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Health and Economic Impacts of Air Pollution in China: A Comparison of the General Equilibrium Approach and Human Capital Approach

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In China, combustion of fossil fuels and biomass has produced serious air pollution that does harm to human health. Based on dose-response relationships derived from epidemiological studies, the authors calculated the number of deaths and people with health problems which were thought to be attributable to China's air pollution in the year of 2000. In order to estimate the corresponding economic impacts from the national point of view, the general equilibrium approach was selected as an analysis tool for this study. A computable general equilibrium (CGE) model was constructed involving 39 sectors and 32 commodities. The human capital approach (HCA) was also used for comparison. The economic burden of disease for people estimated by HCA was equivalent to 1.26‰ (ranging from 0.44‰ to 1.84‰) of China's gross domestic product (GDP). China's GDP loss estimated by the general equilibrium approach reached 0.38‰ (ranging from 0.16‰ to 0.51‰). The difference between the two approaches and the implications of the results were discussed.

Key words: Air pollution; Health; Economic impact; CGE model; Human capital approach

INTRODUCTION

China is the world's largest producer and consumer of coal[1]. Constrained by the availability of energy resources and the stage of economic development, China relies on coal as the fuel for much of its economic progress. At the same time, it has produced large amounts of particulates and sulfur dioxide. A report released in 1998 by the World Health Organization (WHO) noted that of the 10 most polluted cities in the world, seven were in China. Solid fuels in the form of biomass and coal are still the main energy sources for rural residents, leading to serious indoor air pollution.

Although the contribution of air pollution to mortality and morbidity is well known, there is a need for a clearer understanding of the economic impact resulting from the health effects of air pollution. The basis of a cost-benefit analysis is that it can help policymakers to make a choice as to whether priority should go to environmental protection projects or other projects (traffic, education, health services, *etc*.) in light of the available funds. Economic analysis is therefore regarded as an efficient tool that can provide more persuasive explanations than moral arguments alone. Economic impacts can be observed from the standpoints of the people and the country, respectively.

In terms of the people, the health effects of air pollution mean increased medical expenditure and decreased income. Here, decreased income is composed of two parts: the actual forfeited income due to absence from work and the future forfeited income due to mortality. This method of assessment, which reflects people's economic burden of disease, is called the human capital approach.

In terms of the country, GDP is a common indicator that reflects a nation's overall economic situation. The human capital approach is inappropriate for estimating the GDP loss of a country because forfeited future income due to mortality is not a value-added loss, actual forfeited income due to absence from work is a partial value-added loss, and medical expenditure comprises one element of GDP that will alter the structure of final demand. As a matter of fact, national economic

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fluctuations are under the constraints of supply and demand, any changes of which will alter the economic balance. With regard to the health effects of air pollution, it decreases the labor supply and increases the final demand for health services. From a national point of view, an economic study should explore the chain reactions and synthetic impacts produced by these factors.

We have therefore adopted the general equilibrium approach for this study because it addresses problems by explicitly recognizing the fact that even when a change has a direct impact on one sector of the economy, there are always indirect impacts on other sectors. For comparison, the human capital approach is simultaneously applied to the same question under discussion in this analysis.

In the next section, the dose-response relationship due to air pollution is explained. In the subsequent sections, the methodologies of and results obtained by the computable general equilibrium (CGE) model and human capital approach (HCA) are shown. The formulation of these two methodologies is described in the Appendix. The conclusions of this study are set out in the final section.

QUANTIFICATION OF HEALTH EFFECTS

Description of Dose-response Relationship (D-R)

The first procedure in health impact assessment generally requires linkage of the changes of health status (mortality or morbidity) with each unit change of pollutant concentration. Although epidemiological studies on D-R provide a basis to quantify excess cases of mortality and morbidity, the existing epidemiological technique is still too limited to explicitly attribute certain health effect to a specific pollutant because air pollution is a complex mixture of pollutants that are highly correlated with each other. They might come from similar sources or be affected in similar ways by meteorological factors. Simply summing up the attributable number of cases, pollutant-by-pollutant will probably lead to double-counting. The most dominant pollutant therefore has to be selected for a study such as the present study. In view of the current environmental status of China, particulate matter was selected as a surrogate pollutant because it is a conspicuous pollutant in China, its impacts on health are confirmed by most toxicological and epidemiological studies[2-6], and a threshold below which no effects occur is not defined yet among the pollutants[7]. In order to maintain consistency with most other studies, PM_{10} (airborne particulate matter with a diameter of 10 μm or less) was selected for this study. Since some studies used other measures of particulate matter such as TSP (total suspended particulates) and $PM_{2.5}$ (airborne particulate matter with a diameter of 2.5 μm or less), the following conversions were applied: $PM_{10} = TSP \cdot 0.55$ and $PM_{2.5} = PM_{10} \cdot 0.65$.

Among the statistical techniques of epidemiological studies, the Poisson regression model is commonly used for acute health effects and the Cox proportional hazards model or logistic regression model for chronic health effects. Whichever model is employed, the relationship between the concentration and health effect can be basically expressed in exponential terms as follows:

$$\beta = \frac{\ln RR}{C - C_0} = \frac{\ln RR}{\Delta C} \tag{1}$$

where RR: relative risk (logistic model provides odds ratio [OR]); ΔC: unit change of concentration (C_0: baseline concentration, C: given concentration); β: D-R coefficient.

Based on equation 1, the excess number of cases induced by air pollution can be calculated by the following equation:

$$E = POP \cdot M \cdot (e^{\beta \cdot \Delta C} - 1) \tag{2}$$

where E: excess number of cases; POP: exposed population; M: baseline mortality or morbidity.

