Journal of Cleaner Production 172 (2018) 743–757

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

How harmful is air pollution to economic development? New evidence from $PM_{2.5}$ concentrations of Chinese cities

Yu Hao [a, b, c, d, e, *, 1], Hui Peng [a, b], T. Temulun [b, i, 1], Li-Qun Liu [b], Jie Mao [b], Zhi-Nan Lu [f, g], Hao Chen [a, b, d, e, h]

[a] Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing 100081, China
[b] School of Management and Economics, Beijing Institute of Technology, Beijing 100081, China
[c] Sustainable Development Research Institute for Economy and Society of Beijing, Beijing 100081, China
[d] Collaborative Innovation Center of Electric Vehicles in Beijing, Beijing 100081, China
[e] Beijing Key Lab of Energy Economics and Environmental Management, Beijing 100081, China
[f] Thrombosis and Vascular Medicine Center, State Key Laboratory of Cardiovascular Disease, Fuwai Hospital, Chinese Academy of Medical Sciences and Peking Union Medical College, Beijing, 100037, China
[g] Cardiology Department, Centro Hospitalar Conde de São Januário, Macao 999078, China
[h] Energy Policy Research Group (EPRG), Cambridge Judge Business School, University of Cambridge, Trumpington Street, Cambridge CB2 1AG, UK
[i] Centro de Estudios Monetarios y Financieros (CEMFI), Madrid 28014, Spain

ARTICLE INFO

Article history:
Received 13 March 2017
Received in revised form
7 September 2017
Accepted 18 October 2017
Available online 1 November 2017

Keywords:
Air pollution
$PM_{2.5}$ concentrations
Economic development
Simultaneous equations model
Chinese cities

ABSTRACT

In recent years, haze pollution has frequently shrouded most regions of northern and eastern China. Air pollution has drawn increasing attention at home and abroad. However, the potential negative impacts of environmental pollution on economic development have long been ignored. Considering the possible effect of economic growth on environmental pollution, the conventional ordinary least squares (OLS) estimation may suffer from endogeneity biases caused by possible bilateral causality. In this paper, using city-level panel data for the period between 2013 and 2015, the influence of $PM_{2.5}$ concentrations on per capita GDP is estimated through a carefully designed simultaneous equations model for the first time. To control for fixed effects, a series of time dummies and region dummies are also introduced. The estimation results indicate that haze pollution indeed has a significantly negative impact on economic development. On average, as of 2015, when other conditions are equal, an increase of 5 $\mu g/m^3$ in $PM_{2.5}$ concentrations may cause a decrease of approximately 2500 yuan in GDP per capita. In addition, the results suggest that sustainable economic growth may help reduce $PM_{2.5}$ concentrations, which in turn benefits economic development.

1. Introduction

Ever since the beginning of the “reform and opening up”, China's economy has been growing at a breakneck pace. However, at the same time, China's environmental quality has deteriorated remarkably, particularly evident by the notorious haze pollution that has occurred frequently in many northern and eastern regions of China in recent years. In other words, there seems to be a tradeoff between economic growth and the deterioration of environment, which can also be observed in many developing countries and newly industrialized countries. On one hand, economic growth puts pressure on the environment inevitably due to an increasing population, industrialization and dynamic economic activities. On the other hand, the environment may have a feedback effect on social-economic activities (Lopez, 1994; Pao and Tsai, 2010; Azam, 2016). Specifically, Lopez (1994) treated the environment as an important input factor of production, whereas Azam (2016) explicitly explored and verified the negative effects of environmental deterioration on economic development using multinational panel data. In recent years, air pollution has become increasingly serious and drawn more and more attention in many

* Corresponding author. Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing 100081, China.

E-mail addresses: haoyuking@gmail.com, haoyuking@bit.edu.cn (Y. Hao), 1071800038@qq.com (H. Peng), temulun_b612@163.com (T. Temulun), adallq@163.com (L.-Q. Liu), maoj94@126.com (J. Mao), lzn1982hy@163.com (Z.-N. Lu), Chenhao9133@126.com (H. Chen).

[1] These authors contributed equally to this study and share first authorship.

https://doi.org/10.1016/j.jclepro.2017.10.195
0959-6526/

developing countries, such as the so-called BRICS, which is the acronym for an association of five major developing countries with relatively rapid economic growth rates in recent years: Brazil, Russia, India, China and South Africa. As for China, haze pollution, of which the main component is fine particles (i.e., $PM_{2.5}$), has posed a great threat to residents' health and even sustainable economic development. Some studies have investigated the causes of haze in China. For instance, Li and Zhang (2014) found that excluding meteorological conditions, an unsustainable economic development model plays an important role in the formation of haze pollution. Weather and meteorological conditions to a great extent affect air quality (Yang et al., 2017). Moreover, there is evidence that the concentrations of $PM_{2.5}$ in many northern Chinese cities apparently have seasonal patterns: the concentrations tend to be higher in the winter due to household heating, whereas the concentrations are generally lower in the summer when coal consumption is considerably lower. Specifically, because China's economic development heavily relies on the consumption of fossil energy, especially coal, pollutant emissions have ballooned as the economy has boosted (Hao et al., 2015). In addition, automobile exhaust contributes significantly to the formation of haze (Zheng et al., 2005; Wang et al., 2006). The total number of private cars has reached 172 million by 2015, and in some large cities such as Beijing, Shanghai, Shenzhen and Tianjin, the number exceeded 2 million.

Maintaining the sustainability of economic growth is a large challenge to many emerging countries. Some early studies have noted that environmental deterioration may limit or even reduce economic activities (Barbier, 1994; Pearce and Warford, 1993). Literally speaking, pollution may affect economic development directly and indirectly through its influences on public health and productivity. For instance, there has been evidence that air pollution is directly associated with respiratory and cardiovascular diseases, such as lung cancer (Tie et al., 2009) and asthma (Neidell, 2004). Among the various types of air pollutants, particulate matters receive special attention because they are the main contents of haze pollution, which has recently appeared in may northern and eastern areas of China, including the Chinese capital city of Beijing and the most economically prosperous megacity of Shanghai. Some studies have found that haze pollution is negatively linked to respiratory and cardiopulmonary diseases (Pope et al., 2002; Dockery and Pope, 1994). Additionally, the findings of some research indicate that exposure to a certain level of $PM_{2.5}$ concentrations is significantly associated with mortality in the long run (Dockery et al., 1993; Pope et al., 1995; Jerrett et al., 2005) and even in the short run (Din et al., 2013). Using data from European and American cities indicates, some researchers also found that the mortality rate rises remarkably when human beings are exposed to PM_{10} for 24 h (Katsouyanni et al., 2001; Samet et al., 2000). Another study indicates that Asian cities also report an increase in the rate of mortality when PM_{10} concentrations are higher (HEI International Oversight Committee, 2004).

