Health benefits of improving air quality in Taiyuan, China

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\textbf{A B S T R A C T}

Since 2000, the government in Shanxi province has mounted several initiatives and mandated factory shutdowns with the goal of reducing coal burning emissions and the environmental impacts of industrialization. We estimated the health benefits associated with air quality improvement from 2001 to 2010 in Taiyuan, Shanxi Province, using disability-adjusted life years (DALYs) and monetized the health benefits using value of statistical life (VOSL). Data were collected on annual average concentrations of particulate matter less than 10 μm in aerodynamic diameter (PM\textsubscript{10}) and relevant health outcomes in Taiyuan from 2001 to 2010. Selected exposure–response functions were used to calculate the cases of death or disease attributable to PM\textsubscript{10} annually over a 10-year period. These were summed to calculate the DALYs lost and their monetary value associated with PM\textsubscript{10} each year between 2001 and 2010. Air quality improvement from 2001 to 2010 was estimated to have prevented 2810 premature deaths, 951 new cases of chronic bronchitis, 141,457 cases of outpatient visits, 969 cases of emergency-room visits and 31,810 cases of hospital admissions. The DALYs (VOSL) decreased by 56.92% (52.68%) from 52,937 (7274 million Yuan) in 2001 to 22,807 (3442 million Yuan) in 2010. Premature deaths accounted for almost 95% of the total DALYs. Our analysis demonstrates that air pollution abatement during the last decade in Taiyuan has generated substantial health benefits.

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1. Introduction

The World Health Organization (WHO) has identified ambient air pollution as a high priority in its global burden of disease (GBD) initiative, estimating that air pollution is responsible for 1.4% of all deaths and 0.8% of disability-adjusted life years (DALYs) globally (Anon, 2002). Several epidemiological studies have shown that chronic exposure to PM\textsubscript{10} and PM\textsubscript{2.5} increases risk of cardiovascular and respiratory diseases (Zhang et al., 2014), as well as lung cancer (Anon, 2011a; Raaschou-Nielsen et al., 2013).

Taiyuan, the capital of Shanxi Province, is one of the major centers in China for energy production and chemical and metallurgical industries. The production of coal reached about 34 million tons in 2003, accounting for 2.5% of the total coal production in China (Anon, 2004a). The annual coal consumption in Shanxi Province was around 25 million tons in 2003 (Anon, 2004b). From 1978 to 2002, rates of energy consumption grew at a slower rate than GDP in China. However, beginning in 2001 with China’s entry into the World Trade Organization, intense economic development in Taiyuan resulted in deteriorated air quality and increases in air pollutants, such as particulate matter (PM), sulfur dioxide (SO\textsubscript{2}), nitrogen dioxide (NO\textsubscript{2}), carbon monoxide (CO), and ozone (O\textsubscript{3}) (Zhang et al., 2011). Numerous studies have demonstrated that poor air quality adversely impacts human health (Anon, 2011b; Perera et al., 2008; Tang et al., 2006) and causes significant economic loss (Pérez et al., 2009; Ragas et al., 2011). From 2003 to 2005, Shanxi province was home to one of the most polluted cities in China, according to the ranking of the air pollution index documented under the national surveillance of environmental protection (Anon, 2003a). Shanxi province also had very high total energy consumption, and energy intensity of the regional domestic product (RDP) was 2.4 times higher than the national average, contributing to a very low efficiency of energy (Zhang et al., 2011).