Selection of D-R Coefficients for This Study

All the D-R coefficients and related baseline data adopted for this study are listed in Tables 1 and 2, respectively.

Mortality Time-series studies capture only cases in which death can be triggered by air pollution exposures shortly before death, while cohort studies capture all air pollution-related categories of death, including deaths of persons whose underlying health condition might lead to premature death not related to the level of pollution shortly before death[31]. Generally speaking, acute and chronic mortality represent the likely lower and upper boundary effects on mortality, respectively.

D-R studies on acute mortality in China are limited to time-series studies in several large cites, such as Beijing, Shenyang, Chongqing, Shanghai, and Hong Kong[32-37]. Various measures of particulate matter have been used in these studies, such as TSP, PM_{10}, and $PM_{2.5}$. After pooling these estimations and making a comparison with some relevant international studies[8,38-39], a similar degree of response can be found between Chinese and American studies, even though they dealt with exposures to different pollution concentration levels (Fig. 1). The American study adopted a large-scale time-series study that selected PM_{10} as a unified indicator and resulted in a small variation, so its stability can be considered to be better than that of

TABLE 1

Dose-Response Studies and Coefficients Adopted in This Analysis

Health Effects	Reference	Age	Disease Definition	Coefficient (95% CI)
Mortality				
Acute	[8]	All	<800	0.000270 (0.000172, 0.000367)
Chronic	[9]	>30	All	0.004165 (0.002286, 0.006132)
Hospital admissions				
Cardiovascular				0.000785 (0.000661, 0.000909)
	[10]	20-64	390-429	
	[11]	All	390-429	
	[12]	All	390-429	
	[13]	All	396-429	
	[14]	All	390-429	
	[15]	All	410-414	
	[16]	All	410-414	
	[17]	30-	103-144*	
	[18]	All	410-429	
	[19]	All	401-417	
	[20]	All	410-414, 427, 428	
	[21]	All	410, 413, 427, 428	
Cerebrovascular				0.000417 (0.000072, 0.000762)
	[10]	20-	430-448	
	[17]	30-	14-17, 22*	
	[18]	All	430-436	
	[16]	All	430-438	
Respiratory				0.001858 (0.001196, 0.002520)
	[22]	All	460-519	
	[11]	All	460-519	
	[23]	All	460-519	
	[17]	30-	75-101*	
	[18]	All	466, 480-496	
	[20]	All	464-466, 480-496	
	[24]	All	466, 480-485, 490-493	
	[19]	All	466, 480-486, 490-493, 496	
	[15]	All	464,466, 480-487, 490-493, 496	
	[16]	All	460-466, 471-478, 480-487, 490-496	
Hospital Visits				
Internal Medicine	[25]	-	-	0.013736 (0.010768, 0.016794)
Pediatrics	[25]	-	-	0.015507 (0.010409, 0.020604)
Prevalence				
Chronic Bronchitis	[26]	25-	Patients' responses	0.004770 (0.001733, 0.007372)
AURTI	[26]	25-	Patients' responses	0.004770 (0, 0.008546)

Note. The International Classification of Diseases, Revision 9 is applied to the disease definition except for diseases marked with an asterisk (*), to which the All-Patient-Refined Diagnosis-Related Group is applied. The coefficient of hospital visits means the relationship between the increased percentage of visits and each increase of $\sqrt{PM_{10}}$.

TABLE 2

Baseline Data Used in This Analysis

	Baseline Data	
	Urban	Rural
Mortality Per Year (‰)		
All Ages (Non-accident) [a]	3.93	6.04
30- (All Causes) [b]	7.02	10.73
Hospital Admissions Per Year (‰) [c]		
Cardiovascular (All Ages)	4.99	2.97
Cerebrovascular (All Ages)	4.20	4.18
Respiratory (All Ages)	6.31	5.72
Hospital Visits Per Year (‰)[c]		
Internal Medicine	2668.28	2978.83
Pediatrics	283.72	223.04
Prevalence Rate Per Year (‰)[c]		
Chronic Bronchitis (25-)	18.09	10.57
AURTI (25-)	1159.1	1158.5
Average Medical Expenditure Per Inpatient (Yuan)[c]		
Cardiovascular (All Ages)	5214	1754
Cerebrovascular (All Ages)	5377	3715
Respiratory (All Ages)	2934	801
Average Medical Expenditure Per Outpatient (RMB)[c]	51.6	16.8
Average Medical Expenses in Self-treatment Group (Yuan)		
Chronic Bronchitis[d]	383.09	127.07
AURTI[e]	47.29	20.04
Average Workdays Lost Per Inpatient[c]		
Cardiovascular (All Ages)	25.8	15.5
Cerebrovascular (All Ages)	33.3	24.6
Respiratory (All Ages)	17.5	8.2
Average Workdays Lost for Each Occurrence of Illness Per Outpatient		
15-64[f]	0.91	2.14
Life Expectancy in 2000[g]	75.2	69.5

Note. [a]Annual health statistics data[27]; [b] Dataset of the Fifth Census[28]; [c] Second National Health Services Survey[29]; [d] Inquiry from experts at Chinese Center for Disease Control and Prevention; [e] The cost here is the average expenditure in the self-treatment group because no specific data is available for AURTI[29]; [f]Author's calculation based on the second National Health Services Survey; [g] Brief report on health development from 1997 to 2001[30].