As for China, in recent years, haze pollution has become increasingly severe and drawn broad attention at home and abroad. Currently, air pollution is no longer a problem for certain cities or regions but a national issue. According to the annual Air Quality Guideline of World Health Organization (WHO), the safe threshold values are10 $\mu g/m^3$ and 20 $\mu g/m^3$ for the annual mean $PM_{2.5}$ and PM_{10} concentrations, respectively (WHO, 2006). However, in 2015, in only 1 out of 367 Chinese cities (i.e., Nyingchi City in Tibet) was the air quality good enough, with the concentrations of $PM_{2.5}$ and PM_{10} being below the safe threshold values suggested by the WHO. Even if the standard is relaxed to the 24-h mean of $PM_{2.5}$ (25 $\mu g/m^3$), only 25 of all 367 cities were qualified in terms of air quality in 2015. As shown in Fig. 1, the majority of the 147 cities that reported urban air quality in 2014 had $PM_{2.5}$ concentrations higher than 49 $\mu g/m^3$, which is approximately twice as high as the WHO guidelines. Fig. 1 indicates a clear pattern for China's haze pollution: the cities in the Beijing-Tianjin-Hebei region (including Megacities of Beijing and Tianjin and Hebei province) suffer from the most serious air pollution, the $PM_{2.5}$ concentrations in the Yangtze River Delta region (including Shanghai, Jiangsu and Zhejiang) are also substantially high, and southern China (e.g., Guangxi, Guangdong and Hainan) has fairly good air quality (although the $PM_{2.5}$ concentrations of the cities in south China are still considerably higher than the WHO's safety standard). Compared with other countries, China's $PM_{2.5}$ pollution is also very significant. Fig. 2 depicts the average $PM_{2.5}$ concentrations in 2008 and 2014 and corresponding average annual growth rates in seven developed countries and Poland, which is also a transition economy and has a similar per capita GDP as China. As shown in Table 2, China had the highest $PM_{2.5}$ concentrations in both 2008 and 2014, and the gap in $PM_{2.5}$ concentrations between China and the selected developed countries is considerable. Even compared with Poland, China is much more polluted. In 2008, China's $PM_{2.5}$ concentrations were 1.6 times Poland's level, and this ratio rose to 2.3 in 2014. Moreover, except Canada (for which the $PM_{2.5}$ concentrations growth rate was very near zero), China is the only country seeing a positive growth rate during this period.

Extant studies have pointed out that health conditions may influence family income (Smith, 1999) and therefore may further affect residents' affordability of quality health care. Moreover, almost all socio-economic activities are restricted or limited when there is haze pollution. For instance, schools may have to be suspended and factories may need to stop manufacturing.[2] The forced restrictions on socio-economic activities may affect the amount of time invested in economic activities and therefore social wealth and residents' income. Besides, a number of rich and middle-class Chinese have been moving away from or seriously considering to leave the serious polluted cities in China, which may cause the capital outflow and brain drain and eventually damage local economic growth (Graff Zivin and Neidell, 2013).[3] In summary, haze pollution not only does harm to human beings but also has serious negative impacts on the sustainable development of China's economy.[4] Some recent studies have evaluated the health damage and corresponding economic costs of air pollution in China (Zhang et al., 2007; Hou et al., 2010; Huang et al., 2012; Matus et al., 2012; Chen et al., 2017). Using different approaches, the existing estimations indicate that the economic loss incurred by air pollution through its negative effects on public health was considerably high and accounted for at least 0.7% of GDP. Therefore, it is high time to curb haze pollution and reverse its unfavorable growing trend. In fact, the Chinese government has already taken some initial steps to control the emission of air pollutants, especially $PM_{2.5}$. According to the 13th Five-Year Plan (2016–2020), the average concentrations of

[2] For more information on the restrained social-economic activities when there is haze pollution, one can refer to a series of media reports, including http://edition.cnn.com/2015/12/07/asia/china-beijing-pollution-red-alert/(accessed 07/08/2017).

[3] Recently there have been a growing number of media reports about the phenomenon that China's environmental pollution has begun to drive high-quality labor force and rich people to less polluted areas or leave China entirely. For instance, one could refer to http://www.nytimes.com/2013/11/23/world/asia/urbanites-flee-chinas-smog-for-blue-skies.html?pagewanted=all and http://www.atimes.com/article/housing-education-immigration-healthcare-how-does-smog-alter-chinese-lifestyles/(accessed 07/08/2017).

[4] There has been some anecdotal evidence for the harm of air pollution to residents' health and economic growth in China. For instance, one can refer to http://www.abc.net.au/news/2016-02-09/beijing's-air-quality-improving-but-not-without-cost/7146360 and http://www.cfr.org/china/chinas-environmental-crisis/p12608 (accessed 07/08/2017).

