Quantitative analysis of economic impacts of health damages caused by air pollution in China

Public Policy Design Program
Name Xie Yang,   Adviser name Toshihiko Masui
公共システムプログラム

14D55140 氏名 Xie Yang   指導教員 増井 利彦

ABSTRACT

China experiences rapid economic development during the past 30 years. Meanwhile, it encounters severe unprecedented environmental problems, especially ambient air pollution. It is recognized that exposure to high outdoor air pollution contributes acute and chronic health effects. These kinds of health problems also lead to additional health expenditure, premature death, work day loss, school absence and reduction of labor's productivity, which also have negative impacts on the economy. This study aims to quantify the health and economic impacts of $PM_{2.5}$ and ozone pollution in 30 provinces in China by combining the four different kinds of models.

1. Introduction

China surpassed the U.S. to become the world largest carbon emitter in 2007[1]. In 2010, China overtook Japan and became the country with the second largest gross domestic product (GDP) in the world. China's energy consumption and carbon emissions have been accelerating under the influence of urbanization and industrialization. In 2011, China became the largest consumer of fossil fuels and China's total CO2 emissions are about 9 billion million ton (Mt), which accounted for 23% of the total emissions in the world. In 2012, carbon emissions from fossil fuel combustion and cement production reached 8.50Gt CO2. While in 1950, China's carbon emissions were only 5.46 Mt CO2. During last 60 years, the total CO2 emissions increased more than 100 times.

People experience a wide range of health effects from being exposed to air pollution[2-5]. Effects can be broken down into short-term effects and long-term effects. Nearly 2.5 million people die worldwide each year from the effects of outdoor or indoor air pollution[6] [7] calculated a global respiratory mortality per year of about 773 thousand, 186 thousand by lung cancer and 2.0 million by cardiovascular disease. The global mean per capita mortality caused by air pollution is about 0.1 % per year. The highest premature mortality rates are found in the Southeast Asia and Western Pacific regions, about 25 % and 46% of the global rate, respectively. People react differently to different types of air pollutants. Young children and older adults, whose immune systems tend to be weaker, are more sensitive to air pollution[5, 8, 9]. Conditions such as asthma, heart disease, and lung disease can be made worse by exposure to air pollution. The health effects are related to the length of exposure time and amount and type of pollutants[10].

One study examined the air quality and health benefits of 14 specific emission control measures targeting BC and methane. They estimated that, for $PM_{2.5}$ and ozone, respectively, fully implementing these measures could reduce global population-weighted average surface concentrations by 23-34% and 7-17% and avoid 0.6-4.4 and 0.04-0.52 million annual premature deaths globally in 2030. More than 80% of the health benefits are estimated to occur in Asia[11]. Ozone exposure is also related to respiratory symptoms and the use of asthma medication for asthmatic school children using maintenance medication [12]. These health problems can pose heavy economic burdens by further increasing health expenditure, increasing work day loss, and decreasing the labor supply [13, 14]. In the USA, health-related loss of productive time costs employers UDS225.5 billion per year [15].

A study in China found that by improving ozone and PM pollution, China's GDP would have increased by USD 22 billion in 1975 and USD 112 billion (about 5% of GDP) in 2005[16]. Xia et al. developed I-O model to capture both direct economic costs and indirect cascading effects throughout inter-regional production supply chains and the indirect effects greatly outnumber the direct effects in most Chinese provinces. They found that the total economic losses of 346.26 billion CNY (approximately 1.1% of the national GDP) based on the number of affected the Chinese employees whose work time in years was reduced due to mortality, hospital admissions and outpatient visits related

$PM_{2.5}$ pollution in 2007[17]. The Chinese government and population increase their concern on the air pollution issue, because they are growing realization of the health threat from high level of fine particles. The Chinese government has launched series air pollution control policy to improve air quality[18-21].