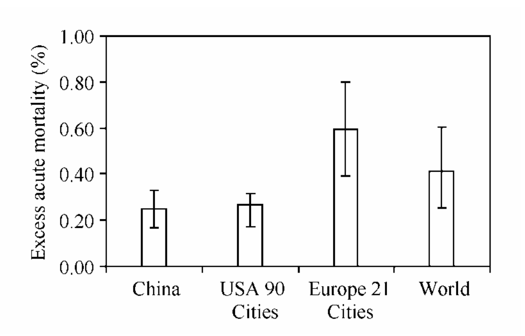

FIG. 1. Excess acute mortality rate resulting from each 10 μg/m^3 change in PM_{10} concentration.

other studies. For a chronic mortality study, a cohort study is more appropriate than a cross-section study. However, the available cohort studies are very limited in number and most of them have been executed in the USA[9, 40]. Among these, a study of 154 USA cities showed a lower estimation and a smaller variation. Only one Chinese study in Benxi City provided information on the dose-response relationship and the method used in this study was the cross-section method instead of the cohort method. When the results are compared, the Chinese population shows a lower chronic response to long-term exposure to air pollution (Fig. 2).

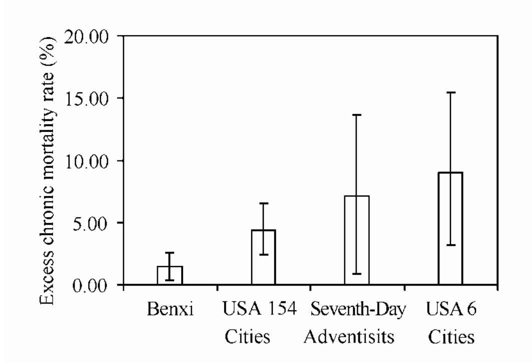

FIG. 2. Excess chronic mortality rate resulting from each 10 μg/m^3 change in PM_{10} concentration.

Therefore, this study adopted the acute coefficient from the study of 90 USA cities as the lower limit, and the 5th percentile chronic coefficient from the study of 154 USA cities as the upper limit. The average level of excess mortality estimation for the Chinese populationwas the mean value of acute and chronic cases.

Morbidity China began to study the relationship between daily hospital visits and daily air pollution in the 1990s[25,41-42]. Significant positive correlations have been found in internal medicine and pediatrics.

Studies on hospital admissions are still not available in the Chinese mainland. According to the current epidemiological information, hospital admissions are mainly correlated with respiratory and circulatory diseases. The International Classification of Disease (ICD-9) codes contained in these studies vary substantially, and it is difficult to determine which is more correct. We therefore divided diseases into three groups: respiratory diseases (ICD-9 460-519), cardiovascular diseases dominated by heart diseases (ICD-9 390-429) and cerebrovascular diseases (ICD-9 430-448) on the assumption that the diseases likely affected by air pollution should be included in these three groups.

Chronic bronchitis and acute upper respiratory tract infection (AURTI) are important health effects from air pollution. Studies on chronic bronchitis are limited. Although there is evidence that long-term exposure to particulates can give rise to new cases of chronic bronchitis[43-45], official and authentic information on the incidence rate of chronic bronchitis is scarce in China. Hence, we decided to borrow the results of a cross-section study on chronic bronchitis and AURTI in China[26]. Since some of the patients with chronic bronchitis and AURTI were contained in the calculation of hospital admissions and visits, we only needed to calculate the patients who performed self-treatment in order to avoid double counting. According to the Second China's National Health Services Survey[29], 49.93% of urban patients and 33.16% of rural patients do not visit a doctor for some reasons. Among these patients, 48.13% of urban patients and 44.93% of rural patients buy medicines and perform self-treatment.

Estimation of the changes in health effects associated with concentrations in a given location should ideally be based on studies conducted locally. However, it is impossible to obtain local studies for each health effect. In the case of China, most coefficients have to be extrapolated from those of other countries. When a coefficient was estimated by several studies in several locations, we used meta-analysis to obtain an "average estimation" via Intercooled Stata 7.0 for Windows 98/95/NT (Stata Corporation) in order to reduce the uncertainty that would arise if a particular study is relied on. A MEDLINE search was carried out to review the published papers based on the following inclusion criteria. ① Baseline data of the targeted health effect should be available in China; ② the classification or definition of the disease should be clear; ③ coefficients from large-scale and long-term epidemiological studies are preferable; ④ studies in which the target population covers all ages are preferable; ⑤ sub-clinical health effects, e.g., lung function, nonspecific immune function, humoral function and low birth weight, are excluded from this assessment because of their uncertain evolutions. If heterogeneity was found among studies, the pooled coefficient estimated by the random effect model was employed. Otherwise the fixed effect model was used.

Some Assumptions Made in This Study

Workday loss due to illness The Second China's National Health Service Survey[29] provides the information on workday loss of inpatients by disease. Data for outpatients of pediatrics and internal medicine are scarce. Therefore, we assumed that each pediatrics visit will caused a loss of 0.5 workdays and outpatients of internal medicine were mainly composed of adults and the elderly. Their age composition equaled the age composition of adult visits. Based on the Survey, the percentages for the 15-64 age group were 70.02% and 83.44% of adult visits in urban and rural areas, respectively. The average number of visits per occurrence of illness was 1.72 and 1.79 for urban and rural areas, respectively. Average workday losses for each occurrence of illness per worker were 0.91 and 2.14 for urban and rural areas, respectively.

Exposed population (1) Outdoor air pollution is the main problem in urban areas whereas indoor air pollution constitutes the main problem in rural areas. China's air quality standards were taken as the benchmark, that is, 0.10 mg/m^3 (Grade II) for outdoor air[46] and 0.15 mg/m^3 for indoor air[47].