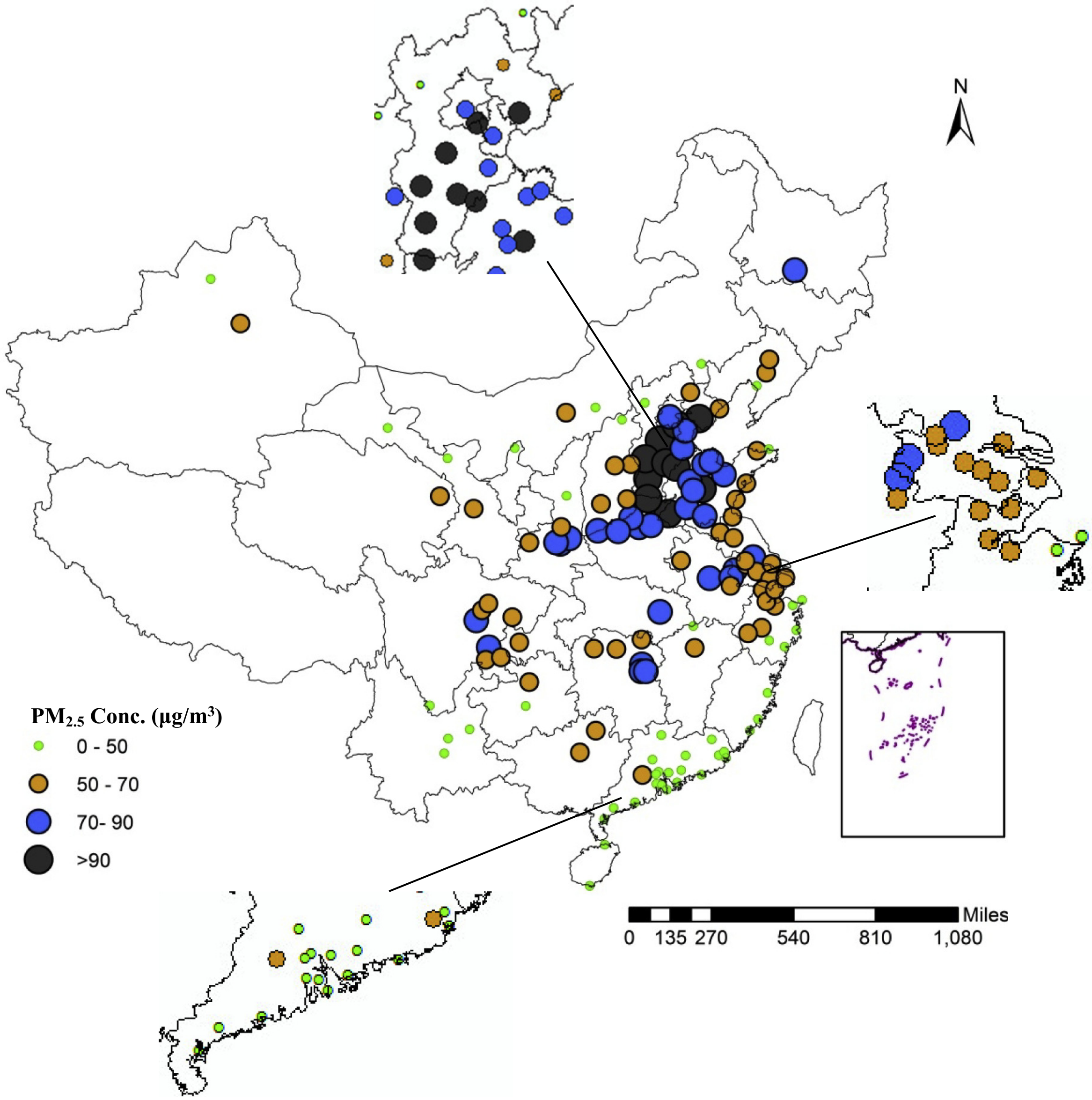

Fig. 1. Annual average $PM_{2.5}$ concentrations of 147 monitored Chinese cities in 2014.

$PM_{2.5}$ should be cut by 25%. Additionally, China has pledged to reduce the use of coal by setting a cap and promoting the development of renewable and sustainable energy. However, there are still some doubts on the actual effects of government policies and regulations. Now a large open question is whether the Chinese environmental policy is merely a type of green-washing on an epic scale or whether economic repercussions exist (Hering and Poncet, 2014).

So far, a growing body of literature has already examined the impacts of economic development on the environment, with many utilizing the Environmental Kuznets Curve (EKC) model as the main empirical framework. The EKC model describes an inverted-U pattern in the correlation between environmental quality and economic growth: pollution may first increase to a peak and then decrease with continuous economic growth. After the pioneer works of Grossman and Krueger (1991, 1995), a series of literature emerged later on (e.g., Selden and Song, 1994; Suri and Chapman, 1998; Torras and Boyce, 1998; Barrett and Graddy, 2000). As Tiba and Omri (2017) summarized, various types of pollutants, including emissions and/or concentrations of air and water pollutants and solid waste, have been utilized as indicators of the environment in the research on the EKC. However, the results of previous empirical studies are highly controversial, and no conclusion on whether the EKC exists has yet been drawn. As for the indices for air quality, including SO_2, suspended particulate matters (SPM, especially $PM_{2.5}$ and PM_{10}), Carbon dioxide and Nitrogen dioxide, there is some evidence that the inverted U-shaped EKC exists (e.g., Shafik and Bandyopadhyay, 1992; Selden and Song, 1994; Holtz-Eakin and Selden, 1995; Ang, 2007). However, some other studies have concluded that the relationship between air pollution and GDP per capita is N-shaped (Friedl and Getzner, 2003) or monotonically increasing (Holtz-Eakin and Selden, 1995).

The influence of environmental performance on economic development and the potential EKC relationship suggest that the synthesized relationship between environmental quality and economic development might be bilateral. As a result, the conventional OLS estimation might suffer from the endogeneity caused by possible bilateral causality between economic development and

