air quality, health assessment, and economic models to evaluate the long-term health and economic impacts of air pollution under climate change mitigation and Shared Socioeconomic Pathway (SSP) scenarios in South Korea (Fig. 1). Emissions data, with input from databases for SSPs and Representative Concentration Pathways (RCPs), were generated using the Asia-Pacific Integrated Assessment/Computable General Equilibrium (AIM/CGE) model (Fujimori et al., 2012). Based on gridded emission data, an air quality model (the Community Multiscale Air Quality modeling system; CMAQ) was used to calculate the annual atmospheric particulate matter with an aerodynamic diameter of < 2.5 µm ($PM_{2.5}$) and ozone (O_3) concentrations in relevant Asian regions. The health impact assessment model estimated the health impacts of $PM_{2.5}$ and O_3 concentrations, which were then combined with the Integrated Model of Energy, Environment, and Economy for Sustainable Development/Computable General Equilibrium (IMED|CGE) to monetize the economic value of these health impacts in South Korea. Mitigation costs were estimated in the IMED|CGE model using carbon prices from multiple mainstream Integrated Assessment Models (IAMs) for comparison purposes. Finally, we quantified the health co-benefits of air pollution reduction resulting from climate change mitigation in South Korea.

2.2. Scenarios

This study assessed three dimensions: SSPs, climate change mitigation, and air quality (Table A1). SSPs provide broad, basic descriptions of anticipated global socioeconomic status in the current century and are sufficient to differentiate between the socioeconomic challenges of mitigation and adaptation (O'Neill et al., 2014). Among the five SSPs, SSP2 ("middle-of-the-road") was chosen to analyze the co-benefits for socioeconomic transition in this study. SSP2 is a reference scenario in which future socioeconomic changes are assumed to be similar to current trends, i.e., an interim scenario between SSP1 and SSP3 (Ebi, 2013; Rao et al., 2017). For comparison purposes, SSP3, which is characterized by "regional rivalry" and significant challenges to mitigation and adaptation, was also included in our assessment to estimate influences of socioeconomic elements under similar climatic conditions. Essentially, SSP3 has elevated greenhouse gas (GHG) emissions from the land-use sector associated with high population levels and reduced bioenergy, carbon capture, storage, and afforestation potential, which are the key countermeasures to achieve stringent climate targets. A scenario stabilizing the radiative forcing level at $3.4\ W/m^2$ was considered for the climate change mitigation aspect of this study; this scenario has 50% chance of achieving the target of the Paris Agreement (i.e., restricting the increase in global temperatures to well below 2.0 °C) by the end of the century. Although climate conditions at a forcing level of $2.6\ W/m^2$ (RCP 2.6) have higher chances (66%) of meeting the target, this condition is not feasible for an SSP3 scenario (Fujimori et al., 2017). Several mitigation studies have set their stabilization scenario at $3.4\ W/m^2$, which has a high level of policy relevance (Clarke et al., 2014). By comparing scenarios for no mitigation and mitigation at $3.4\ W/m^2$, we calculated the costs of climate change mitigation. For macroeconomic benefits associated with air quality improvement assessments, we quantified the health effects of air pollution for each SSP by including and excluding air pollution effects in the model.

2.3. AIM/CGE model

The implementation protocol of the AIM/CGE is described in Fujimori et al. (2012) and therefore is only described briefly here. The AIM/CGE model is a multi-region, multi-sector, and multi-gas recursive dynamic general equilibrium model that considers interactions of all economic goods and production factors (Fujimori et al., 2017, 2012). AIM/CGE is widely used to investigate climate change mitigation and its impacts with respect to renewable energy, GHG policies, carbon tax, and CO_2 mitigation (Fujimori et al., 2016; Masui et al., 2010; Matsumoto and Masui, 2011; Thepkhun et al., 2013). The role of the AIM/CGE model in this study is two-fold. Firstly, it was used to generate global primary air pollutant emissions, which were then downscaled to a gridded level that includes South Korea. Secondly, it was used to calculate the trajectory of a global carbon tax that is consistent with a radiative forcing level of $3.4\ W/m^2$, which was then applied in the IMED|CGE model for South Korea. This study conducted simulations from 2005 to 2050, with 0.5° gridded emission data and one-year time steps.

2.4. IMED|CGE model for South Korea

Since the AIM/CGE global model does not represent South Korea as a separate region, it cannot be used to evaluate the macroeconomic impacts of air pollution-related health effects. Therefore, the IMED|CGE model, developed by the Laboratory of Energy, Environmental Economics, and Policy at Peking University (http://scholar.pku.edu.cn/hanchengdai/imedcge), was extended for this study to cover South Korea. The IMED|CGE model is a multi-sector, multi-region, recursive dynamic CGE model and has been used to assess the economic costs of climate change mitigation, especially at sub-national levels in China (Li et al., 2018; Qi et al., 2018; Tian et al., 2018; Weng et al., 2018). The version used for this study includes 14 global regions and 3 intra-national regions of China (Table A2). The following assumptions, consistent between the two CGE models, were made: (1) both models adopted SSP2 and SSP3 pathways for GDP growth rates and population up to the year 2050, and (2) the IMED|CGE model used the carbon tax