Regulations for greater air pollution control were launched in 2003, with implementation of industrial restructuring by the Shanxi Provincial Government (Anon, 2003b). This policy was followed by additional regulations regarding audits to investigate and reduce the consumption of energy and the use and production of toxic and hazardous materials (Anon, 2003b, 2005a). The State Council approved the National Tenth Five-Year Plan for Environmental Protection in 2001, which implemented regulations emphasizing...
both pollution prevention and control with ecological conservation (Zhang and Wen, 2008). Throughout the 10th Five Year Plan period from 2001 to 2006, mainly the cities of Taiyuan, Datong, and Yangquan participated in emission abatement actions through use of clean fuel, district heating, and elimination of some boilers. However, the goals for this period were largely unmet (Anon, 2005a). Therefore, in 2005, the Chinese government set targets for energy efficiency for the 11th Five Year Plan (2006–2010) to reduce energy intensity of the economy by 20%. In 2006, the State Council published a Decision on Strengthening Energy Conservation, which disaggregated provincial energy-saving targets into goals for each city. Starting in November 2006, the Shanxi government made various efforts to reduce air pollution, including issuing government orders, auditing companies with high production of toxic and hazardous materials, and establishing supervision measures for the government’s administrative role in environmental protection. From 2006 to 2010, the Shanxi Provincial Government focused on environmental protection in densely populated areas with more environmental problems, releasing a series of government orders setting pollutant emission standards for coal, thermal power, metallurgical, chemical, coking, construction and paper industries, planning tasks for environmental protection safeguards (Anon, 2006a), and introducing a new energy industrial ground-work to improve resource utilization and reduce pollutant emissions (Anon, 2006b). These orders were implemented the following year. In 2008, the Shanxi government issued a notice of implementation of environmental protection enforcement directed to all levels of government, detailing a comprehensive list of actions to determine the number of industries and the pollutant emissions from each facility, and status of compliance with environmental laws.

Several studies have estimated the health damage due to air pollution both in health and monetary terms (Kan and Chen, 2004; Kan et al., 2004). For example, in Tianjin, China, the total economic cost associated with air pollution was estimated to be US$1.1 billion, about 3.7% of Tianjin’s gross domestic product (GDP) in 2003 (Zhou and Tol, 2005). In Beijing, the economic costs of air pollution-related health effects during the 5 years between 2000 and 2004 were estimated to be between US$1670 million and $3655 million annually, accounting for about 6.5% of Beijing’s GDP each year (Zhang et al., 2007).

DALYs were developed in the 1990s for the Global Burden of Disease (GBD) study. DALYs are a summary “health gap” indicator of the loss of healthy years of life. One DALY indicates one lost healthy year due to premature mortality or disability (Murray and Lopez, 1996a,b). Health gap indicators are additive across a set of disease or injury categories (Mathers et al., 2006). DALYs therefore provide an aggregate measure that integrates all air pollution-related health effects (Yang et al., 2013).

The monetized benefit of reduced mortality risk is captured in the concept of VOSL, which is a summary measure of the willingness-to-pay (WTP) for a mortality risk reduction, and a key input into the calculation of the benefits of policies or projects that affect mortality risk or excess death (Svensson, 2009). The objective of the present study was to estimate the health benefits associated with air quality improvement from 2001 to 2010 in Taiyuan using DALYs and VOSL.

2. Methods

We selected the city of Taiyuan in Shanxi Province as a case study because it is home to numerous industrial enterprises for energy, heavy, and chemical industries. The total population of Taiyuan in 2000 was 3,344 million people, with a population density of 479 person/km². As of 2005, there were 2,570,000 registered citizens of Taiyuan (Anon, 2009). The municipality of Taiyuan is 6988 km². Taiyuan has a forest area of 146,700 ha. and total grassland area of 422.5 km² (Anon, 2007). The birth rate is 8.05 births/1000 people. In 2008, the GDP was 14,680.95 remminbi (RMB) per capita and the average income was 15,230 RMB.

2.1. Air quality

Ambient air pollution consists of a mix of various pollutants (e.g., PM, SO2, NO2, CO, and O3). Because these pollutants are closely correlated, it is impossible to attribute the observed health effects to any one specific pollutant. The problem of “double counting” occurs when the health effects associated with multiple pollutants are summed. Consistent with most previous studies conducted in the developing world, we selected PM as the indicator of the air pollution mixture because numerous epidemiologic studies have demonstrated that PM exerts the most significant adverse health effects among the various pollutants (Pope and Dockery, 2006). PM10 is used in this study instead of PM2.5, as PM2.5 has only recently emerged as a routinely monitored air pollutant in Taiyuan as in most Chinese cities. Therefore much of the retrospective data available are on PM10. The annual average PM10 concentrations used in this analysis represent the average of the levels monitored by all 8 urban stations in Taiyuan, China, including the Jianhe, Jiancaoping, Jinsheng, Nanzhai, Taoyuan, Wucheng, Xiaodian, and Jinyuan districts (Anon, 2009).