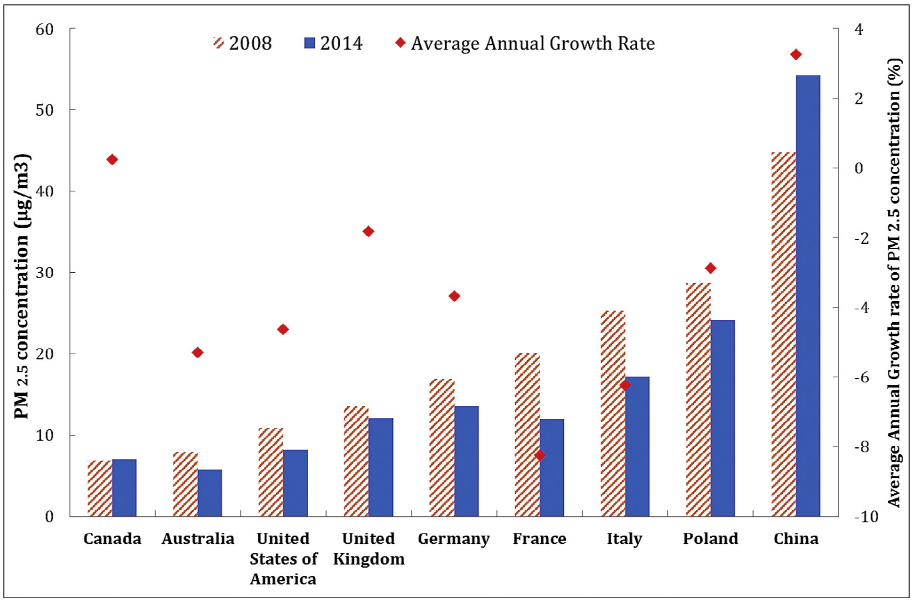

Fig. 2. Average $PM_{2.5}$ concentrations and corresponding average annual growth rates in selected countries between 2008 and 2014. *Notes*: The average $PM_{2.5}$ concentrations in all the countries except China for both 2008 and 2014 and in China in 2014 are collected from the World Health Organization (WHO) database (available at http://www.who.int/gho/phe/outdoor_air_pollution/en/). Average $PM_{2.5}$ concentrations in China in 2008 are calculated by taking the average of 112 cities' data, which are converted from PM_{10} concentrations, because $PM_{2.5}$ concentrations have been regularly reported only since 2013. The conversion ratios between $PM_{2.5}$ and PM_{10} are taken from Table 1 of Mu and Zhang's (2015) study.

environment, which may yield biased estimation results (Stern, 2004; Tiba and Omri, 2017). On one hand, pollution negatively affects economic growth through its impacts on residents' health and/or working ability (Graff Zivin and Neidell, 2012; Din et al., 2013; Hanna and Oliva, 2015); on the other hand, economic growth makes it possible to find various feasible solutions to solve environmental problems and improve environmental quality, as the EKC implies. To control for the potential endogeneity, some specific estimation methods should be employed, such as the simultaneous equations model (SEM). The instrumental variable (IV) method is a traditional and commonly utilized methodology to handle endogeneity (Wooldridge, 2016). However, because in practice, it is not easy to find the appropriate instrumental variables, the use of IV method is to some extent constrained. So far, there have been a number of studies that utilize simultaneous equations to investigate the relationship between economic growth and environmental quality. For example, in a recent study, Omri (2013) conducted an empirical study using the SEM to find the existence of bilateral causality between economic growth and CO_2 emissions, as well as between energy consumption and economic growth. Tiba and Omri (2017) conducted a synthesized review on the relationships between energy, environment and economic growth covering the period between 1978 and 2014. More works on the causality between environment and economic development can be found in this distinguished review paper.

Despite the rapid growth of literature on the relationship between environmental performance and economic development, few studies have focused on air pollution, especially the haze pollution that troubles many developing countries and regions currently. So far, there have been only a few studies that have attempted to investigate the association between haze pollution and economic growth. For instance, Hung and Shaw (2004) applied a simultaneous approach to examine the bilateral causality between per capita income and various air pollutant emissions in Taiwan. Hao and Liu (2016) investigated the existence of the EKC for $PM_{2.5}$ concentrations in Chinese cities using spatial econometric models. Using provincial panel data, Xu and Lin (2016) analyzed the influential factors of $PM_{2.5}$ emissions at the regional level in China. Their estimation results indicate that economic growth was a decisive factor of $PM_{2.5}$ emissions during the sample period 2001–2012. Wang et al. (2016a) investigated public environment awareness of air pollution and its relationship with smog prevention in China. They found that approximately 60% of the respondents interviewed would like to support activities for coping with smog, and the ratios of the respondents who would practice to use public transportation and use energy saving appliances are 77.67% and 72.74%, respectively. In a similar study, Sun et al. (2016) conducted a survey for Chinese citizens and found that the average amount of willingness to pay is 382.6RMB per person per year. Given that haze pollution has become so serious in China that air pollution severely threatens China's sustainable development and the construction of a harmonious society, this study explores how and to what extent haze pollution affects China's economic growth. A carefully designed SEM is employed to control for potential endogeneity.

Therefore, the main contribution of this study is threefold. First, this study extents the research on the economic cost of environmental pollution to the Chinese context using structural models (simultaneous equations) and indicators of air pollution concentration. The utilization of the structural models is appropriate because the macro data are utilized in this study. Moreover, SEM is used to handle with potential endogeneity that may be caused by bilateral causality. Second, this study investigates the economic consequences of $PM_{2.5}$ concentration, which is a status variable. Abundant works have examined the relationship between economic growth and the emissions of various pollutants such as SO_2 and CO_2 (e.g., Selden and Song, 1994; Holtz-Eakin and Selden, 1995; Song et al., 2008; Kang et al., 2016). It should be noted that the pollutant emissions are process variables. Comparatively, the status variables (pollutant concentrations) are better indicators for the environmental quality than process variables (pollutant emissions), because higher emissions do not definitely lead to higher concentrations due to differences in geographic location characteristics and atmospheric conditions. Furthermore, during the 13th "Five-Year Plan" period, China's environmental protection strategies have been shifted from merely focusing on total emissions control that is related to the process variable of emissions to dual foci on both environmental quality targets (status variables) and total emissions targets. As such, the estimation results using status variables have important policy implications. Third, the most recent monitor data of urban $PM_{2.5}$ concentrations are utilized to highlight the impacts of air pollution on economic development. Given that air pollution, especially haze pollution, has become increasingly significant in many cities of China in recent years, the utilization of urban $PM_{2.5}$ concentrations could give some hints to the policymakers for judging and weighing the costs and benefits of dealing with this most urgent environmental problem in China nowadays. In a recent influential study, Li et al. (2017) stressed that Chinese government's environmental regulations may effectively reduce pollutant emissions and therefore sufficiently improve air quality. One important reason for the ignorance of the complicated relationship between air quality and emissions in previous literature is lack of data, since city-level monitor data of $PM_{2.5}$ concentrations were unavailable before 2013. In this regard, this study draws a full picture on the interplay between air pollution and economic development by eliminating the endogeneity bias.