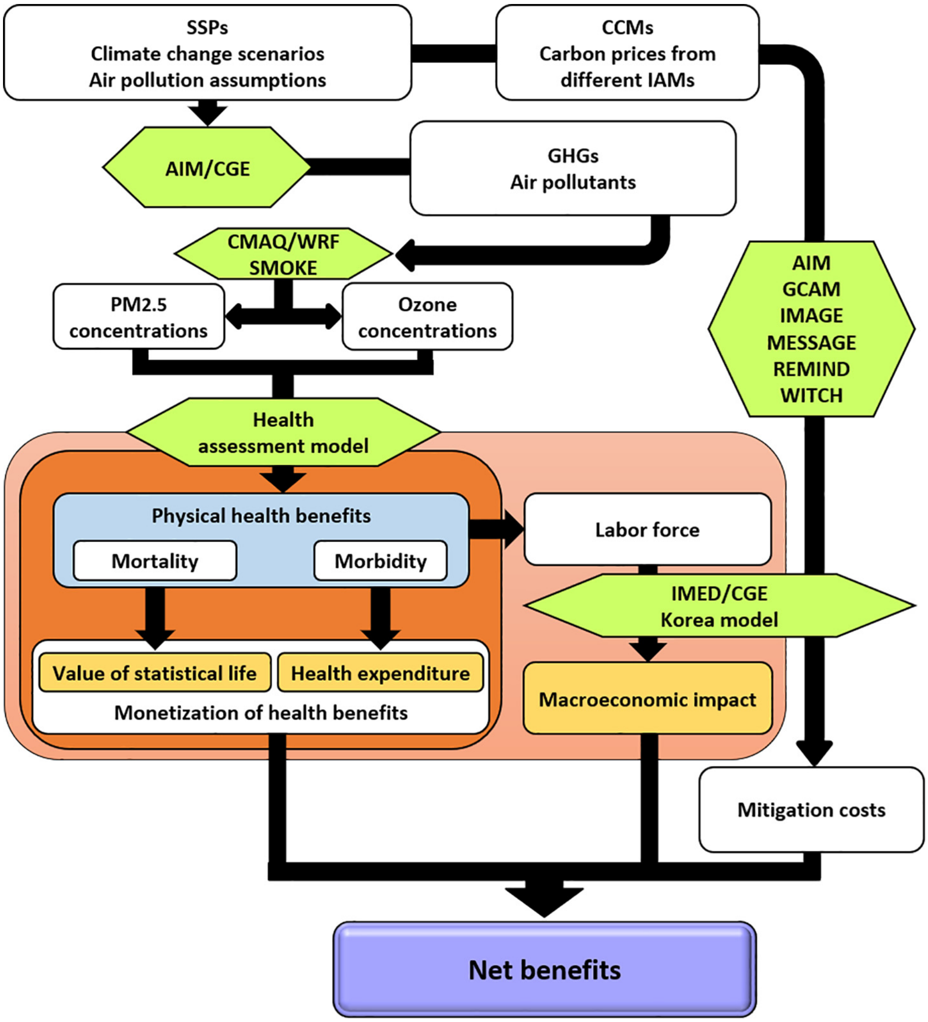

Fig. 1. Interdisciplinary multi-modeling approach to evaluate health and air quality co-benefits of air pollution mitigation. Abbreviations: SSPs, Shared Socioeconomic Pathways; AIM/CGE, Asia-Pacific Integrated Assessment/Computable General Equilibrium; GHGs, Greenhouse Gases; CMAQ, Community Multiscale Air Quality; WRF, Weather Research and Forecasting; $PM_{2.5}$, Particulate matter with an aerodynamic diameter of < 2.5 μm.

trajectory generated by different global AIM/CGE under the 3.4 W/m^2 mitigation scenario (Table A3).

2.5. CMAQ/WRF

$PM_{2.5}$ and O_3 are two key air pollutants linked to fossil fuel combustion and GHG emissions that are harmful to human health. To address regional air pollution problems, we simulated $PM_{2.5}$ and O_3 concentrations in South Korea using the CMAQ model developed by the United States Environmental Protection Agency (U.S. EPA) (Ching and Byun, 1999). CMAQ was used to calculate the annual average of mean daily $PM_{2.5}$ and daily 8-h maximum O_3 concentrations in 2005 and 2050 with 80 km × 80 km grids. The Weather Research and Forecasting (WRF) model was used to generate the meteorological variable fields required by CMAQ (Skamarock et al., 2008). WRF is a mesoscale numerical weather prediction system developed by the National Oceanic and Atmospheric Administration and maintained by the National Center for Environmental Prediction. The SMOKE (Sparse Matrix Operator Kernel Emissions) system, which was developed by the U.S. EPA and is maintained by the Carolina Environmental Program at the University of North Carolina, was used to develop the emissions processing system. The emissions time pattern follows Woo et al (Woo et al., 2012). We used WRF version 3.4.1, CMAQ version 5.0.1, and the CB05 chemical module in CMAQ, which is consistent with those used in our previous study (Xie et al., 2018).

2.6. Health impact assessment model

The association between pollutant concentration levels and health outcomes is expressed as a concentration-response function (CRF), which quantifies the magnitude of the expected proportional change in health outcomes due to a given change in concentration:

$$\mathrm{CRF(C)}_{p,s,y,e} = \begin{cases} 0, & \mathrm{C}_{p,s,y} - \mathrm{C}_{0p} \le 0 \\ (\exp(\beta(\mathrm{C}_{p,s,y} - \mathrm{C}_{0p}) - 1), \textit{ for linear} & \mathrm{C}_{p,s,y} - \mathrm{C}_{0p} > 0 \\ \quad \textit{function}, & \\ \alpha(1 - \exp(-\gamma(\mathrm{C}_{p,s,y} - \mathrm{C}_{0p})^{\delta})), \textit{ for} & \mathrm{C}_{p,s,y} - \mathrm{C}_{0p} > 0 \\ \quad \textit{nonlinear function}, & \end{cases} \tag{1}$$