(2) According to an environmental report, two-thirds of the urban population were exposed to ambient air pollution in 2000[48], accounting for around 2.9 hundred million people. The annual average concentration of PM_{10} in China in 2000 was 0.16 mg/m^3[49]. This concentration was assumed to represent the average situation of polluted cities.

(3) According to an estimation by experts at the Academy of Macroeconomic Research, NDRC, 74.4% of the rural population use biomass and 25.6% use coal for cooking and heating[50]. A rural family may use both biomass and coal. The figure of 74.4% is regarded as a conservative estimation of the exposed population affected by indoor air pollution only in the cold season (around four months). The daily average PM_{10} concentration is 0.596 mg/m^3, a mean obtained by logarithmic conversion of concentrations[51-55]. For adults, the time spent indoors is 10.92 h for men and 14.34 h for women[53]. For children, we assume that the time of exposure is the same as that of women. Thus, 104 million rural people are exposed to indoor air pollution throughout the course of a year, of which 49 million are men and 55 million are women.

Avoidable Cases in 2000

Based on the related dose-response relationships and assumptions, the avoidable cases of mortality and morbidity in China in 2000 were estimated for the scenario of air quality meeting China's air quality standards (Table 3).

Deaths attributable to air pollution were 290 000, accounting for 4.01% of total deaths. The total days of absence from work were 120 million days. Thus, labor loss due to deaths and workday loss (an average of 251 workdays per worker in a year was used for China's situation) was 590 000 (0.26-0.77), accounting for 0.68‰ (0.30-0.89‰) of the labor population. Labor loss was used as an input variable for the CGE model.

ECONOMIC IMPACT OF HEALTH RELATED WITH AIR POLLUTION

Human Capital Approach

Methodology The health impacts were summarized by human capital approach from three aspects: premature deaths, workday loss and excess medical expenditure. The economic loss of a premature death equaled the discounted flow of future earnings if the person did not die, with the person's age weight and productivity weight taken into consideration. The method of calculation is described in the Appendix. The economic loss per workday equaled the wage per day per worker. Calculation of medical expenditure was based on the cost-of-illness directly.

Results Economic losses due to workday loss and premature deaths were 2.84 (0.12-3.29) 10^9 yuan and 4.95 (1.47-8.18) 10^9 yuan, respectively. The total medical expenditure attributable to air pollution was up to 3.51 (1.32-4.96) 10^9 yuan, which is 1.22% (0.46%-1.72%) of the national personal health expenditure. The total economic loss is equivalent to 1.26‰ (0.44‰-1.84‰) of China's GDP in 2000. (Table 4). The excess medical expenditure obtained here was also used as an input variable in the CGE model.

General Equilibrium Approach

Although the human capital approach exhibits the negative economic impact of health deterioration, it does not unveil the mechanism by which health factors can affect economic activity. In fact, the two health factors induced by air pollution, namely, labor

TABLE 3

Avoidable Cases of Mortality and Morbidity Due to Air Pollution

	Urban (Lower; Upper)	Rural (Lower; Upper)	Total (Lower; Upper)
Deaths	78 914 (18 420; 138,331)	215 423 (71 384; 352 890)	294 337 (89 804; 491 221)
Labor Deaths	25 000 (5 840; 43 814)	63 786 (20 748; 105 441)	88 786 (26 588; 149 255)
Hospital Admissions	293 500 (183 780; 399 963)	503 537 (332 296; 641 449)	797 037 (516 076; 1 041 412)
Cardiovascular	69 361 (51 223; 87 346)	94 224 (72 380; 114 140)	163 585 (123 603; 201 486)
Cerebrovascular	30 235 (5 275; 54 685)	73 849 (13 751; 125 375)	104 084 (19 026; 180 060)
Respiratory	193 904 (127 282; 257 932)	335 464 (246 164; 401 933)	529 368 (373 446; 659 865)
Hospital visits	30 553 553 (23 601 311; 37 387 218)	48 109 865 (38 281 296; 57 290 788)	78 663 418 (61 882 607; 94 678 006)
Internal Medicine	27 292 186 (21 383 362; 33 109 354)	44 422 928 (35 670 220; 52 634 876)	71 715 114 (57 053 582; 85 744 230)
Pediatrics	3 261 367 (2 217 949; 4 277 864)	3 686 937 (2 611 077; 4 655 912)	6 948 304 (4 829 026; 8 933 776)
Prevalence			
Chronic Bronchitis	1 311 568 (520 420; 1 883 693)	969 862 (592 732; 1 059 942)	2 281 430 (1 113 152; 2 943 635)
AURTI	84 041 096 (0; 135 458 256)	106 289 616 (0; 117 997 824)	190 330 712 (0; 253 456 080)
Workday Loss	38 642 384 (14 987 562; 54 294 588)	86 876 728 (43 447 296; 101 475 040)	125,519,112 (58 434 858; 155 769 628)
Labor Loss Due To Workday Loss	153 953 (59 711; 220 777)	346 122 (173 096; 406 454)	500 075 (232 807; 627 231)
Total Labor Loss	178 954 (65 551; 264 591)	409 908 (193 844; 511 895)	588 862 (259 395; 776 486)

Note. Labor loss due to workday loss=workday loss/251(average workdays per worker).