Although there are many studies try to evaluate the health and economic impact in China. Most of existing studies use the willingness to pay method, focused on historic years and one region or national level. This study tries to assess the health and economic impact of air pollution in 30 provinces in China in 2030 and find a cost-effective air pollution control options for each province. For the above purposes, this study incorporated health-related environmental damages into a computable general equilibrium (CGE) model in combination with the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS)-China model that provides primary emissions data for an air quality Goddard Earth Observing System (GEOS)-Chem model (GEOS-Chem) model that calculates PM2.5 and ozone concentration. Integrated assessment method explicitly describes labor supply changes and dissimilar economic impacts in China's 30 provinces. This study can draw a picture of how changes in $PM_{2.5}$ and ozone pollution will affect health expenditure, labor supply, and overall economy about the market impacts in China's 30 provinces. More specifically, this study is innovative in terms of the following aspects.

2. Methodology

This study is about quantitative analysis of economic impacts on health damages caused by air pollution in China in the future. To achieve this purpose, several models are needed for energy consumption, air pollutants primary emissions, $PM_{2.5}$ and ozone concentration, health impact and economic assessment. Firstly, Asia-Pacific Integrated Assessment(AIM)/CGE-China model predicts energy consumption projection. GAINS-China model uses the energy projection data to calculate air pollutants emissions and provincial average $PM_{2.5}$ concentration in 30 provinces of China. GEOS-Chem model is used for air quality simulation, including gridded $PM_{2.5}$ and ozone concentration. Health impacts are quantified by health assessment model, including mortality, morbidity and work time loss. Finally, AIM/CGE-China model evaluates the economic impact based on the work time loss due to air pollution.

First, air quality assessment: combining AIM/CGE-China model, GAINS-China model and GEOS-Chem model. Second, health impact assessment: using health impact assessment model to quantify the number of mortality, morbidity, health expenditure and work time loss. Third, economic assessment: using AIM/CGE-China model and willingness to pay to evaluate the economic impact of air pollution.

Health impacts as the results of mortality and morbidity are converted to annual total medical expenditure and per capita work loss caused by $PM_{2.5}$ and ozone pollution, which are then used as a change in the household expenditure pattern and labor participation rate by the CGE model to determine the macroeconomic impacts. The health assessment model is extended to quantify the health impacts of $PM_{2.5}$ [22] and ozone pollution and monetize the value of such health impacts in China. Exposure to incremental $PM_{2.5}$ and ozone leads to health problem called health endpoints, which are categorized into morbidity and mortality.

In AIM/CGE-China model, economic driving forces include labor, expenditure pattern, technology, resource and policy. The change of these five factors will lead to output change of AIM/CGE-China model. Air pollution leads to labor supply reduction because of mortality and morbidity, and increases health expenditure on air pollution-related health endpoints. Both of labor reduction and health expenditure have impacts on labor and expenditure pattern. The changes of economic driving forces in CGE model will result in impact on economy, energy and environment. By using AIM/CGE-China model, the impact of air pollution on the economy can be quantified.

Computable general equilibrium(CGE) model

AIM/CGE-China model, applied in this study can be classified as a multi-sector, multi-region, recursive dynamic CGE model that covers 22 economic commodities and corresponding sectors, and eight power generation technologies. It includes 30 provincial units of China (excluding Tibet, Hong Kong, Macau and Taiwan due to data availability) and one region of the rest of the world. This CGE model is solved by Mathematical Programming System for General Equilibrium under General Algebraic Modeling System (GAMS/MPSGE) [23], at a one-year time step. The following paragraphs discuss the key technical features of this model to allow for a deeper understanding of associated modeling results.

Health assessment model

A health assessment model quantifies the health endpoints from air pollutants exposure, calculates additional health expenditure and work time loss due to air pollution-related health outcome following the same approach2. For other Asian countries, we adjust health care medical cost based on per capita GDP. Health impacts, including mortality and morbidity, are converted to annual total medical expenditure and per capita work time loss caused by $PM_{2.5}$ and ozone pollution, which is then used as a change in the labor participation rate in the AIM/CGE model to assess the economic impact of air pollution. In this health assessment model, air pollutants only include $PM_{2.5}$ and ozone. Health endpoint and Concentration-Response Functions(CRFs) follow the same method3. We use gridded population data, which is consistent with our assumptions.