where *p, s, y,* and *e* represent pollutants ($PM_{2.5}$ and O_3), scenario, year, and health endpoints category, respectively. The threshold model (Eq. (1)) was applied based on results from previous epidemiological literature (Amann et al., 2008; Fall et al., 1976; Jerrett et al., 2009) and implies that CRF(C) is 0, i.e., there are no adverse health impacts, when the pollutant concentration level is lower than the threshold value of C_0 (10 $\mu g/m^3$ for $PM_{2.5}$ and 70 $\mu g/m^3$; 35 ppb, for O_3) (Berman et al., 2012; Pope III et al., 2002). Detailed information of disease- and age-specific mortality using linear or non-linear CRFs from recent studies can be found in the supplementary material (Tables A4 and A5) (Amann et al., 2008; Burnett et al., 2018; Fall et al., 1976; Jin, 2017; Malley et al., 2017; OECD, 2016; Turner et al., 2016; Xie, 2011). Health endpoints (EPs), categorized into mortality and morbidity, were derived from the CRF. The EP was calculated using the following equation:

$$EP_{p,s,y,m,e} = I_{0m,e} \cdot CRF\,(\mathrm{C})_{p,s,y,m,e} \cdot Pop_{y,m} \tag{2}$$

where *Pop* represents population, *m* is an endpoint category (non-accidental mortality), and I_0 is the reported baseline incidence rate for each endpoint. For morbidity, this study adopts the CRFs from Clean Air for Europe (CAFE), which provided the relationship between cases of each morbidity and one unit of incremental air pollutant (Bickel and Friedrich, 2004; Hurley et al., 2005). The population and mortality rate for the last 20 years, as well as predicted data through 2050, were obtained from Statistics Korea (Table A6). The EPs were then used to estimate the valuation of avoided premature mortality, health expenditure (HE) of both outpatient and hospital admissions, and annual total work loss hours (WLH). We estimated the value of statistical life (VSL) by applying the willingness to pay (WTP) approach (West et al., 2013). We adopted the WTP values from the OECD (OECD, 2016) and a recent study from Jin (2017) (Table A7).

$$VSL_{p,s,y,e} = WTP_{s,y,e} \times \left(\frac{GDPPC_y}{GDPPC_{2010}}\right)^{0.5} \tag{3}$$

$$Valuation\ \ of\ \ avoided\ \ premature\ \ mortality = VSL_{p,s,y,e} \times EP_{p,s,y,\text{"}mt\text{"},e} \tag{4}$$

where “*mt*” is a subset (mortality) of *m*. The national average per capita GDP in 2010 was used as a reference with an income elasticity of 0.5 for each scenario (Aldy, 2015; Viscusi and Aldy, 2003). The valuation of avoided premature mortality is estimated by multiplying VSL with the number of avoided deaths. For health expenditures due to morbidity, total endpoints were multiplied by the cost of outpatient and hospital admissions using the following equations:

$$HE_{p,s,y,m,e} = EP_{p,s,y,m,e} \cdot Price_{s,y,e} \tag{5}$$

$$Price_{s,y,e} = \beta_{s,e} \cdot GDPPC_{s,y} + \theta_{s,e} \tag{6}$$

where health expenditure (HE) is total additional health expenditure (USD/year) and *Price* is the price of the medical service (USD/case). The medical service price for hospital admission is a function of the *GDPPC*, which represents per capita GDP from the CGE model (Xie et al., 2019). The parameters β and θ were estimated through regression analysis of the statistical price, using health service price per case data for hospital admissions between 2003 and 2012, obtained from the Health Insurance Review and Assessment Service of Korea (Table A8). Health service price per case for outpatients was assumed constant in the near future due to nonlinearity, along with *GDPPC* from past years (Table A9). Additional health expenditure possibly includes a household expenditure pattern change, which means that, as more money is spent on medical services, less money is available for other commodities. WLH is a summation of the hours of lost work due to both morbidity and mortality (European Comission, 2005):

$$WLH_{p,s,y} = \sum_{m} (EP_{p,s,y,\text{"}mr\text{"},\text{"wlh"}}) + \sum_{e,y^t<y} (EP_{p,s,y^t,\text{"mt"},\text{"wlh"}}) \cdot MR \cdot HPY \tag{7}$$

where “*mr*” is a subset (morbidity) of *m*, “*wlh*” is a subset of Work Loss Hours of *e*, and *MR* is the mortality rate in the entire population. *HPY* is per capita annual working hours (8 h/day × 5 days/week × 52 weeks/year = 2800 h/year). The annual per capita work loss rate (WLR) is obtained by dividing WLH by the working population (15–65 years old) and annual working hours:

$$WLR_{p,s,y} = \frac{WLH_{p,s,y}}{P_{y,\text{"}15-65\text{"}} \cdot HPY} \tag{8}$$

The resulting lost work time was then used as the annual per capita work loss rate in the CGE model to determine macroeconomic impacts. In the CGE model, WLR is used to calculate the actual labor force after subtracting work loss:

$$LAB_{p,s,y} = LAB0_{\text{"ref"},y} \cdot (1 - WLR_{p,s,y}) \tag{9}$$

where *LAB* represents the labor force after considering work loss and *LAB0* represents the labor force in the reference scenario.

2.7. *Mitigation costs*

Integrated assessments of how climate policy interacts with associated mitigation costs can be performed by a variety of models with different functional structures. Cost represents GDP loss from climate change mitigation policy in the IAMs. We considered carbon prices of six IAMs to estimate mitigation costs from the database maintained by International Institute for Applied Systems Analysis (IIASA): the AIM/CGE model, the Global Change Assessment Model (GCAM) (Edmonds et al., 1994), the Integrated Model to Assess the Greenhouse Effect (IMAGE) (Rotmans, 2012), the Model for Energy Supply Strategy Alternatives and its General Environmental Impact (MESSAGE) (Schrattenholzer, 1981), the Regional Model of Investments and Development (REMIND) (Luderer et al., 2015), and the World Induced Technical Change Hybrid (WITCH) (Bosetti et al., 2006). The carbon prices are then imposed to the economy of South Korea in the IMED/CGE model to quantify the GDP loss of achieving 2.0 °C target.