TABLE 4

Economic Loss Due to Health Related With Air Pollution Using Human Capital Approach (Unit: 10^9 Yuan)

	Urban (Lower, Upper)	Rural (Lower, Upper)	Total (Lower, Upper)
Premature Death	2.83 (0.70, 4.87)	2.12 (0.76, 3.32)	4.95 (1.47, 8.18)
Workday Loss	1.50 (0.58, 2.15)	1.34 (0.57, 1.15)	2.84 (0.12, 3.29)
Excess Medical Expenditure	2.36 (0.85, 3.47)	1.15 (0.47, 1.49)	3.51 (1.32, 4.96)
Total	6.69 (2.14, 10.5)	4.41 (1.80, 6.15)	11.3 (3.94, 16.4)
Relativity to GDP (‰)	0.75 (0.24, 1.17)	0.52 (0.20, 0.67)	1.26 (0.44, 1.84)

loss and excess medical expenditure, have played a significantly role in the economy. Labor loss has a negative impact on production activity. On the other hand, excess medical expenditure theoretically changes only the consumption pattern. This is the most important point of difference. Therefore, we need to rely on a CGE model to investigate the relationships between health factors and economic activities and to trace the resulting economic impacts.

Structure of the China CGE model (AIM/Material China) We quantitatively analyzed the health impacts on China's economy using a China CGE model called AIM/Material China. Fig. 3 shows the relationships between economic activities and health effects. In this study, the labor loss and excess medical expenditure due to air pollution were introduced into the CGE model and their economic impacts were assessed. The model structure was explained in detail in the Appendix.

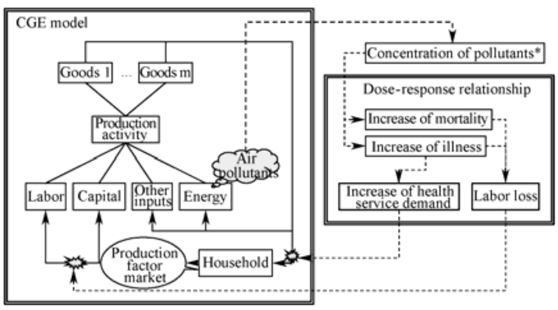

FIG. 3. Outline of relationships between economic activities and health related with air pollution. *: Air diffusion model which is to link pollutant emission and concentration is being developed. We made some assumption on concentration instead in the study.

Based on the China energy balance table [56] and the China 124-sector input/output table for 1997[57], the economic activity in China in 1997 was reproduced in the form of 39 sectors and 32 commodities (Table 5). Since this model was developed for the climate change issue, power plants were disaggregated in detail. First, initial equilibrium calibration of the model was performed by reproducing the benchmark data set of 1997 that formed the basis for its construction, and technology parameters up to 2000 were calibrated to conform with the economic activities in 2000. The economic impacts of air pollution in 2000 were then assessed by introducing the quantified health effects as described in the previous section.

Scenarios Four scenarios were proposed for this analysis.

(1) BAU scenario (BAU) was used as the reference scenario without considering the health impacts from air pollution. This reference scenario could depict the annual GDP growth rate of 7.4% from 1997 to 2000, being quite similar to the actual statistics for GDP. That is to say, the model has successfully reproduced the actual conditions in China.

(2) Scenario 1 (S1) was used to estimate the total impacts of labor loss and excess medical expenditure on the national economy due to air pollution in 2000. Labor loss consists of labor deaths and workday loss. The labor population means the population aged between 15 and 64 years. According to the calculation outlined above, China's labor loss due to air pollution in 2000 was 0.68‰ (0.30‰-0.89‰) of the total labor population and the excess medical expenditure was 3.51 (1.32-4.96) 10^9 yuan.

(3) Scenario 2 (S2) was used to estimate the economic impacts of labor loss only.

(4) Scenario 3 (S3) was used to estimate the economic impacts of excess medical expenditure only.

In the following, the simulation results for the year 2000 were evaluated.

Results

(1) Impacts on GDP

Compared with BAU scenario, both labor loss and excess medical expenditure were unfavorable for the growth of economy (Fig. 4). Under S1, the total GDP loss of China was up to 0.380‰ (0.162‰-0.511‰). Economic activities suffered a negative impact from the labor loss under S2 and the attributable GDP loss was 0.365‰ (0.157‰-0.491‰).

TABLE 5

Sectors and Commodities in AIM/Material China Model

No.	Sector	Commodity	Industry
1	AGR	Agriculture, Forestry, and Fishery	I
2	M_C	Coal Mining	II
3	M_O	Crude Oil Exploration	II
4	M_G	Natural Gas Exploration	II
5	MIN	Other Mining	II
6	FOD	Food and Tobacco Products	II
7	TEX	Textile Production	II
8	WOD	Production of Wood and Wood Products	II
9	PAP	Paper and Pulp Production	II
10	OIL	Oil Refinery	II
11	COL	Coking	II
12	CHM	Chemical Products	II
13	NMP	Nonmetallic Mineral Products	II
14	STL	Iron and Steel	II
15	NFR	Nonferrous Metals	II
16	MET	Metalworking Machinery	II
17	ENV	Equipment and Production for Environmental Protection	II
18	OHI	Other Machinery Products	II
19	REP	Maintenance and Repair of Machinery and Equipment	II
20	OLI	Other Manufacturing Products	II
21	WST	Wastes	II
22	ELC	Coal-based Power Generation*	II
23	ELG	Gas-based Power Generation*	II
24	ELO	Oil-based Power Generation*	II
25	ELH	Hydropower Generation*	II
26	ELN	Nuclear Power Generation*	II
27	ELP	Photovoltaic Generation*	II
28	ELW	Wind Power Generation*	II
29	ELB	Biomass Power Generation*	II
30	HET	Steam and Hot Water	II
31	GAS	Gas	II
32	WTR	Water	II
33	CNS	Construction	II
34	T_F	Freight Transport	III
35	COM	Commerce	III
36	RES	Restaurants	III
37	T_P	Passenger Transport	III
38	HEL	Health Service	III
39	OSR	Other Services	III

Note. *ELE is used to represent the commodity of electricity.