The rest of the paper is organized as follows. Section 2 describes the econometric methodology. Section 3 illustrates the source of the data and gives the specific description of variables. Section 4 analyzes the empirical findings. Section 5 concludes this paper and puts forward concerns about the future.

2. Methodology

As emphasized in the previous section, the main purpose of this research is to evaluate the negative influences of haze pollution on China's economic growth. To achieve this purpose, the appropriate regression models are conducted and estimated. To address the potential endogeneity problem from which single-equation models may suffer, a simultaneous equations model is utilized.

2.1. Economic growth model

In this study, the level of economic development is measured by GDP per capita. To gauge the economic impacts of haze pollution, the level of $PM_{2.5}$ concentrations is simply introduced as an explanatory variable. Considering the specific features of China's economy, three important influential factors of China's economic development are introduced as explanatory variables: Foreign Direct Investment (FDI) per capita (lfdiperc), investment in fixed assets per capita (lfixed) and trade openness (openness), which is measured as the ratio of the sum of exports and imports to GDP. Following the settings of the neoclassical growth framework utilized frequently in economic growth literature such as Solow (1956) and Mankiw et al. (1992), the production function is assumed to be Cobb-Douglass style. Therefore, after taking logarithm for both sides, the production function would be turned into the linear logarithmic form as shown in Eq. (1). It is noteworthy that using the logarithmic form of the variables means the estimated coefficients are essentially elasticities of the dependent variable compared with the corresponding explanatory variables (i.e., how many percentages will the dependent variable change in response to a change in the corresponding explanatory variables by one percentage). In addition, FDI per capita and investment in fixed assets per capita are both in logarithmic form to reduce the impacts of potential heteroscedasticity.

$$\mathrm{lgdpperc} = \beta_0 + \beta_1 \mathrm{lpm25} + \beta_2 \mathrm{fdiperc} + \beta_3 \mathrm{openness} + \beta_4 \mathrm{lfixed} + \mathrm{u} \tag{1}$$

The control variables utilized in Eq. (1) are as follows:

2.1.1. FDI

Some researchers have already verified that FDI has a positive impact on economic growth (Alfaro et al., 2004; Li and Liu, 2005; Yao, 2006). In addition, it has also been found that some other factors, including human capital, may positively influence on economic growth through the impact of FDI (Li and Liu, 2005). Additionally, adopting foreign technology promotes FDI growth and economic growth (Borensztein et al., 1998). However, the difference in the match of technology and human capital in different countries suggests that the positive link between FDI and economic growth is conditional and may vary under different environments (Borensztein et al., 1998).

2.1.2. Trade openness

Measured by exports and imports, trade openness is linked to economic growth because exports are a part of the calculation of GDP. Generally speaking, trade openness contributes positively to economic growth (Harrison, 1996; Frankel and Romer, 1999). In contrast, as Yanikkaya (2003) noted, although in some developing countries there are still various types of trade barriers, of which the purpose is to protect domestic industries and restrict international trade, the effects of the barriers on economic growth might still be positive. Therefore, the net effect of trade openness on economic development requires further investigation.

2.1.3. Fixed asset investment

Investment, especially fixed asset investment, plays a very important role in China's development. Since the mid-1990s, the ratio of investment to GDP has been steadily approximately 50%. Some previous studies have also found evidence of positive contributions of China's investment on GDP growth (e.g., Chow and Lin, 2002). Therefore, per capita fixed asset investment is introduced as another explanatory variable to capture the effects of this growth engine of China's economy.

To eliminate the population effect, per capita values of FDI and fixed asset investment are utilized. It is noteworthy that there might be other influential factors of GDP per capita, including culture, living habits and customs. Because these factors are difficult to be measured quantitatively, and also because the economic theory and extant studies suggest that the most important variables that may influence China's economic development are fixed asset investment, FDI and foreign trade (e.g., Chow, 1993; Liu et al., 2002; Tang et al., 2008), therefore the other potential influential factors are included and reflected in the residual term u (Wooldridge, 2016). As shown later in the empirical study section, the estimation results for Eq. (1) are basically consistent and in line with theory and previous relevant studies no matter when single-equation or simultaneous equation model (SEM) are estimated. As a result, the explanatory variables explicitly appeared in Eq. (1) should be the most important influential factors of GDP per capita, and the estimation results are quite robust.

2.2. Regression model for the economic and social determinants of $PM_{2.5}$ concentrations

As interpreted previously, the EKC Model is commonly utilized to describe the relationship between environmental quality and economic development. Following previous studies on the EKC, such as Selden and Song (1994) and Song et al. (2008), quadratic and cubic forms of the $PM_{2.5}$ concentrations are introduced to capture the possible nonlinear relationship between haze pollution and economic development. Specifically, the cubic form is included to allow multiple turning points (Song et al., 2008).

Despite the growing body of literature on the empirical studies of EKC relationship, the theoretical explanations for the existence of EKC are still scarce. The Green Solow Model (GSM) developed by Brock and Taylor (2005, 2010) is a prominent exception. GSM is literally a neoclassical framework that incorporates the textbook Solow (1956) model with exogenous pollutant emissions as a byproduct of the production process. According to GSM, there are two opposing impacts on the pollutant emissions: the economic growth contributes to the increase in the emissions generated in the production, while the technology progress in abatement and the investment on environmental protection would reduce emissions. The dynamics of the environmental quality depends on the relative strengths of these two opposing impacts, and the inverted-U shaped EKC exists only when the effect of reduction in emissions eventually overwhelms the effect of increasing emissions led by economic growth. Hao and Wei (2015) verified that GSM is valid for China and there would be a turning point in CO_2 emissions. As a result, in this study the EKC style equation that describes the inverted-U shaped relationship between $PM_{2.5}$ concentrations and GDP per capita is based on the GSM framework.