2.8. *Co-benefit analysis*

We quantified the co-benefits of climate change mitigation in South Korea by monetizing the economic value of health impacts due to $PM_{2.5}$ and O_3 pollution. Health benefits are based on improvements in air quality due to climate change mitigation, which includes health expenditure savings from reductions in morbidity, welfare savings of avoided premature mortality, and reductions from work loss hours in labor supply due to reductions in morbidity and mortality.

3. Results

3.1. *Air pollutant concentrations*

Climate mitigation will affect global air pollutant emissions significantly in this century. As shown in Fig. A2, emissions of all four pollutants, including BC, NMVOC, NO_x, and SO_2, show great reduction potentials in all three SSPs. Accordingly, the annual averages for daily mean $PM_{2.5}$ ($\mu g/m^3$) and daily 8-h maximum O_3 ($\mu g/m^3$) concentrations, as well as changes with respect to SSP2 and SSP3 scenarios, are shown in Fig. 2. SSP3 air quality in 2050 is significantly worse than that of SSP2, which is mainly due to high aerosol emissions in SSP3 (Fujimori et al., 2017). For $PM_{2.5}$, the noticeably polluted area in 2005 is the Seoul Capital Area (SCA), which includes the Incheon metropolis and Gyeonggi Province (Fig. 2A and I). This area is approximately 11,704 km^2, only 12% of South Korea’s total area (99,392 km^2). Approximately half of the country’s population (25 million) is currently located in the SCA. The population is expected to increase by 52% by 2020. By 2050, the $PM_{2.5}$ concentration is expected to decrease, due to a decrease in primary air pollutant emissions (Fig. 2B and J). $PM_{2.5}$ is substantially reduced under SSP2 (Fig. 2C), whereas concentrations increase under SSP3 (Fig. 2K). Reductions in $PM_{2.5}$ due to climate change mitigation are considerably higher for SSP3 (Fig. 2L) than SSP2 (Fig. 2D). O_3 pollution was severe on the Korean peninsula in 2005. In all areas, the average concentration of O_3 was above 80 $\mu g/m^3$ (Fig. 2E and M), which is higher than the previously suggested threshold for respiratory and circulatory mortality (70 $\mu g/m^3$). Such levels may lead to adverse health effects (Turner et al., 2016). The southeastern region of South Korea has been characterized by particularly high concentrations of O_3 (Fig. 2E and M). Busan had the highest concentrations, followed by Ulsan, a consequence of emissions from both automobiles