The excess health service demand under S3 also decreased GDP, although only the consumption pattern was introduced, with an attributable GDP loss of 0.014‰ (0.005‰-0.020‰).

(2) Impacts on final consumption

Compared with BAU, S1 showed that the total final consumption in China was reduced by 0.63‰ (0.27‰-0.85‰), in which labor loss led to a decrease of 0.56‰ (0.24‰-0.75‰) and excess medical expenditure led to a decrease of 0.07‰ (0.03‰-0.10‰) (Fig. 4).

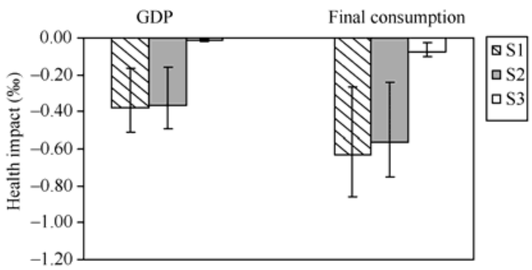

FIG. 4. Health impacts on GDP and final consumption.

Fig. 5 shows the changes of consumption patterns compared with BAU scenario. The labor loss reduced the consumption of each commodity. On the other hand, the excess health service demand had almost no impact on the total final consumption because it only changed the consumption pattern. Even so, this slight shift resulted in a negative impact on the economy. Moreover, the consumption change also led to production changes. For example, the increase of health service demand stimulated the chemical industry in order to produce more medicines. The CGE analysis revealed not only the total economic impact but also detailed structural changes.

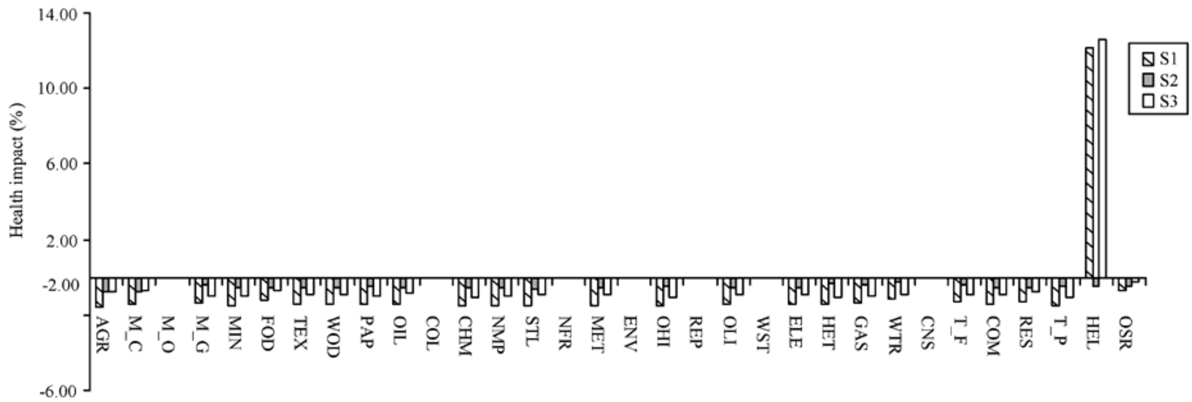

FIG. 5. Health impact of air pollution on final consumption by commodity. Names of commodities correspond to those in Table 5.

DISCUSSION

Comparison of the Two Approaches

This study analyzed the likely economic impacts of health related with air pollution in China by CGE approach and HCA. The economic losses estimated by CGE approach and HCA were 0.38‰ and 1.26‰ of China's GDP in 2000, respectively. The difference may arise from the methodology of calculating the economic impacts (Table 6).

Differences in analyzing the economic impacts of exogenous shocks between the two approaches

(1) Labor loss General equilibrium is a theoretical foundation of the CGE model, the structure of which is based on input-output table. Within the CGE model, the modified labor supply is reallocated to all sectors based on the input-output relation across sectors. By doing this, the economic impact of labor loss is disaggregated to all production sectors as well. Total household income decreases correspondingly because of the decrease in labor endowment. Subsequently, the final consumption decreases. The decrease of final consumption means a decrease of demand that further influences the supply from production sectors. By synthesizing these effects, labor loss produces a much more significant negative impact on China's GDP.

In the human capital approach, a life is valued by the total of that person's forfeited income converted into the present value. This type of life valuation may vary with the values selected for age weight, productivity weight, and discounting rate. Moreover, it raises a question about equity because the value of a life depends on the person's contribution to society, so values for children and the elderly are usually understated. The CGE approach takes the actual numerical labor input as an input variable instead of the tradeoff between currency price and life. What is more important, GDP is value-added in terms of the newly produced value during the production process, including depreciation of fixed capital, compensation

TABLE 6

Comparison of Methodologies of Human Capital Approach and Computable General Equilibrium Approach

	HCA	CGE
Time Horizon	Takes the Future Labor Loss Into Account.	Takes Only the Target Year into Account.
Method of Calculation	Average Income is Used for Evaluation of Deaths and Workday Loss.	Based on the Actual Numerical Value of Labor Loss, Labor Input is Reallocated for New Calculation.
Medical Expenditure	Completely Negative Impact.	Increase of Medical Expenditure Itself has a Positive Impact on GDP, because final Consumption Increases Through the Excess Demand for Health Services.
		On the Other Hand, if the Total Income Does not Increase by the Amount of Excess Health Service Demand, other Final Consumption Decreases. This Means a Negative Impact on GDP.
		The total Economic Impact is Determined from the Direct and Indirect Effects of Each Sectoral Activity in China.

of employees, net taxes on production, and operating surplus. When the human capital approach is examined, it is obvious that, forfeited future income due to mortality has no relationship with actual economic activity and forfeited income due to workday loss does not reflect overall loss of value-added at a given time.