Health equation (2):

$$EP_{p,r,s,y,m,e,v}(C) = \begin{cases} P_{r,y,m} \times (RR_{p,r,s,y,m,e,v}(C) - 1), & \text{for morbidity} \\ P_{r,y,m} \times (RR_{p,r,s,y,m,e,v}(C) - 1) \times I_{r,\text{"all cause"}}, & \text{for mortality} \end{cases}$$

where

RR(C): Relative risk for endpoint at concentration C [case/person/year or day/person/year]

EP: Health endpoint [case/year or day/year]

C: Concentration level of pollutant

C0: Threshold concentration that causes health impacts (10 ug/m3 for $PM_{2.5}$ and 70 ug/m3 for ozone.)

CRF: Concentration-response function

P: Population, aged 15-65 for work loss day, age 25-65 for Ischemic heart disease and Stroke, and entire cohort for other endpoints

$\hat{I}$: cause-specific mortality rate

I: Reported average annual disease incidence (mortality) rate for endpoint

$I_{r,\text{"all cause"}}$: Reported average annual natural death rate for endpoint

α, γ, δ: Parameters that determine the shape of the non-linear concentration-response relationship for chronic mortality.

Suffix p, r, s, y, m, e, v represent pollutant ($PM_{2.5}$ and O_3), region, scenario, year, endpoint category (morbidity or mortality), endpoint, value range (medium, low and high), respectively.

Scenarios

Three scenarios are constructed in this study, namely, Reference, WoPol and WPol scenarios, based on the air pollution control policy.

Reference scenario assumes that the health impacts air pollution are ignored, regardless of how serious the pollution is. There is no additional health service cost, premature death, or work day loss from $PM_{2.5}$ pollution. The scenario simulates an ideal situation that does not exist but can be used to evaluate the negative impacts of pollution and benefits by comparing with the other scenarios. In addition, this scenario provides assumptions of the future social economic development, mainly including GDP and population, and data on $PM_{2.5}$ concentration.

WoPol: This scenario corresponds no-Tech scenario in Reference[1] which assumes penetration rate of mitigation technology remains the same as 2005 and additional emissions from energy combustion remain uncontrolled throughout the modeling period. It does not represent reality but is meant to show the impact of air quality policies.

WPol: This scenario corresponds no-Tech scenario in Reference [24] which reflects current air pollution policies in China, considering sectoral and provincial differences concerning emission limit values and time of their introduction. WPol assumes the existence of intensive air-pollution-control technologies. Various air-pollution-control technologies are used to reduce pollutant emissions and $PM_{2.5}$ concentration to levels much lower than those in reference and WoPol scenario.

In addition, this study also set up a scenario named WPol2 from GEOS-Chem simulation, in which more intensive air pollutant control technologies are adopted, and emissions of NOx, VOC, CO are further reduced by 50% and CH4 is further reduced by 20% from the WPol scenario in 2030. This scenario is used for probing sensitivity of ozone pollution control. However, the ozone-related primary emissions reduction also has impact on $PM_{2.5}$ concentration.

3. Impact of $PM_{2.5}$ pollution

Results show that the health and economic impacts may be substantial in provinces with high $PM_{2.5}$ concentration. In the WoPol scenario without air pollution control policy, this study estimates that China experiences a 2.0% GDP loss and

210 billion CNY in health expenditure from $PM_{2.5}$ pollution in 2030. By contrast, with control policy in the WPol scenario, a control cost of 830 billion CNY (0.79% of GDP) versus a net benefit of 0.38% of China's GDP from improving $PM_{2.5}$pollution is projected. At the provincial level, GDP loss in 2030 in the WoPol scenario is high in Tianjin (3.1%), Shanghai (3.0%), Henan (2.3%), Beijing (2.8%), and Hebei (2.6%). The top five provinces with highest additional health expenditure are Henan, Sichuan, Shandong, Hebei and Jiangsu. Controlling $PM_{2.5}$ pollution could bring net positive benefits in two-thirds of provinces in China, Tianjin, Shanghai, Beijing, Henan, Jiangsu, and Hebei experience most benefit from air pollution control technology, and these provinces have higher $PM_{2.5}$ pollution and dense population distribution. Conversely, net benefits are negative in Ningxia, Guizhou, Shanxi, Gansu and Yunnan provinces with low GDP loss but relatively high control cost.