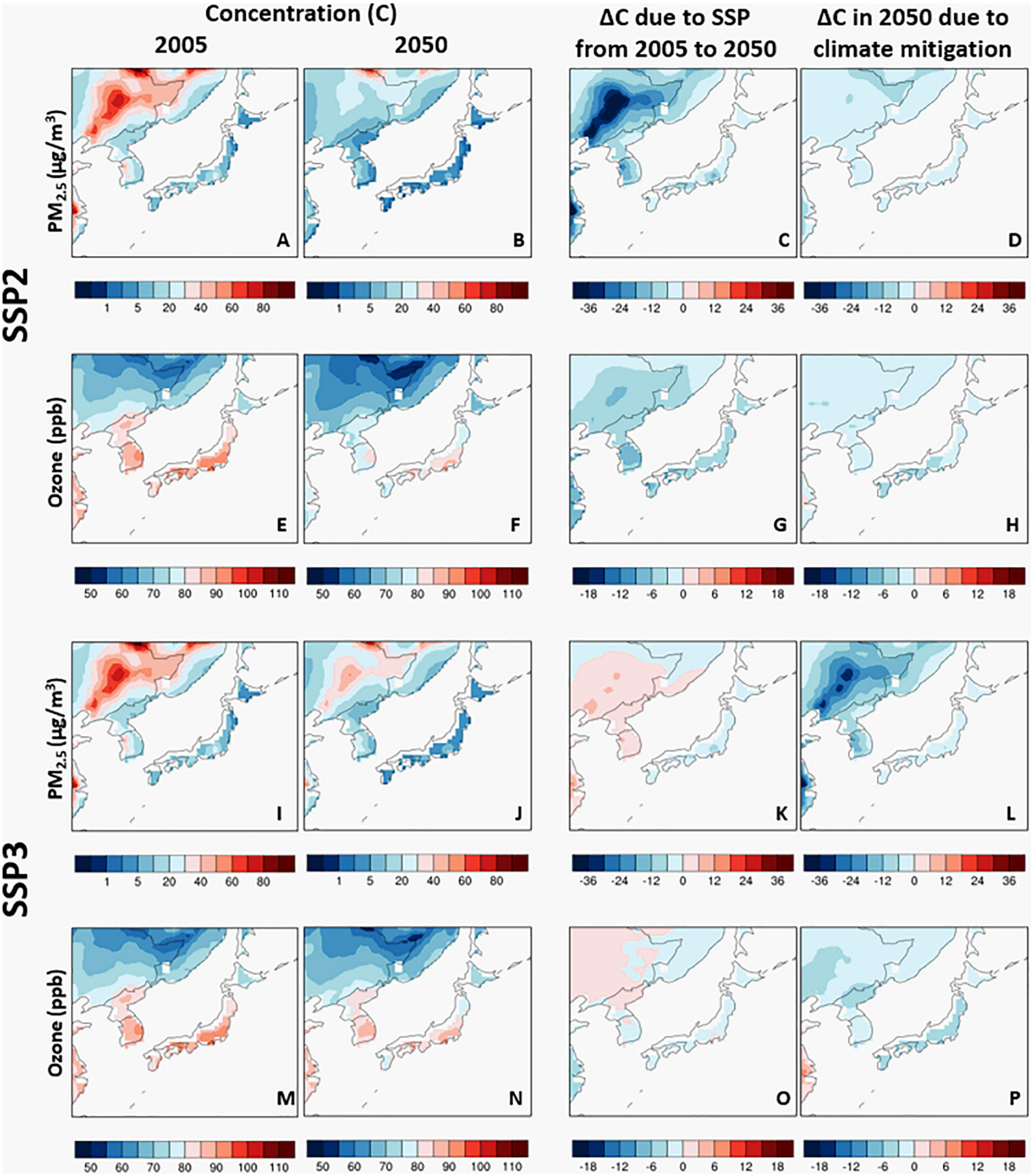

Fig. 2. Spatial distribution of projected $PM_{2.5}$ and O_3 concentrations. The color indicates the magnitude of concentrations and their changes. (A), (E), (I), and (M) are concentrations in 2005; (B), (F), (J), and (N) are concentrations in 2050 based on the MT_AP scenario; (C), (G), (K), and (O) are concentration changes from 2005 to 2050 due to socioeconomic development (in the BL_AP scenario); and (D), (H), (L), and (P) are concentration changes based on the BL_NO to MT_AP scenarios in 2050 due to climate change mitigation. Note: MT, climate mitigation scenario; AP, air pollution impacts; BL, baseline scenario without climate mitigation; NO, no air pollution impact.

and ships (Song et al., 2010). Both Busan and Ulsan are port cities, and Busan is home to the largest port in South Korea. Sources of pollutants that generate high concentrations of O_3 are mainly anthropogenic emissions of volatile organic compounds (VOCs) and nitrogen oxides (NO_x) from internal combustion engines, such as those in automobiles and ships (Zhang et al., 2004). From 2005 to 2050, simulated O_3 concentrations decrease to below 80 μg/m^3, except in the Busan area under SSP2. For SSP3, O_3 concentrations remain above 80 μg/m^3.

3.2. Health impacts of $PM_{2.5}$ and O_3

Exposure to air pollution leads to numerous health problems. Toxicological (Huang et al., 2009) and epidemiological studies (Atkinson et al., 2015; Schwartz et al., 2002) have confirmed the negative health effects of $PM_{2.5}$. Exposure to high levels of O_3 is also associated with adverse health effects, including negative reactions in toxicological studies (Larsen et al., 2010) and clinical trials (Gong Jr. et al., 1986), as well as increased hospital admissions (Dominici et al., 2006), emergency department visits (Tian et al., 2018), and mortality

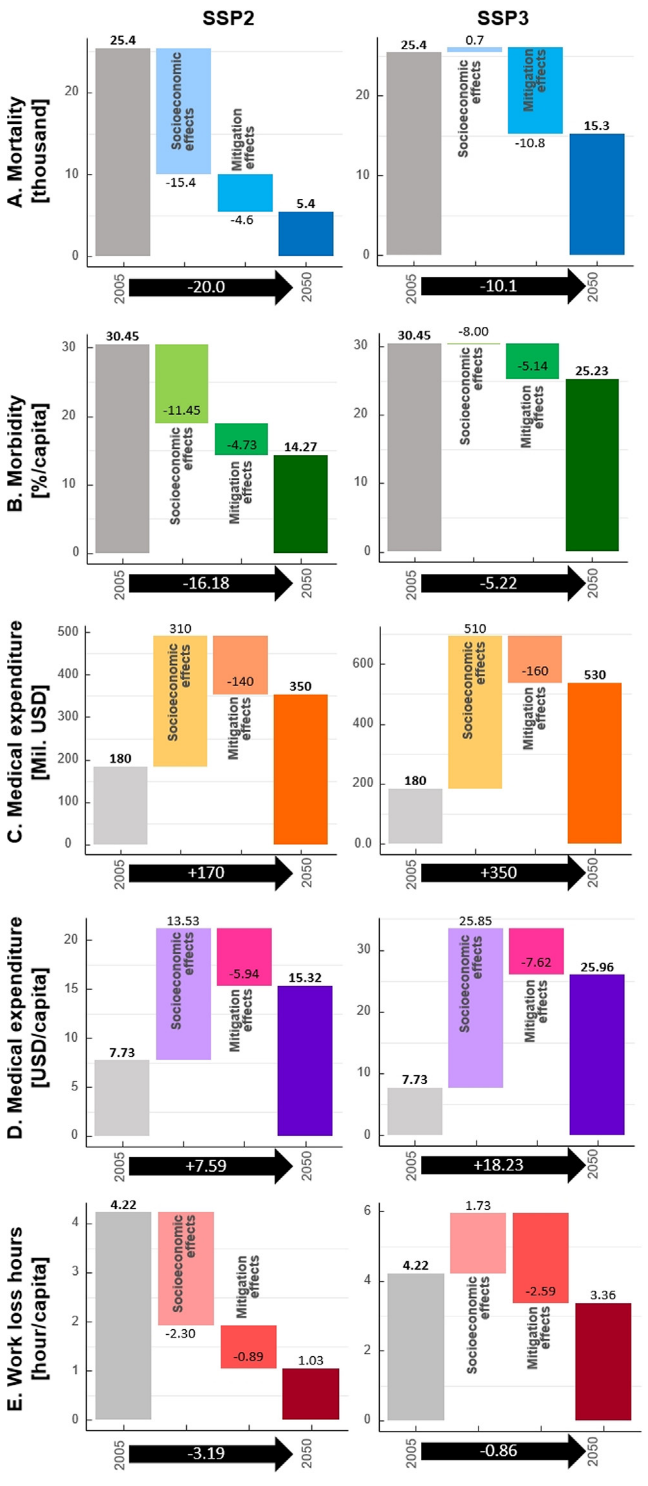

Fig. 3. Country-level values between 2005 and 2050 due to $PM_{2.5}$ and O_3 concentrations with respect to climate change mitigation scenarios and SSPs in South Korea. Impacts: (A) Number of premature deaths, (B) Morbidity risk per capita, (C) Total health expenditure from outpatient visits and hospital admissions, (D) Health expenditure per capita from outpatient visits and hospital admissions, and (E) Work loss hours per capita.