Previous studies have verified that there are various sources of haze pollution. For example, Sun et al. (2006) noted that human beings' activities are primarily responsible for the formation of haze pollution. In another study, using data from southern city of Guangzhou, Wang et al. (2006) confirms that vehicle exhaust and coal combustion account for a large proportion of pollutant particles. Therefore, following previous studies, some control variables that may affect $PM_{2.5}$ concentrations are also included in the regression model. In this regard, the regression model of determining the economic and social influential factors of $PM_{2.5}$ has an EKC style as follows:

$$\begin{aligned}\mathbf{lpm25} = \gamma_0 + \gamma_1 lgdpperc + \gamma_2 lgdpperc^2 + \gamma_3 fdipergdp \\ + \gamma_4 lpop + \gamma_5 secondratio + \gamma_6 openness + u \qquad (2)\end{aligned}$$

Similar to Eq. (1), the parameters $\gamma_1 - \gamma_7$ in Eq. (2) are coefficients to be estimated. lpm25 stands for the logarithmic form of $PM_{2.5}$ concentrations. lgdpperc and lgdpperc^2 represent the logarithmic GDP per capita and its squared term, respectively. The estimated coefficients of these two variables in regression Eq. (2) determine the existence of the inverted-U shaped EKC relationship between $PM_{2.5}$ concentrations and GDP per capita. It should be noted that, in some recent studies, the cubic term of GDP per capita is sometimes introduced as an explanatory variable to allow for more general shape of EKC. For the detailed discussions on the possible shapes of EKC when GDP per capita, its squared and cubic terms are introduced, one could refer to Galeotti et al. (2006) and Kaika and Zervas (2013). We have also tried to incorporate the cubic term of GDP per capita in the EKC regression Eq. (2), but the coefficients of GDP per capita and its squared term turn insignificant, suggesting the introduction of the cubed GDP per capita is not reasonable. Due to space limit, the estimation results of introducing GDP per capita and its squared and cubic terms are not reported in this paper but available upon request. fdipergdp, lpop, secondratio and openness represent the ratio of FDI to GDP, the logarithm of population density, the ratio of the secondary industry value-added to GDP, and trade openness, respectively. The last four variables are chosen as control variables, the reasons for which are as follows:

2.2.1. Population density

On one hand, a city with higher population density may have better chance to develop energy-intensive industry, which usually needs a large labor force. On the other hand, the accumulation of population makes the intensive usage of energy possible (e.g., central heating). In addition, in a city with a higher population density, pollution may be more harmful and therefore the pressure to curb air pollution may be higher for the government (Liao et al., 2015). As a result, the net effect of population density on air pollution requires further investigation. Hao and Liu (2016) examined and verified the inverted-U shaped EKC relationship between $PM_{2.5}$ concentrations in 73 Chinese cities in 2013 using spatial econometric models. They also found that population density is negatively related with urban $PM_{2.5}$ concentrations.

2.2.2. Ratio of the secondary industry value-added to GDP

Secondary industry includes mining, manufacturing, electricity supply and construction. Fossil fuel combustion in these industries contributes greatly to air pollution. As He (2009) noted, the size of secondary industry has an impact on air pollution in both direct and indirect ways. In the context of China, steel, cement and electricity production are the most energy- and pollution-intensive industries. Following previous studies, such as Auffhammer and Carson (2008) and Hao and Liu (2016), the ratio of secondary industry value-added to GDP is introduced as another control variable.

2.2.3. Trade openness

The effect of trade openness on the environment has not yet been determined. Similar research on air pollutants such as CO_2 discussed the impact in China (Jalil and Mahmud, 2009; Ang, 2009). However, there is still controversy over the direction of this impact. Whereas openness may promote the export of goods that require more energy and causes more pollution than others (Ang, 2009), the inflow of technology may reduce energy consumption (Du et al., 2012). Therefore, a net effect has to be examined.

2.2.4. Ratio of FDI to GDP

FDI reflects the amount of foreign capital infusion, and the impact of FDI on environment may also be in two directions. On one hand, industrialized nations may transfer their pollution-intensive industries into developing countries in the form of FDI, which is known as the pollution haven hypothesis (e.g., Baumol and Oates, 1988; Copeland and Taylor, 1995). On the other hand, more advanced and greener production technology could also be brought in with FDI, which is beneficial to environmental quality (Letchumanan and Kodama, 2000; Eskeland and Harrison, 2003). To eliminate the effect of economic scale, the ratio of FDI to GDP is introduced as another control variable.

2.3. Estimation method: simultaneous equations model

According to Eqs. (1) and (2), the environment quality and economic performance may have an influence on each other; therefore, there might be potential endogeneity caused by the bilateral causality between environmental quality and economic development. The conventional OLS estimations of single regression equations simply ignore the endogeneity and may suffer bias, leading to unreliable results (Wooldridge, 2016). To handle the endogeneity caused by the potential bilateral causality between economic growth and air pollution, the simultaneous equations model (SEM) can be utilized. Another commonly used method to handle endogeneity is the instrumental variable (IV) method. However, because it is usually very difficult to find appropriate instrumental variables, as it is in this study, and because the endogeneity is mainly caused by potential bilateral causality, the SEM method is preferred.[5] Concretely, the SEM consists of Eqs. (1) and (2). Both equations are fully identified because in each equation, there is at least one exogenous or predetermined variable that appears explicitly in the other equation. The two-stage least squares (2SLS) method developed by Theil (1953) and Basmann (1957) is the basic approach for the SEM. The three-stage least squares (3SLS) estimation introduced by Zellner and Theil (1962) is more advanced than 2SLS because 3SLS takes into consideration the contemporaneous correlation of disturbances across the equations in the SEM. In addition, as Kennedy (2011) stressed, 3SLS is generally believed to be more consistent and asymptotically more efficient; therefore, it is preferred to 2SLS if the disturbances of the separate equations are correlated. In addition, to control for the time-invariant factors that may affect environmental quality, such as climate, landform and residents' energy consumption habits, regional dummies are added in Eq. (2).

In recent years, some studies have utilized the SEM method to address the endogeneity between environmental performance and economic development. For instance, Hung and Shaw (2004) applied an SEM to investigate the existence of the EKC in Taiwan, and they found evidence of an inverted U-shaped relationship between the pollutant emissions of NO_2 and CO and income.