2.2. Health outcomes

We selected the health endpoints according to the following criteria: 1) the health outcome had been found in other studies to be significantly associated with particulate air pollution; 2) the corresponding exposure–response coefficient was available in single-pollutant models; 3) the incidence rate in the population was available; and 4) the DALYs and VOSL could be quantified. As others have done to estimate health effects, we relied first on local health data for Taiyuan. If local data were not available for Shanxi Province, national data were used. Specifically, the size of the urban population was drawn from the China Urban Construction Statistical Yearbook (Anon, 2001–2010a), crude mortality rates were taken from the Statistic Bulletin of the National Economy, Social Development in Taiyuan City (Anon, 2001–2010b), incidence rates of chronic bronchitis were obtained from the World Bank (Anon, 2007), outpatient and emergency room visits were obtained from China Health Statistical Yearbooks (Fuhlbrigge et al., 2001), and hospital admission data were obtained from Shanxi Health Yearbooks (Anon, 2001–2010c).

After considerable literature review in this area, data collection was performed by two independent data operators. All input data were double-checked by a third operator.

2.3. Estimation of health effects

To develop estimates of public health impacts of air pollution, we relied on published studies on air pollution and health using concentration–response (C–R) coefficients derived from studies in China and worldwide (Cao et al., 2009; Chen et al., 2010; Jing, 2000; Ma, 1992; Pope et al., 2002). Since most of the epidemiologic studies linking air pollution and health endpoints were based on a relative risk model in the form of Poisson regression, the excess cases at a given concentration C can be given by:

\[ E = \exp(\beta \times (C - C_0)) \times E_0 \]  

(1)

(Zhang et al., 2006a) where C and C0 are the actual concentration and the assumed threshold level, respectively, and E and E0 are the corresponding health effects at concentrations of C and C0. β is the coefficient of the exposure–response (C–R) function between PM10 and the health outcome. E is the product of the size of the exposed population and the incidence rate of a health endpoint.

The national annual standard concentration of PM10 (40 μg/m³) was selected as the annual threshold level as it is the primary standard of the Chinese National Standard. The annual average PM10 concentration (C) was based on air monitoring data from the 8 stations in Taiyuan.
C–R functions of PM$_{10}$ for each selected health endpoint were derived from available epidemiologic studies and were used to quantify the health effects of outdoor air pollution. The C–R coefficients from peer-reviewed Chinese studies (Jing, 2000; Ma, 1992) were preferred whenever they were available. These studies were published in the Chinese Journal of Public Health and Journal of Environment and Health, a core journal in China and the only environmental health professional academic journal, respectively. Therefore, these studies provide reliable data for our selected C–R functions. Further, if there were several studies describing the C–R coefficients for the same health endpoint, we used the combined estimates derived from a simple meta-analysis. Table 1 summarizes the PM$_{10}$ C–R coefficients of the selected health outcomes used in the analysis.

\( E - E_0 \) is the attributable number of cases due to PM$_{10}$. As mentioned, using the number for size of the exposed population, mortality, and incidence rates \((\beta, C, \text{and} C_0)\), we calculated the number of excess cases attributable to PM$_{10}$ in Taiyuan each year from 2001 to 2010.

### 2.4. Estimation of DALYs and VOSL due to ambient air pollution

The adopted approach was recommended by the World Bank (Lvovsky and Maddison, 2000). For mortality due to air pollution, 10 DALYs are attributed to each death (Lvovsky and Maddison, 2000). The morbidity estimates were converted to DALYs as recommended by the World Bank (Lvovsky and Maddison, 2000) (Table 2 provides the conversion factors).

Since there were no data on VOSL in Taiyuan, the value at the national level was obtained from literature in China in 2008, indicating that a life-year-loss associated with air pollution in 2008 was 1.59 million RMB (Xu, 2013). The VOSL is linear to the logarithmic annual per-capita income. We calculated the VOSL of the other years according to the annual per-capita income in the corresponding year, which was obtained from China Urban Life and Price Yearbook (Brunekreef and Holgate, 2002).

### 3. Results

#### 3.1. Health effects due to PM$_{10}$

Taiyuan was found to be one of the most polluted cities in China, which was a result of the outdated industrial plants within the Shanxi Province and the lack of government regulation. As a result, a series of proposals were issued by the local county authorities, as well as city officials in Taiyuan, designating more responsibilities to local jurisdictions to oversee and audit companies for compliance to new laws mandating cleaner production processes. A list of some essential jurisdictions to oversee and audit companies for compliance to new laws was calculated in Taiyuan should encourage the authorities to implement more stringent measures. For example, promotion of centralized heating, renovation of briquette dedicated boilers, and popularization of the use of clean fuel (Table 3).