Table 1
Valuation of avoided premature mortality in South Korea (billion USD, 95% confidence intervals).

Scenario		2030	2050
SSP2	*BL_AP*	52 (10, 96.19)	51.19 (10.82, 93.3)
	MT_AP	38.83 (7.9, 71.18)	27.59 (7.38, 48.28)
SSP3	*BL_AP*	91.19 (13.76, 173.38)	122.01 (17.97, 232.56)
	MT_AP	63.17 (10.94, 118.28)	71.58 (12.89, 133.39)

Note: BL, baseline scenario without climate mitigation; AP, air pollution impacts; MT, climate mitigation scenario.

(Kim et al., 2004), in epidemiological studies. Fig. 3A shows avoided premature mortality (25,400 non-accidental deaths) due to outdoor air pollution in South Korea (95% confidence interval (C.I.): 23,400–56,600) in 2005. Compared with the 2005 reference year, climate change mitigation toward the 3.4 W/m^2 target could prevent 20,000 (95% C.I.: 12,800–43,000) premature deaths by 2050 under SSP2 and 10,100 (95% C.I.: 6600–21,800) under SSP3. In 2050, the valuation of avoided premature mortality under SSP2 is estimated to be 27.6 billion USD (95% C.I.: 7.4–48.3) with climate change mitigation and 51.2 billion USD (95% C.I.: 10.8–93.3) without, whereas under SSP3, the valuation of avoided premature mortality is estimated to be 71.6 billion USD (95% C.I.: 12.9–133.4) with climate change mitigation and 122 billion USD (95% C.I.: 18.0–232.6) without (Table 1). Therefore, VSL-related benefits in 2050 due to climate change mitigation are 23.6 billion USD under SSP2 and 50.4 billion USD under SSP3, indicating that benefits under SSP3 are approximately double that of SSP2.

In 2050, reduction in the risk of morbidity due to air pollution will be 16.2% under SSP2 and 5.2% under SSP3 (Fig. 3B). By 2050, SSP2 and SSP3 will have reduced possible hospital visits per year due to air pollution by 14.3% and 25.2%, respectively, compared with 2005 (30.5%) (Fig. 3B). Total additional health expenditure related to air pollution in 2005 amounted to 180 million USD, which will increase to 350 and 530 million USD for SSP2 and SSP3, respectively (Fig. 3C). The per capita health expenditure on air pollution will also increase by 7.6 and 18.2 USD per capita under SSP2 and SSP3, respectively (Fig. 3D). Although the morbidity risk would decrease due to climate change mitigation, total additional health expenditure would increase, which is a consequence of increased GDP and income in 2050.

Air pollution leads to negative economic impacts due to labor supply reduction. Premature death and morbidity as a consequence of exposure to air pollution cause work time loss (Fig. 3D). The per capita work loss hours were 4.22 h in 2005; this would drop to 1.03 and 3.36 h under the SSP2 and SSP3 scenarios, respectively, in 2050 (Fig. 3E). Decomposed results into morbidity and mortality can be found in Fig. A3.

3.3. Cost-benefit analysis

Improvements in air quality will decrease premature deaths and disability, which will lead to a reduction in direct health expenditure and work time loss. Benefits stemming from improvements in air quality and climate change mitigation are shown in Fig. 4, including total economic benefits (23.6 billion USD) due to reduced avoided premature mortality, direct health expenditure savings (0.14 billion USD) due to reductions in morbidity risk, and GDP gains due to reduced work time loss from both morbidity and mortality (0.38 billion USD). The total benefit would be 2.7% of the National GDP of South Korea compared with the base year of 2005 (898 billion USD). Compared with GDP gains from reduction of health expenditure and work loss hours, the total benefit of avoided premature deaths are relatively high. The co-benefit pattern shows an upward trend, mainly driven by the monetization of avoided premature deaths due to an increase in GDP per capita. Air quality improvement also has positive impacts on labor productivity, which is beneficial to the economy (Hanna and Oliva, 2015). Climate change also has direct impact on labor productivity (Kjellstrom et al., 2009; Zhang et al., 2017). On the other hand, the cost of climate change mitigation policy in 2050, as estimated by the IMED/CGE model, is a maximum of 8.50 billion USD (using carbon price of