3. Data

China did not monitor urban $PM_{2.5}$ concentrations unit late 2012. In 2013, the first group of observation stations was established, and urban $PM_{2.5}$ concentrations were regularly reported in 73 Chinese cities. The number of cities that report air quality has been expanding rapidly since then. In 2014, 147 cities were monitored. Since 2015, all of the 367 prefecture-level cities in mainland China have been monitored. The sample period of the data utilized in this study is 2013–2015; therefore, the available data for each year are different. Hence, in this study, different estimation techniques, including a pooled panel regression and panel data SEM, are employed to ensure that all available data could be fully used.

As mentioned in the previous section, the key factors examined in this study are air quality and economic development. Considering the fact that the main components of haze pollution are fine particles ($PM_{2.5}$), the city-level $PM_{2.5}$ concentrations are utilized as the main indicator for air quality. The historical data for urban $PM_{2.5}$ concentrations are taken from the *Online Monitoring and Analysis Platform for China's Air Quality* (OMAPCQ), which collects real-time reports from all air quality inspection sites across the country.[6] The original data provided in OMAPCQ are monthly. For the purpose of empirical estimation, the annual average $PM_{2.5}$ concentrations are then calculated as the arithmetic average of monthly levels, because the statistics of most of the other explanatory variables, including secondary industry value-added, volume of import and export and FDI, are only collected on a yearly basis. Although taking average in effect makes the series smooth by averaging the high indices in wintertime and the low indices in summertime, the annual average $PM_{2.5}$ is still a good indicator for the level of haze pollution. The main reason is twofold. First of all, the short-run air pollution may be affected by the extreme weather events (e.g., typhoon, torrential rain, unusual high temperature). Second, the annual average $PM_{2.5}$ basically reflects the severity of the air pollution as the citizens perceive. As shown in Fig. 1, the level of annual average $PM_{2.5}$ concentrations in northern and eastern China is higher than that in the southern region, which is basically consistent with the situation when serious haze pollution broke out in wintertime. Moreover, some recent studies also utilized the annual average $PM_{2.5}$ concentrations as is in this study (e.g., Hao and Liu, 2016; Ma et al., 2016; Stern and Zha, 2016). As for economic development, following plenty of previous studies, real GDP per capita is utilized. The GDP data are from *China Statistical Yearbooks* of various years and *China City Statistical Yearbooks* of various years, and the GDP data are converted into real terms using constant 2000 prices. All the other variables are directly collected or calculated by authors using data from the *China Statistical Yearbooks*, *China City Statistical Yearbooks* and *statistical communiqué of individual cities on the national economic and social development* of various years.

As a summary, the descriptive statistics and definitions of all variables utilized in this study are reported in Table 1.

Moreover, to improve the validity of the estimated results and decrease the relevance of variables, at first the generalized mixed three-stage least-squares estimation is performed using three-year pooled data. Additionally, to reduce the heteroscedasticity, some variables are converted to logarithmic form. Moreover, the utilization of three-year panel data makes it possible to test the robustness of the estimation results by choosing different samples and controlling for the fixed effects. Prior to conducting the empirical estimations, to show the relationship between haze pollution and the level of economic development, a scatter plot of GDP per capita and $PM_{2.5}$ concentrations for all sample cities during the sample period was created, as depicted in following Fig. 3.

As shown clearly in Fig. 3, the simple linear fitness curve of the quadratic function is downward sloping, suggesting that $PM_{2.5}$ concentrations may have a negative impact on GDP per capita. Interestingly, it is worth noting that for the first-tier megacities in China with a relatively high level of economic development (i.e., Beijing, Guangzhou, Shanghai and Shenzhen), the negative relationship between $PM_{2.5}$ concentrations and GDP per capita appears to be obvious, as shown in Fig. 3 (the observations for each of the cities are represented by a series of dots with a specific color). However, the goodness of fit (R^2) for the fitness curve is considerably low, which indicates that the potential endogeneity may be nontrivial and may affect the goodness of fit. Therefore, more formal and elaborate estimations are necessary, as will be utilized in the following section.

4. Empirical results and discussions

In this section, both the single equation model and the simultaneous equations model are estimated. Although it potentially suffers from endogeneity, the estimation results of the single equation model could be considered as a comparison to the results of the simultaneous equations model.

4.1. Estimation results for single equation models

Tables 2 and 3 present the panel data estimation results for Eqs. (1) and (2) alone, i.e., the economic growth function and the economic and social determinants of $PM_{2.5}$ concentrations equation, respectively.

In Table 2, the estimation results of Eq. (1) are given. To control for the effects of time-invariant factors, panel data fixed-effects

[5] As an anonymous reviewer pointed out, it is noteworthy that, in addition to structural methods, reduced-form models (in particular quasi-experimental designs) are widely used to do causal inference and solve the endogeneity issue. Because this study explores macro interrelationship between air pollution and economic growth, the structural method (SEM) is utilized.

[6] The official website for the *Online Monitoring and Analysis Platform for China's Air Quality* is http://www.aqistudy.cn/(in Chinese). Under the column "Statistical Ranking", the historical monthly average levels of $PM_{2.5}$ concentrations, PM_{10} concentrations and Air Quality Index (AQI) are calculated and reported for all cities with air inspection sites.

Table 1
Descriptive statistics of the variables.

Variables	Definition	Units	Mean	Std. dev	Min	Max
PM25	Yearly average concentration of $PM_{2.5}$	μg/m^3	55.7	22.3	9.9	160.2
gdpperc	Actual per capita GDP (at constant 2000 prices)	Yuan	40,856.3	27,257.5	6539.1	296,561.4
secondratio	The ratio of secondary industry value-added to GDP		0.48	0.10	0.02	0.86
openness	The ratio of imports and exports to GDP		5.4	113.2	0	2644.4
fdipergdp	FDI as a share of GDP		0.02	0.02	0	0.25
fdiperca	Per capita FDI	Yuan	1485.2	1703.2	0.1	12,350.0
Pop	Population density	Person/km^2	530.2	486.7	10.0	5698.0
fixed	per capita fixed asset investment	Yuan	44,540.3	25,261.6	0.8	300,655.7

estimations are conducted. According to the results of different regression specifications shown in the four columns of Table 2, the impact of $PM_{2.5}$ concentrations on GDP per capita is negative. However, the estimated coefficients turn out to be not very significant (at most at a significance level of 10%). Additionally, the magnitudes of the estimated coefficients are not remarkable, as the largest coefficient in absolute value is −0.086 (model 2.3). In addition, the coefficients of trade openness are estimated to be significantly negative, suggesting that trade has a negative influence on China's economic performance, which is opposite to theoretical implications and conventional wisdom. The unsatisfactory estimation results indicate that the endogeneity may indeed cause estimation biases.