### 4. Discussion

Ambient air pollution is a severe environmental problem and also a major public health concern in Taiyuan. Taiyuan has been the focus of attention because of its heavy pollution, forcing the government to intervene, which has resulted in improved air quality during the last decade.

Our results suggest that the air quality improvement from 2001 to 2010 resulted in substantial health benefits, avoiding 30,130 DALYs or a 56.92% decrease and 3831 total loss of VOSL or a 52.68% reduction. Reduction of premature deaths accounted for almost all of the decrease.

The substantial health benefits calculated in Taiyuan should encourage the government to intervene, which has resulted in improved air quality during the last decade.

### Table 1

<table>
<thead>
<tr>
<th>Health endpoints</th>
<th>PM$_{10}$ C–R Coefficients</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Premature death</td>
<td>0.0043</td>
<td>Pope et al. (2002)</td>
</tr>
<tr>
<td>Chronic bronchitis</td>
<td>0.0045</td>
<td>Ma (1992)</td>
</tr>
<tr>
<td>Outpatient visit</td>
<td>0.0011</td>
<td>Jing (2000)</td>
</tr>
<tr>
<td>Emergency room visit</td>
<td>0.0001</td>
<td>Cao et al. (2009)</td>
</tr>
<tr>
<td>Hospital admission</td>
<td>0.0018</td>
<td>Chen et al. (2010)</td>
</tr>
</tbody>
</table>

\( \beta \) refers to the increase in the incidence of the respective health endpoints (%) corresponding to a 1 µg/m$^3$ increase in PM$_{10}$.

From 2001–2010, there was a generally decreasing trend in the attributable number of cases due to PM$_{10}$ in Taiyuan. In 2001, it was estimated that the health loss associated with PM$_{10}$ in Taiyuan included 4948 premature deaths, 1786 new cases of chronic bronchitis, 275,292 cases of outpatient visits, 1798 cases of emergency-room visits, and 46,247 cases of total hospital admissions. In 2010, the estimates decreased to 2138 premature deaths, 835 new cases of chronic bronchitis, 133,835 cases of outpatient visits, 829 cases of emergency-room visits, and 14,437 cases of total hospital admissions. It should be noted that the size of the exposed population and the crude mortality rates might vary by year, affecting the annual effect estimates of air pollution. The higher mortality rates in 2003 and 2009 were likely due to the SARS epidemic (Koplan et al., 2013; Qin et al., 2005) and the H1N1 pandemic (Dawood et al., 2012; Yang et al., 2012; Yu et al., 2013), respectively, and contributed to the higher estimates of deaths and cases of illness in 2004 and 2009.

### Table 2

<table>
<thead>
<tr>
<th>Health Endpoints</th>
<th>DALYs per 10,000 cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Premature death</td>
<td>100,000</td>
</tr>
<tr>
<td>Chronic bronchitis</td>
<td>12,037</td>
</tr>
<tr>
<td>Outpatient visit</td>
<td>3</td>
</tr>
<tr>
<td>Emergency room visit</td>
<td>3</td>
</tr>
<tr>
<td>Hospital admission</td>
<td>264</td>
</tr>
</tbody>
</table>

Using the unit values (described in detail in Table 1) and quantified health effects, we computed the corresponding annual DALYs over the ten-year period (Table 4). Total DALYs as shown in Table 4 are the product of unit values described in Table 2 and the attributed cases from Table 3.

The total DALYs associated with air pollution in Taiyuan was 52,937 in 2001 and 22,807 in 2010. Among all health consequences, premature deaths predominated in the value of the total DALYs, accounting for almost 95% of the total loss. Total DALYs from air pollution revealed a generally decreasing trend from the year 2001 to 2010.