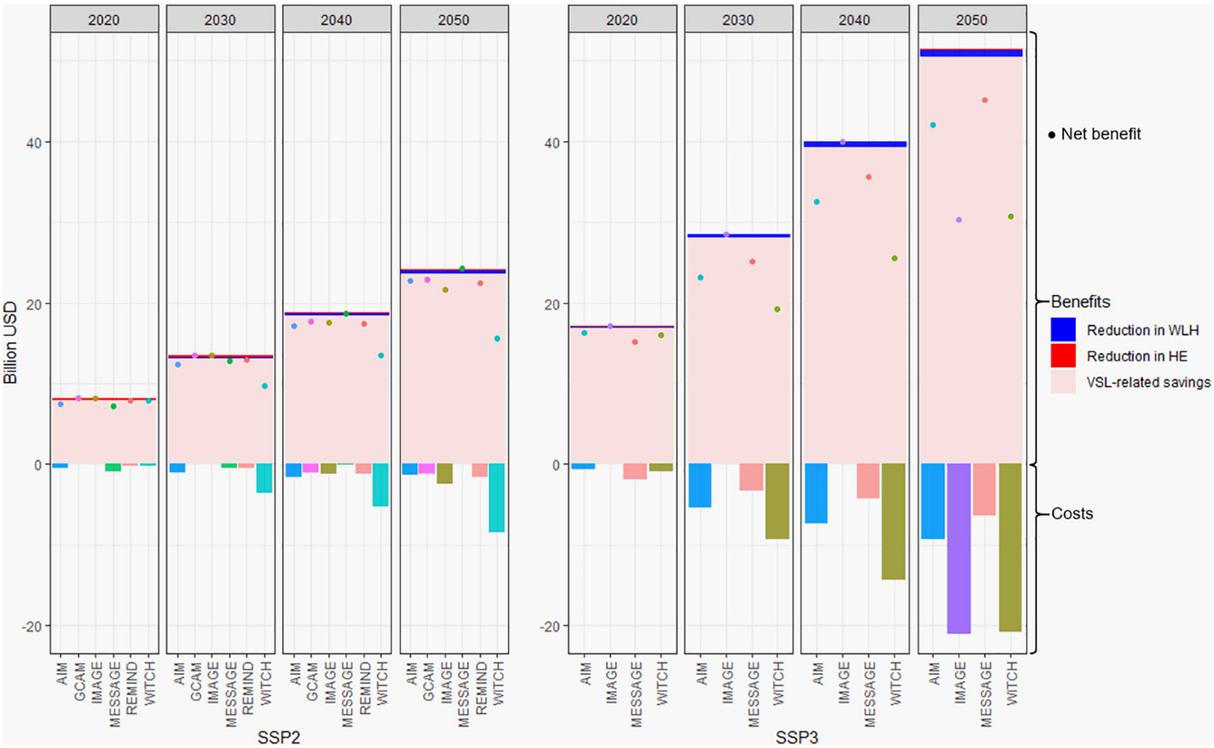

Fig. 4. Health co-benefit analysis of climate change mitigation in South Korea towards 2050 (billion USD).

WITCH) in SSP2 and 21.15 billion USD (using carbon price of IMAGE) in SSP3 (Table A10). GDP would increase using carbon price of the MESSAGE model with respect to SSP2 by 2050 due to reduced imports compared with business as usual (BaU) in the SSP2 mitigation scenario, although other economic indicators, such as consumption, investment, government expenditure, and exports, have negative impacts. Monetized co-benefit estimates in 2050 range from 15.62 (WITCH carbon price) to 24.21 (MESSAGE carbon price) billion USD for SSP2 and from 30.36 (IMAGE carbon price) to 45.16 (MESSAGE carbon price) billion USD for SSP3 (Fig. 4).

The economic benefits from climate change mitigation by 2050 are higher than climate change mitigation costs for both SSP2 and SSP3 regardless of the IAMs. Taking into account only the health impacts, the benefits of climate change mitigation outweigh its mitigation cost in South Korea, which is consistent with the findings of other studies for different countries (Li et al., 2018; Saari et al., 2015; Thompson et al., 2014; West et al., 2013; Zhang et al., 2017). It should be noted that the interpretation of total benefits measured by VSL and WLH should be careful. VSL approach measures the non-market value of mortality of all population cohorts based on willingness to pay principle. By contrast, WLH approach measures the equilibrium market value of avoided morbidity and mortality for those aged between 15 and 65. Whether they could be added up remains questionable. In Fig. 4, although we have added them up when calculating the net benefits, an additional point is to illustrate both ways of valuation and their relative sizes. In addition, even excluding the gain from reduced work hour loss, the net benefit would not change much (Fig. A5).

4. Discussion

Our integrated assessment reveals that climate change mitigation could reduce a substantial portion of $PM_{2.5}$ and O_3 concentrations and the health benefits alone outweigh the costs of cutting GHG emissions in South Korea. South Korea's mitigation effort is both an international commitment to the new climate system and a future national long-term strategy with respective benefits. Co-benefit analysis focused on the global implications of climate policies, as pledged in the NDCs and 2 °C target, also showed that air quality co-benefits offset the costs of climate policy globally (Vandyck et al., 2018). However, South Korea's current NDC, including a target of reducing GHG emissions excluding land use, land-use change and forestry (LULUCF) by 37% below BaU emissions by 2030 (UNFCC, 2015), has been rated as "Inadequate" by Climate Action Tracker' evaluation, as it is far off the Paris target level to be achieved domestically (Climate Action Tracker Consortium, 2015).

Similar to other countries, air quality and health co-benefits provide sufficient motivation for the transition to a low-carbon future, particularly since the benefits are mostly local and will be experienced in the very near future (West et al., 2013). As proposed in the Paris Agreement, most countries have set GHG reduction targets to be achieved through the transformation of energy systems, i.e., decarbonization of the energy supply mix, combined with reduced energy consumption through efficiency gains. In South Korea, coal is set to remain a core part of the energy mix (IEA, 2016), which ranks seventh in global coal consumption (Enerdata, 2015), and the fact that national coal consumption has increased since 1990 reflects the increasing GHG emission trend (Fig. A4) (Olivier et al., 2016). Climate mitigation policies are expected to provide the impetus to eliminate South Korea's dependence on coal and further develop renewable energy. Both these efforts would reduce CO_2 and air pollutant emissions, given that the country's current energy mix is dependent on fossil fuels and unsustainable development patterns. Furthermore, the Paris Agreement requires that OECD countries discontinue the use of coal-fired power plants by 2030. The Korean government suspended eight coal-fired power plants that were over 30 years old for one month in June 2017, to reduce domestic air pollution, and this had a positive temporary impact on domestic air quality. The Korean Ministry of Environment (MOE) stated that the closure of these eight plants resulted in a reduction of 304 tons of $PM_{2.5}$ emissions across the country, accounting for 15% of the country's 1975 tons of emissions from coal-fired power plants (53 plants) (MOE, 2017). Three of these plants have remained closed since July 2017, while operation of the other five was temporarily suspended from March to