(2) Medical expenditure The human capital approach regards excess medical expenditure directly as a negative economic impact accounting 0.392‰ of GDP. The key aspect here is the loss of patients rather than GDP. On the one hand, medical expenditure comes from income and income is one component of GDP. On the other hand, when the increase of health service demand alone does not lead to an increase of China's final consumption, its negative impact on the country's GDP is weak. The negative impact derives from the decreased consumption of other commodities. Of course, we cannot say that air pollution is preferable, even if it has a stronger positive economic impact.

When facing this reality, the human capital approach only addresses some of the effects while the CGE approach addresses the relationships between parts and the entirety.

Different points of view of the two approaches in addressing impacts The general equilibrium approach stands on the side of the macroeconomic framework where various sectors are closely interrelated. In brief, currency circulates between the consumers and producers. The consumers provide labor and capital to the producers for income. Under the constraint of income level, the consumers decide the proportion of consumption and investment to maximize the consumers' utility. Under the constraints of capital and labor input, the producers produce commodities to maximize the producers' profits at a certain level of prices. After selling the produced commodities on the market, the producers receive income. The operation and stability of the national economic system follow the rule that any adjustment always moves toward a balance between supply and demand. In this study, any change of the labor supply or heath service demand shifted the original economic balance to a new balance in order to maximize the consumers' utility and the producers' profits. Moreover, fluctuation of GDP under different scenarios when compared with the BAU scenario was attributed to the health related with air pollution.

Therefore, the CGE approach is suitable for the assessment of health impacts on the national economy. The assessment of the human capital approach represents the patients' economic burden of disease, as it only takes patients as the object of study. In this case, reseachers always need to undertake a careful investigotion for which approach is fit for the study objective. What's more, researchers have the obligation to aculately convey the meaning of any results of health economic impact assessments to policymakers, which is very important for the avoidance of possible misleading decision-making.

Uncertainties in This Study

Uncertainty is an unavoidable problem in any study. The possible uncertainties in this study may be as follows. ① The general equilibrium approach attempts to simulate the real system of the national economy. However, CGE model is idealistic and different from reality because the real economy is always dynamic. Meanwhile, the limited availability of data forced us to arbitrarily specify some of the parameters, such as elasticity of substitution. ② This study only focused on PM_{10} as an indicator of air pollution. If evidence for the independent health effects of all pollutants, the economic impacts of health might be much higher. ③ The majority of dose-response functions adopted in this study were based on international studies. The extrapolation of other countries' situations to China raises the question of reliability. This weakness is not easy to overcome until the differences between China and other countries in terms of exposure patterns, toxicity of particles, socioeconomic factors, and their impacts on health are disclosed. ④ Only quantifiable diseases were estimated in this study, the health impacts of air pollution were probably underestimated. The main damage to humans caused by air pollution consists of sub-clinical symptoms and physiological and biochemical changes are very difficult to be quantified.

Although there are uncertainties, we believe that our estimation of the health impacts of air pollution on China's economy is objective. Firstly, the CGE model follows the rules of balance between input and output and between supply and demand. These rules are the foundation of any market behavior. Secondly, the CGE model reproduces China's economic system through benchmark calibration. Thirdly, our estimation of health effects is fairly conservative and the related confidence intervals are shown.

CONCLUSION AND FUTURE WORK

Due to health damage caused by air pollution in 2000, China had a 0.38‰ (0.162‰-0.511‰) GDP loss, while the Chinese people endured a loss of 1.26‰ (0.44‰-1.84‰) of GDP. Although the health impacts of air pollution resulted in a huge loss for China's economy, the pain that the Chinese people have to endure is several times higher. With regards to the burden of disease, it is generally considered that the human capital approach cannot measure the loss of utility due to pain or suffering or the loss of leisure time. Thus, the human capital approach can provide a lower estimate of the economic burden of illness. In view of this problem, the approach of "willingness to pay" has become very popular in recent years because of its ability to capture the intangible variable of pain. Although we did not apply the willingness-to-pay approach in this study, both economic theory and a case taken up by the World Bank[58] in China revealed that this approach could yield a valua several times higher than the human capital approach.

The major implication of this study is that air pollution can slow down China's economic growth by declining health and living standards of the people. From this point of view, environmental conservation policies are becoming increasingly important for China. It is generally thought that environmental conservation and economic development conflict at the early stage of economic development. However, efforts to achieve economic growth do not justify the sacrifice of people's health and quality of life. In order to achieve a sustainable society, policymakers in China have begun to explore feasible policies for the country's sustainable development. Whatever policy is adopted, health impact is such a key factor for the development of economy.

As for future work, a variety of sophisticated techniques can be used to measure the economic impacts of health. These techniques provide valuable information on various consequences of pollution abatement. Application of the CGE model is a new approach. This study only considered the economic impacts resulting from the health. In fact, CGE model can transparently demonstrate that the mechanisms by which exogenous shocks, such as policies, technology improvements affect the economy with multi-sectoral interactions. As the next step, we are going to simulate the integrated economic impacts of the combination of energy and environmental policies, as well as and health improvement based on the China CGE model.