The VOSL was 1.59 million RMB (Xu, 2013) and the annual per-capita income was 16,299 RMB in 2008 (Anon, 2011c), and the logarithmic coefficient was 2.65 \(\log(16,299/1.59)\). The VOSLs for the other years were calculated based on the logarithmic coefficient and the average annual income (Ashida et al., 1986). The total VOSL loss was the product of the death toll and the VOSL (Table 5).
coal-fired boilers, built 6 km² coal-free areas, and renovated and modified almost 400 boilers to burn clean fuel (Anon, 2006c). According to government reports, 12 industrial sources of pollution were shut down in 2005 to a cumulative 121 closures by 2012. Increasing the charge rates for emissions is another approach that has been shown to be effective in reducing air pollution in some regions of China (Wang, 1999, 2004). Our findings indicate that substantial health benefits could be expected as air pollution levels are further decreased, encouraging even more aggressive air pollution control programs in Taiyuan and in other regions of China.

The DALYs approach has a strong methodological framework and a firm theoretical grounding. It has been widely accepted by public health experts and employed to measure the global and regional burdens of disease (Murray and Lopez, 1997). As a summary measure of population health, the impact of air pollution in terms of DALYs has the advantage of direct comparison with the overall impact of disease in various countries and cities, as well as with diseases from other major environmental problems. As such, the WHO and World Bank have taken DALYs as a standard measure of the burden of disease in China. Yang and colleagues conducted an analysis comparing China against other G20 countries using the results of the Global Burden of Diseases, Injuries and Risk Factors Study 2010 (Yang et al., 2013). Two sources of particulate matter, ambient air pollution and household air pollution, respectively, ranked fourth and fifth in terms of DALY rate in 2010. In China, between 1990 and 2010, the number of years of life lost (YLLs) attributable to neonatal causes, diarrhea, pneumonia and communicable diseases in children declined dramatically, instead moving towards cardiovascular and cancer YLLs at older ages. A previous study has also looked specifically on the effect of ambient air pollution on human health and calculated that DALYs lost for Shanghai in 2000 were 103,064 (Zhang et al., 2006b). As in the present study, the predominant factors contributing to total DALYs lost were premature deaths and chronic bronchitis.

<table>
<thead>
<tr>
<th>Time</th>
<th>Title</th>
<th>Summary</th>
<th>Pollution Sources Closed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>Regulations for the Implementation of Clean Production Audit in Shanxi Province Shanxi Economic Resource Issue[2005] NO.75</td>
<td>• Audit high energy consumption, high material consumption, high pollutions, and proposes to reduce the use and production of toxic and hazardous materials; reduce energy consumption; material waste and junk productions. • Select technologically, financially and environmentally feasible clean production plan and processes • Promotes clean production among enterprises, opens the door for recycling economy in Shanxi Province.</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Implementation Plan For Shanxi Industrial Pollution Sources To Fully Comply with Waste Emission Standards Shanxi Environmental Dept Issue[2005]No. 90</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>&quot;Desulphurization notice&quot; Shanxi People’s Government</td>
<td>• Establish flue gas desulfurization (FGD) and install online monitoring systems for set number of coal-fired power plants by the end of 2007.</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Timeline of Shanxi Province Environmental Policy Summary from 2003–2008.
<table>
<thead>
<tr>
<th>Year</th>
<th>Document Title</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>&quot;Implementation Opinions on Accelerating the Desulphurization in Coal-Fired Power Plants&quot; General Office of Shanxi People’s Government (The Opinions)</td>
<td>Complete FGD construction in existing power plants. Install FGD in new power plants. Construction was accelerated by using incentive policies.</td>
</tr>
<tr>
<td></td>
<td>Shanxi Provincial People’s Government on the Implemental Decision of Blue Sky and Green Water Project Shanxi Government Issue (2006)No. 15</td>
<td>Implement “blue sky and green water project” in densely populated areas with concentrated industry and more advanced economy and environmental problems. This project marks the beginning of new environmental protection policies in Shanxi Province.</td>
</tr>
<tr>
<td></td>
<td>Solution To Shanxi Provincial Key Industrial Pollution Sources Shanxi Provincial People’s Government Order Number 189</td>
<td>Administrative order proposing solutions for key industrial pollution sources in a systematic and comprehensive way. Aims to achieve standards set for pollutant emissions, and references key industrial pollution sources such as coal, thermal power, metallurgical, chemical, coking, construction, and paper industries.</td>
</tr>
<tr>
<td></td>
<td>“The Control Measures to Pollution Sources from Key Industries (The Measure)” by Shanxi Provincial Government</td>
<td>Phased out production facilities with high energy consumption, heavy pollution and outdated technology. All key industries should install cleaning devices to meet emission standard by 2008 and implement emission permit system and an environmental impact assessment system.</td>
</tr>
</tbody>
</table>