June 2018 (MOE, 2018). In contrast to South Korea's efforts, other countries have succeeded in more aggressive efforts to eliminate coal dependency. The United States considerably reduced the proportion of energy production from coal from 33% in 2007 to 18% in 2017 (U.S. Energy Information Administration, 2018): between 2009 and 2017, 166 coal-fired power plants were permanently closed (U.S. Energy Information Administration, 2017). The European Union is phasing out coal even more rapidly. Belgium has been coal-free since 2016 (Europe Beyond Coal, 2019) and Austria, France, Sweden and Slovakia intend to be coal-free by 2020, 2021, 2022 and 2023, respectively. Other countries have set intentions to be coal-free by 2025 (Hungary, Ireland, and the UK), 2029 (Finland and the Netherlands), and 2030 (Denmark and Portugal) (Table A11) (Europe Beyond Coal, 2019). Research on and investment in highly stable and less costly renewable energy is increasing globally. Denmark plans to increase its share of renewable energy from 51% in 2015 to 100% in 2050. Forty-eight countries that are highly vulnerable to a warming planet and belong to the Climate Vulnerable Forum (e.g., Cambodia, Nepal, and Sudan) have also set goals of converting to 100% renewable energy by 2050. China plans to invest 361 billion USD in renewable energy by 2020. South Korea's current target is 20% renewable energy by 2030, which lags far behind the global trend, despite the ability to comply with the Paris Agreement target through more aggressive measures. A study from Winchester and Reilly (2019) showed the mitigation policy to meet South Korea NDC will reduce 2030 GDP by \$20.6 billion (1.0%) and consumer welfare by 7.9 billion (0.7%), if the benefits from avoided climate damage is not considered. Our estimation in 2050 is 8.5 billion under SSP2 and 21.5 billion under SSP3, which is comparable with their study (Table A12).

The ability to overcome several obstacles requires a comprehensive policy including climate change and energy strategies. Changes in energy policies depend on the current administration, which is a problem with respect to achieving effective climate change mitigation in South Korea. According to Jung (2017), "Sweden could be an instructive example to South Korea of elevating the issue beyond party politics," due to its establishment of bipartisan long-term energy policy: the five major Swedish political parties have agreed to a 100% renewable energy target by 2040. South Korea would likely benefit from a long-term strategy and detailed roadmap for climate change mitigation. In addition, although a politically controversial and sensitive issue, air pollution depends both on domestic emissions and transboundary transport from neighboring countries. Likewise, air pollution improvement under the mitigation scenario is due to domestic mitigation efforts in South Korea and side-effects of mitigation efforts in neighboring countries. Action or inaction of any single country could assist or undermine efforts of other countries; this is especially the case for climate change mitigation. Therefore, collaboration among adjacent countries in Northeast Asia to combat climate change jointly is important, to maximize the co-benefits of improvements in air quality and public health, similar to Europe.

Estimating the public health consequences of air quality under climate change mitigation scenarios is a challenging, multidisciplinary task, combining air pollution modeling, economics, emissions inventories, and public health. Despite our efforts to quantify the health and economic impacts of $PM_{2.5}$ and O_3, there are several limitations that need further investigation: (1) co-benefits related to air quality under climate mitigation that are not covered here include the reduced cost of air pollution control measures and the indoor air quality and its health outcomes; (2) only the concentration levels of $PM_{2.5}$, were considered in this study, assuming equal toxicity among components, but different $PM_{2.5}$ components are known to have different health effects; (3) Climate-chemistry interaction was not considered for projections of air quality under changing climates. This is common in co-benefit analysis, especially in the near-term (2030), yet recent literature has shown that the effect of climate change alone on air pollution could result in significant health implications globally (Silva et al., 2017). Effects would be more significant from long-term analyses, as they increase over time (Garcia-Menendez et al., 2015). Thus, it will potentially introduce significant errors in long-term co-benefits analysis if not addressed adequately (Saari et al., 2019); (4) a fraction of the co-benefits obtained in South Korea may be a result of mitigation efforts of neighboring countries (i.e., transboundary effects); (5) Future research efforts could include more health endpoints that are recently found to be diseases affected by air pollution, such as neurological disease, diabetes and kidney injuries, and finally; (6) morbidity valuation in this study considered the costs from health expenditure for both outpatient and hospital admissions and work-time loss, not including the cost of operating at less than full capacity in the labor force (i.e., job performance).

Assessment of the combined uncertainty throughout the multi-model is promised as possible uncertainty can exist in each model. The AIM/CGE model contains uncertainty surrounding future economic development and energy consumption. The CRFs from different populations may produce uncertainties, as well. The most commonly adopted method to reduce the uncertainties from CRFs is using regionally-derived CRFs (Yin et al., 2017). However, disease- and age-specific CRFs from well-designed long-term air pollution cohort studies are not available for the Korean population yet.

5. Conclusion

In this study, we quantified the health co-benefits of air quality improvements in both $PM_{2.5}$ and ozone concentrations for achieving ambitious targets such as stabilization of the radiative forcing level at 3.4 W/m^2 in South Korea. The results provide evidence of the benefits of meeting greenhouse gas emission targets, by comparing the mitigation costs and economic benefits of air pollution reductions from public health, including VSL-related savings, health expenditure, and work loss time reduction. We found that substantial health gains can be achieved from taking action to slow down climate change and the benefits of air quality and health improvement could offset the total costs of climate mitigation in South Korea. This study provides a solid framework for assessing the effects of air pollution control measures from the viewpoint of public health. Its applicability can be extended to other areas to aid in policy-making and in the determination of the actions and strategies needed to achieve ambitious climate targets.

CRediT authorship contribution statement

Satbyul Estella Kim: Conceptualization, Writing - Original draft. **Xie Yang:** Conceptualization, Writing- Reviewing and Editing. **Hancheng Dai:** Writing- Reviewing and Editing. **Shinichiro Fujimori:** Data curation. **Yasuaki Hijioka:** Supervision. **Yasushi Honda:** Supervision. **Masahiro Hashizume:** Supervision. **Toshihiko Masui:** Supervision. **Tomoko Hasegawa:** Data curation. **Xinghan Xu:** Data curation. **Kan Yi:** Visualization. **Ho Kim:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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