$PM_{2.5}$ concentration

In the most provinces, simulation results show that $PM_{2.5}$ pollution is very serious and $PM_{2.5}$ concentration in both scenarios is much higher than national standard 35 ug/m3 and WHO standard 10 ug/m3 in 2030. However, $PM_{2.5}$ concentration is different from region to region. The $PM_{2.5}$ concentration is much higher in the east of China, especially on the North China Plain, the populous region with more industry. While in the area with less industry and less population, $PM_{2.5}$ concentration is lower. Because $PM_{2.5}$ pollution is related to human activity, especially fossil fuel combustion. Developed area consume more energy and have larger air pollutant emissions.

Health impact of $PM_{2.5}$

Mortality is 9.2 (0.36-9.7) million and 2.3 (0.09-2.4) million people in WoPol and WPol scenario in 2030 in China, which is comparable with other studies[6, 25]. At the provincial level, provinces with higher population density, such as Henan, Shandong, Jiangsu, Hebei and Sichuan, have larger mortality. The mortality in these five provinces is 1000 (77-2100), 900 (67-1800),780 (58-1600),710 (53-1400) and 690 (53-1400) thousand people in WoPol scenario, respectively. In 2005, total morbidity from $PM_{2.5}$ pollution is about 140 million cases in WoPol scenario and 60 million cases in WPol scenario per year. Moreover, the morbidity increases to 230 million cases in WoPol scenario and 70 million cases in WPol scenario per year in 2030. Upper respiratory symptoms are clearly the most frequent health problem about 220 million cases and 54 million cases induced by $PM_{2.5}$ pollution, followed by asthma attacks about 39 million cases and 10 million cases in WoPol scenario and WPol scenario. Chronic bronchitis is also a severe and long-term impact, and chronic bronchitis is about 14 million and 3.6 million in WoPol scenario and WPol scenario in 2030. The work time loss will be higher when the premature death in young labor. The national per capita work time loss in 2030 reaches 56 hours (2.7% of annual total annual work hours) in the WoPol scenario. The $PM_{2.5}$ reduction in the WPol scenario proves to be very effective at reducing the work time loss. In the WPol scenario, the per capital work time loss is 15 hours (0.71% of annual work hours) in 2030.

Sensitivity analysis

A sensitivity analysis is carried out using the different ERFs, linear ERFs, non-linear ERFs and linear ERFs China. the upper and lower bounds of the ERFs acquired from the 95% confidence interval for linear ERFs and linear ERFs China. GDP loss is 2.0% and 0.49% in WoPol and WPol scenario in 2030 for linear ERFs, and the lower and upper bounds are 1.2% and 2.8%, 0.29% and 0.70%. GDP loss is 1.5% and 0.36% in WoPol and WPol scenario in 2030 for linear ERFs China, and the lower and upper bounds are 1.1% and 1.9%, 0.27% and 0.45%. While GDP loss for nonlinear ERFs is 2.0% in WoPol scenario and 0.83% in WPol scenario in 2030, while is between linear ERFs and linear ERFs China.

Cost-benefit analysis

Economic impact at the provincial level in this study can provide valuable policy insights. The GDP gain/control cost ratio is higher than 1 in nearly two-thirds of provinces with richer and denser population. Table 1 shows the cost-benefit analysis from air pollution control policy. The benefit in these provinces is positive, such as Shanghai (5.2), Beijing (4.8), Tianjin (3.4), Jiangsu (2.8), Henan (2.5), and Zhejiang (2.3), because more productive people would benefit from improving $PM_{2.5}$ pollution in these provinces, because more productive people would benefit from improving $PM_{2.5}$ pollution in these provinces. Moreover, these findings demonstrate a much smaller economic benefit in less developed and populated provinces, where the adoption of air-pollution-control technology may incur a big burden and ultimately lead to negative economic impacts, such as Ningxia, Guizhou, Shanxi, Gansu, Heilongjiang, Qinghai, and Xinjiang.