APPENDIX

I. Life valuation using the human capital approach:

$$L = a \cdot YLL \cdot p \cdot I$$

$$a = Cxe^{-\beta \cdot x}$$

where L: economic loss per death; a: age weight that captures the rising and falling value of individual years of life lived at different ages[59]; YLL: years of life lost; p: productivity weight of age group; (0-14 = 0, 15-44 = 0.75, 45-59 = 0.80, and 60- = 0.10[60]); I: income per worker: Theoretically, GDP per capita is better. However, since separate GDP per capita is not available for urban and rural populations, we estimated the income per worker of urban and rural populations based on the *China Labor Statistical Yearbook*[61] at 9371 yuan for urban populations and 3309 yuan for rural populations; C: adjustment constant whose value is 0.1658; x: age; β: coefficient of age weight whose value of 0.04 is chosen arbitrarily.

II. Functions of the AIM/Material China model

This CGE model can show the situation in which the supply and demand of all commodities including production factors are in equilibrium. Moreover, this model can also reproduce pollution generation, management, and emissions. The AIM/Material model has been used in Japan and India to assess environmental policies[62-63].

The following three equations show the market equilibrium of each commodity listed in Table 5:

$$P_i\{\sum_{j=1}^{m} Y_{ji} - (\sum_{j=1}^{m} X_{ij} + C_i + \sum_{j=1}^{m} I_{ij})\} = 0\ ,\ P_i \geqslant 0 \quad \text{and}$$

$$\sum_{j=1}^{m} Y_{ji} - (\sum_{j=1}^{m} X_{ij} + C_i + \sum_{j=1}^{m} I_{ij}) \geqslant 0$$

where p: price; i: commodity; j: sector; Y: output; X: intermediate input; C: final consumption; I: investment.

These equations mean that the price of commodity i is positive when its demand exceeds its supply, and 0 when its supply exceeds its demand.

The capital and labor markets can also be represented by the following equations:

$$P_k\{K^* - \sum_{j=1}^{m} K_j\} = 0, P_k \geqslant 0, K^* - \sum_{j=1}^{m} K_j \geqslant 0$$

$$P_L\{L^* - \sum_{j=1}^{m} L_j\} = 0, P_L \geqslant 0, L^* - \sum_{j=1}^{m} L_j \geqslant 0$$

where K: capital; L: labor; *: maximum supply.

Moreover, pollution is also treated in the same way as other commodities. That is to say, although pollution can be emitted up to the maximum-allowed target, the price of pollution for emissions exceeding the target, equivalent to the marginal reduction cost, is generated in the following equation:

$$P_w\{W^* - \sum_{j=1}^{m} W_j\} = 0, P_w \geqslant 0,$$

$$W^* - \sum_{j=1}^{m} W_j \geqslant 0$$

where W: pollution; *: maximum allowed emissions; P_w: cost per unit of pollution management.

In order to formulate the CGE model, the activity of each sector should be specified. Each production sector should maintain a balance between its input and output as follows:

$$\sum_{i=1}^{n} P_i X_{ij} + P_k K_j + P_L L_j + P_w W_j = \sum_{i=1}^{n} P_i Y_{ij}$$

On the other hand, the production function is formulated using the Leontief function in order to maintain both monetary and material balance:

$$Y_{ij} = \min\left(\frac{X_{ij}}{m_{ij}}, \frac{\alpha_{0j} K_j^{\alpha_{1j}} L_j^{1-\alpha_{1j}}}{g_j}, \frac{W_j}{w_j}\right)$$

where m, g, w: input coefficients in sector j; α_0, α_1: parameters of production function.

The elasticity of substitution between capital and labor is set to 1 (Cobb-Douglas function). In this model, labor can be moved freely among the sectors, although capital cannot move among them. As for the energy inputs which are parts of *Xij*, the elasticity of substitution is assumed to be infinity. On the other hand, the elasticity of substitution of non-energy commodities is assumed to be 0. Based on small country assumption, international commodity prices are supposed to be fixed. The international price of each commodity is uniform among the scenarios.

The pollution management sector manages pollutants and greenhouse gases as byproducts of economic activities. Once the emissions exceed their upper limit, the relevant environmental tax is charged. The pollution management sector works to lower the marginal cost of pollution reduction. The production function is the same as in the other sectors except for the aggregation of capital and labor using the Leontief function.

The final consumption sector comprises the household sector and the government sector. For the household sector, total income comes from endowed capital and labor. For the government sector, total revenue comes from taxes including the environmental tax for pollution reduction. The total revenue equates to the total expenditure on consumption and investment. The demand function is defined using the Cobb-Douglas function. The final consumption sector aggregating the household and government sectors can be shown by the following equation:

$$H = P_k \sum_{j=1}^{m} K_j + P_L \sum_{j=1}^{m} L_j + P_w \sum_{j=1}^{m} W_j \quad ,$$

$$H = \sum_{i=1}^{n} P_i (C_i + \sum_{j=1}^{m} I_{ij}) \quad \text{and} \quad U = \prod_i Ci^{\beta_i}$$

where H: income; U: aggregated final demand; β i: share of final consumption.

Investment is accumulated into the capital stock in each sector. Each investment is calculated from the expected economic growth in each sector. Technology improvement is embodied based on the capital stock and new investment. That is to say, new technology can affect production activity in proportion to the diffusion of that technology.

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