Fig. 1 (continued)
<table>
<thead>
<tr>
<th>Year</th>
<th>Document Title</th>
<th>Key Points</th>
<th>Page</th>
</tr>
</thead>
</table>
• Link party and government official’s political performance to their environmental protection work  
• Puts responsibility of environmental protection, performance assessment, accountability and veto system outside of local authorities. | 2    |
|      | Shanxi Province Key Industrial Pollution Supervision Rules Shanxi Provincial People’s Congress Standing Committee Notice | • Law clearly stating supervision measures for key industrial pollution sources within Shanxi Provincial government.  
• Clearly set up supervisions for government’s administrative role in environmental protection  
• Places regional, corporate restrictions into local legislative system  
• Give environmental department the right for deadline management  
• States the public’s rights to environmental protection, specifically their rights to know, participate and supervise environmental protection.  
• Implement mandatory removal or relocation decisions in areas which need special protection.  
• Establish compensation rules, regulations for joint environmental protection enforcement and administrative penalties for illegal production. |      |
| 2008 | Notice Of Further Strengthening Work On Pollution Reduction Shanxi Government Letter (2008) | From completion of city sewage treatment plant and associated pipeline network construction to speed up constructions of coke oven gas desulphurization program, and increase efforts in shutting down illegal plants, the notice will further strengthening Shanxi’s pollution reduction efforts. | 78   |
|      | Notice of Implementation of Environmental Protection Enforcement In Key Polluted Areas Shanxi Environmental Department Issue (2008) No. 126 | Requires provincial-wide government at all levels to implement all-round industrial pollution clean-up within their jurisdictions.  
• Comprehensive count of the total number of industries and enterprises, their key facilities for pollution preventions and facility performances, conditions of main pollutant emissions, and compliance status of environmental laws and regulations.  
• Performance inspections on the construction and operation of sewage/garbage treatment plants.  
• County (city) authorities to classify industrial pollution source based on actual local situations, and request classification and disposal of industrial pollutions from each enterprises within their jurisdictions. |      |

Fig. 1 (continued).
A previous study model indicating that the negative health impacts of PM are much greater than those of other air pollutants (Ragas et al., 2011). This suggests that maximum health gains can be realized by future policies focusing on reducing PM emissions. Additional studies estimating DALYs in the United States from sources of indoor air pollutants found PM$_{2.5}$ contributed heavily to annual health impacts (Logue et al., 2012). Despite large uncertainty in the DALYs estimates, the impact of chronic exposure to PM$_{2.5}$ emitted by both indoor and outdoor sources is significant (Logue et al., 2012).

The limitations of our analysis should be noted. First, exposure measurement errors could not be excluded when the monitoring results were averaged across various stations as the proxy for the exposure level of general population. Second, PM$_{2.5}$ is known to be a more biologically relevant and a better predictor of health outcomes than PM$_{10}$, due to the ability of fine particles to penetrate deeper into the airways (Anon, 2003c). However, as there were few routine measurements of PM$_{2.5}$, we were not able to analyze the health benefits in relation to PM$_{2.5}$ in Taiyuan. Third, we selected only a few health outcomes that could be quantitatively estimated and translated into monetary values, as shown in Table 5 (Lvovsky and Maddison, 2000). Therefore underestimation was inevitable as outcomes such as restricted activity, anxiety and depression, cancer, neuropsychiatric disorders, and cardiovascular disease were not considered. Lastly, as noted, the size of the exposed population and the crude mortality rates might vary year to year, causing the estimated annual impacts to fluctuate.

As a health impact assessment, this study presents the impact of a decade of various environmental policies that is consistent with previous studies conducted in China. This also confirms changing health trends from previous years as a result of pollution. Furthermore, using DALYs from PM$_{2.5}$ as a summary measure of population health parallel to policies directly mitigating emission sources displays evidence of a direct health and cost benefit with strong public health policy implications.

5. Conclusion

This analysis provides evidence that air pollution abatement during a very recent decade in Taiyuan resulted in substantial health benefits to public health. The study’s findings support even greater air pollution control in Taiyuan to meet the health-based air quality standards. Our results are also useful for further cost–benefit analyses of air pollution management programs in Taiyuan and elsewhere.

Acknowledgments

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