Table 1 Cost-benefit analysis of air pollution (Unit: %)

Region	GDP change	Control cost	Net benefit
China	1.56	-0.79	0.77
Shanghai	2.43	-0.39	2.04
Tianjin	2.44	-0.61	1.83
Beijing	2.17	-0.37	1.80
Jiangsu	1.88	-0.56	1.31
Zhejiang	1.62	-0.52	1.10
Henan	1.61	-0.55	1.05
Hebei	1.99	-1.06	0.93
Shandong	1.79	-0.93	0.87
Liaoning	1.44	-0.69	0.75
Fujian	1.23	-0.49	0.74
Guangdong	1.28	-0.59	0.70
Chongqing	1.46	-0.90	0.56
Jilin	1.31	-0.78	0.53
Hubei	1.46	-1.00	0.45
Anhui	1.22	-0.84	0.37
Xinjiang	1.16	-0.79	0.37
Hunan	1.24	-0.88	0.36
InnerMong	1.41	-1.09	0.32
Sichuan	1.34	-1.08	0.26
Hainan	0.97	-0.73	0.24
Heilongjiang	1.15	-0.92	0.23
Shaanxi	1.35	-1.24	0.11
Guangxi	1.09	-1.03	0.06
Qinghai	1.15	-1.15	0.00
Jiangxi	1.24	-1.24	0.00
Yunnan	1.00	-1.08	-0.08
Gansu	1.10	-1.20	-0.10
Shanxi	1.57	-2.24	-0.67
Guizhou	1.22	-2.10	-0.88
Ningxia	1.34	-2.40	-1.06

4. Impact of ozone pollution

Ozone is the common air pollutant all over the world, including both developing and developed countries. Many studies related to China have reported associations between ozone pollution and morbidity and mortality, but few study focuses on the health and economic effects in China's 30 provinces. This study evaluates the ozone pollution-related health impacts on China's national and provincial economy and compares it with the impacts from $PM_{2.5}$. This study also explored the mitigation potential across 30 provinces of China. This study developed an integrated approach that combines GAINS-China, GEOS-Chem, health assessment model using the latest exposure-response functions, medical prices and VSL, and AIM/CGE-China model. Results show that lower income western provinces encounter more severe health impacts and economic burden due to high natural background, whereas southern and central provinces have relatively lower impacts. Without control policy, China experiences a 4.2 billion USD (equivalent to 0.34‰) GDP loss and 290 billion USD (2.3% of GDP) of life loss in 2030. In contrast, with control policy, GDP and VSL loss reduce to 3.7 (0.03%) and 240 billion USD (2.0%), respectively. Health and economic impacts of ozone pollution are significantly lower than $PM_{2.5}$, but it is a non-ignorable economic burden for the low-income western provinces and much more difficult to mitigate, especially for provinces with high natural background. The central government needs to adopt preferential policies such as subsidies and monetary transfer to such provinces.

Ozone concentration

It shows that ozone concentration is higher in the southwest and lower in the east in China in both scenarios. Provinces in the southwest such as Sichuan (130 ug/m3), Qinghai (130 ug/m3), and Gansu (120 ug/m3) provinces in 2030 in the WoPol scenario. The reason is that ozone concentration comes from two parts of natural background and human activity. human activity dominates (>40%), including Zhejiang, Anhui, Fujian, Jiangxi, Hubei, Hunan, Chongqing, Guizhou. Ozone concentration decreases a lot in these provinces in WPol scenario.

Health impact of ozone

In the WoPol scenario, the concentration in most parts of China will be still above the standard level of 70 ug/m3 in 2030. Only Hainan and Shanghai could meet the national standard, while in the populous regions of Beijing, Tianjin, and Jiangsu ozone concentration is still high, which will cause various health impacts. Table 2 shows the premature death due to ozone pollution in 30 provinces in China. The provinces in the west and central China with higher ozone concentration have server health impacts, such as Sichuan, Qinghai, Jiangxi, Hunan and Chongqing. In 2030, the total national number of chronic mortality is about 580 (230-1200) thousand people in WoPol and 490 (210-1100) thousand people in WPol scenario

Value of statistical life

The market impact of ozone pollution in China is not significant, because some of health impact of ozone pollution cannot be quantified by economic models, such as comfort, wellbeing and premature death in children and elder people. This study uses the non-market method on market choices that involve implicit tradeoffs between risk and money.

Table 2 Mortality due to ozone pollution in China in 2030

Scenario	WoPol	WPol	WPol2
Beijing	4.2	5.7	5.3
Tianjin	0.03	1.2	2.2
Hebei	22	22	18
Shanxi	16	16	13
InnerMong	9.6	9.3	7.3
Liaoning	13	13	9.2
Jilin	9.0	7.3	3.4
Heilongjiang	9.3	7.2	3.1
Shanghai	0.00	0.00	0.21
Jiangsu	8.1	5.8	9.9
Zhejiang	20	15	8.7
Anhui	26	19	11
Fujian	19	15	8.0
Jiangxi	30	22	9.7
Shandong	21	17	16
Henan	28	23	15
Hubei	30	23	12
Hunan	47	35	17
Guangdong	39	37	31
Guangxi	31	22	12
Chongqing	20	16	9.3
Sichuan	74	67	50
Guizhou	26	20	11
Yunnan	25	17	9.3
Shaanxi	24	21	14
Gansu	18	17	13
Qinghai	4.7	4.5	4.1
Ningxia	3.9	3.7	2.8
Xinjiang	9.9	9.3	8.5
China	580	490	340

Economists have developed VSL. These VSL estimates can provide the government with reference point for assessing the benefits of risk reduction. Co-benefits of avoided air pollution mortality and morbidity are monetized using VSL. In 2030, the national VSL lost is about 2300 and 2000 billion CNY in WoPol and WPol scenarios, respectively, which is about 2.3% and 2.0% of the GDP of China. At the provincial level, Sichuan has the highest mortality and moderate per capita GDP. VSL is the highest in Sichuan (320 billion CNY, or 7.6% of GDP in WoPol), followed by the western provinces Gansu (64 billion CNY, or 6.5 % of GDP), Xinjiang (37 billion CNY, or 3.3 % of GDP), and Shaanxi (100 billion CNY, or 5.5 % of GDP). Beside the VSL, Table 3 shows the economic impact of ozone pollution in 30 provinces in China.

Table 3 Economic impact of ozone pollution

Year	2005			2030		
Region	WoPol	WPol	WPol2	WoPol	WPol	WPol2
Beijing	0.96	0.96	0.96	0.88	1.1	1.1
Tianjin	0.57	0.59	0.59	0.14	0.41	0.64
Hebei	0.78	0.77	0.77	0.94	0.93	0.80
Shanxi	1.1	1.0	1.0	1.4	1.3	1.1
InnerMong	0.76	0.74	0.74	1.1	1.1	0.86
Liaoning	0.69	0.66	0.66	0.87	0.85	0.65
Jilin	0.51	0.45	0.45	0.87	0.71	0.39
Heilongjiang	0.35	0.31	0.31	0.63	0.50	0.26
Shanghai	0.00	0.00	0.00	0.00	0.00	0.03
Jiangsu	0.60	0.54	0.54	0.39	0.31	0.43
Zhejiang	0.65	0.58	0.58	1.1	0.87	0.55
Anhui	0.76	0.69	0.69	1.2	0.88	0.60
Fujian	0.78	0.69	0.69	1.4	1.1	0.69
Jiangxi	0.98	0.87	0.87	1.9	1.4	0.75
Shandong	0.62	0.59	0.59	0.67	0.58	0.54
Henan	0.60	0.56	0.56	0.81	0.69	0.50
Hubei	0.85	0.78	0.78	1.4	1.1	0.68
Hunan	1.0	0.95	0.95	1.9	1.4	0.84
Guangdong	1.1	0.99	0.99	1.3	1.2	1.0
Guangxi	0.82	0.76	0.76	1.7	1.2	0.76
Chongqing	1.0	0.95	0.95	1.9	1.5	1.0
Sichuan	1.7	1.6	1.6	2.5	2.3	1.8
Guizhou	0.92	0.84	0.84	1.8	1.4	0.91
Yunnan	0.68	0.61	0.61	1.5	1.1	0.65
Shaanxi	1.1	1.0	1.0	1.7	1.6	1.1
Gansu	1.4	1.3	1.3	1.9	1.8	1.5
Qinghai	1.9	1.9	1.9	2.5	2.4	2.2
Ningxia	1.3	1.2	1.2	1.9	1.8	1.4
Xinjiang	1.1	1.1	1.1	1.5	1.4	1.3
China	0.84	0.79	0.79	1.2	1.1	0.79

5. Conclusion

This study evaluates the economic impacts on health damages caused by $PM_{2.5}$ and ozone pollution in 30 provinces in China, and conducts a cost-benefit analysis of air pollution control policy at the provincial level. Air pollution has negative impact on human health and China's economy, which has been a heavy burden for China. Air pollution control policy can reduce air pollutant concentration significantly and bring net benefit for China. This study also finds significant regional disparity among China's provinces in terms of air quality, health and economic impacts, and the costs and benefits of control air pollution. Provinces with higher GDP and population density have higher benefit from air pollution control policy. Regional collaboration is very important for air pollution reduction.

This study finds it is more difficult to reduce ozone concentration compared with $PM_{2.5}$ pollution [22] because ozone generation process is not in a linear relationship with precursor emissions, implying that in the longer term, ozone pollution will be a more persistent problem in China, and adaptation, e.g. wearing protective masks, adjust lifestyle is more important than mitigation, especially in the urban area. Although ozone precursor emissions have been reduced a lot from WoPol to WPol scenario, the ozone concentration reduction is very limited (less than 10%) in WPol scenario. Even more aggressive reduction efforts are made in the WPol2 scenario, in contrast to $PM_{2.5}$ whose concentration reduces by over 70% in almost all provinces, reduction rates of ozone concentration are merely around 20% in most provinces. Conversely, in urban areas around Beijing, Shanghai and Guangzhou, it even increases.

A similar phenomenon has been reported in previous studies in China. For instance, [26] found that the mixing ratio of ozone increased with the increasing NO_2/NO ratio, whereas the NO_z mixing ratio leveled off when $NO_2/NO_{>8}$. Consequently, the ratio of ozone to NO_z increased to above 10, indicating the shift from VOC-sensitive regime to NO_x-sensitive regime. [27] found that varying and considerable impacts of ozone generation processes in different areas of China depending on the atmospheric abundances of aerosol and NO_x. This is partly because most of $PM_{2.5}$ is from artificial activities like industry and transportation, while relatively less portion from natural sources, such as desert, farmland, burning forest and sea salt. However, for ozone, a significant source is nature emissions which is beyond the control of human activity.

This study also took a closer look at the Beijing-Tianjin-Hebei area, which is one of the most developed regions in China as well as the most polluted region with severe health problems caused by $PM_{2.5}$ pollution. The results show that $PM_{2.5}$ pollution also has significant impact on GDP and welfare in this region. The GDP loss related to $PM_{2.5}$ pollution is about 2.8% in Tianjin, 2.5% in Beijing and 2.2% in Hebei in the WoPol scenario, while welfare loss is 5.1%, 8.1% and 3.4% in Tianjin, Beijing and Hebei, respectively. However, under intensive air pollution control technology, Beijing, Tianjin and Hebei could obtain benefits equivalent to 1.8%, 2.0% and 1.5% of GDP in the WPol scenario. The benefits of air pollutant control technology are higher than the cost in Beijing-Tianjin-Hebei area, and the benefits are highest in Beijing, lower in Tianjin and lowest in Hebei.

When shedding light on the impacts on the sectors, this study found that the labor-intensive sectors will encounter more significant negative impacts since air pollution-related work time decreases will lead to increase in labor price. The increasing of labor price leads to the additional cost of production. These sectors include coal mining, food production, textile, water supply, transportation and agriculture.

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