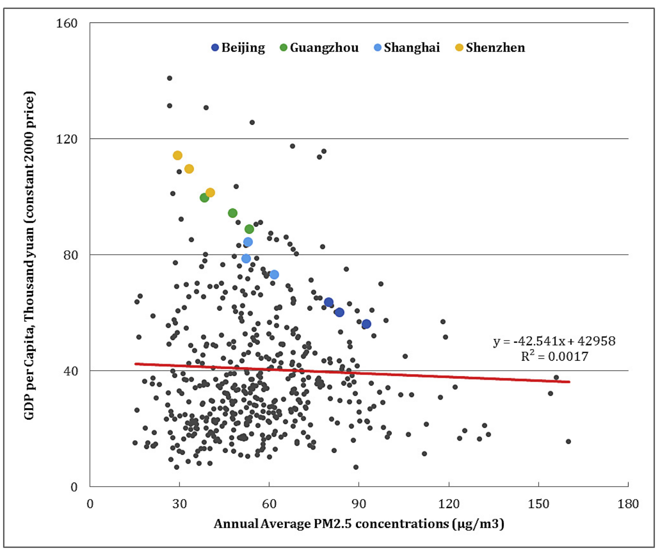

Fig. 3. Scatter plot of GDP per capita against $PM_{2.5}$ concentrations for the pooled data of all cities over the sample period of 2013–2015. *Notes*: 1) The red line is the simple linear fitness curve. 2) The colorful dots represent several megacities: Beijing, Tianjin, Guangzhou and Shenzhen.

In Table 3, the panel data fixed-effects estimation results of single Eq. (2) are reported. The coefficients of per capita GDP and its squared term carry positive and negative signs, respectively. These results indicate that the relationship between economic development on $PM_{2.5}$ concentrations is inverted-U shaped. Moreover, the single equation estimation results indicate that the economic influences of $PM_{2.5}$ pollutions seem to be not large in magnitude. According to the estimation results shown in Table 2, an increase in $PM_{2.5}$ concentrations by 1% would cause a decrease in GDP per capita by less than 0.1%. Or in other words, even if the $PM_{2.5}$ concentrations are halved, per capita GDP could be consequently increased by no more than 5%. However, as previously emphasized, because of the potential bilateral causality between air pollution and economic development, the single equation estimation results might be biased, and therefore it is necessary to conduct more accurate estimations on the basis of SEM, which would be discussed in the following subsection.

However, similar to the estimation results for Eq. (1) alone reported in Table 2, the estimation results for Eq. (2) alone may suffer from estimation biases caused by potential endogeneity. Therefore, to gauge the more accurate relationship between $PM_{2.5}$ concentrations and GDP per capita, the SEM approach is needed, as is to be

Table 2
Estimation results for Eq. (1) only: impacts of $PM_{2.5}$ concentrations on GDP per capita.

Model Dep. Var.	(2.1) lgdpperc	(2.2) lgdpperc	(2.3) lgdpperc	(2.4) lgdpperc
lpm25	−0.032	−0.025	−0.086*	−0.080
	(-0.59)	(-0.47)	(-1.75)	(-1.60)
lfdiperc	0.218***	0.216***	0.166***	0.166***
	(15.90)	(15.73)	(12.36)	(12.28)
openness		−0.0000895		0.0000102
		(-0.52)		(0.07)
lfixed			0.284***	0.281***
			(9.68)	(9.50)
_cons	9.208***	9.193***	6.759***	6.769***
	(41.25)	(40.93)	(20.67)	(20.52)
N	460	458	457	455
R^2	0.3576	0.3550	0.4651	0.4600
AIC	571.5061	481.0813	481.5745	481.5745
BIC	583.8998	497.58	502.176	502.176

Notes: t statistics in parentheses correspond to the above estimated coefficients. *, ** and *** represent significant at 10%, 5% and 1%, respectively.

Table 3
Estimation results for Eq. (2) only: influential factors of $PM_{2.5}$ concentrations.

Model Dep. Var.	(3.1) lpm25	(3.2) lpm25	(3.3) lpm25	(3.4) lpm25
lgdpperc	3.515***	3.052***	3.402***	2.900***
	(3.84)	(3.35)	(3.65)	(3.12)
lgdpperc2	−0.170***	−0.149***	−0.164***	−0.142***
	(-3.89)	(-3.42)	(-3.68)	(-3.18)
fdipergdp	−0.752	−0.687	−0.767	−0.697
	(-0.93)	(-0.86)	(-0.95)	(-0.88)
lpop	0.158***	0.152***	0.160***	0.153***
	(8.16)	(7.97)	(8.09)	(7.86)
secondratio		0.659***		0.654***
		(3.83)		(3.80)
openness			−0.010*	−0.009*
			(-1.76)	(-1.79)
_cons	−15.08***	−12.82***	−14.50***	−12.03**
	(-3.16)	(-2.70)	(-2.98)	(-2.48)
N	480	475	478	473
R^2	0.1490	0.1668	0.1494	0.1670
AIC	385.0600	363.2760	384.1261	362.4699
BIC	405.9289	388.2559	409.1437	391.5836

Notes: t statistics in parentheses correspond to the above estimated coefficients. *, ** and *** represent significant at 10%, 5% and 1%, respectively.

discussed in the next subsection.

4.2. Estimation results for SEM

Given that the number of cities that report $PM_{2.5}$ concentrations increased significantly from 2013 to 2015, different estimation methods are employed to make full use of all available data. First, pooled data for all cities during the sample period are utilized, and the corresponding estimation results by employing 3SLS are reported in Table 4. As expected, the estimation results of the SEM are much better than those of the single equation models in terms of statistical significance and the rationality of estimated coefficients. To ensure the robustness of the estimation results, following extant studies such as Auffhammer and Carson (2008) and Hao and Liu (2016), seven different specifications are utilized, and the corresponding results are labeled as models (4.1)–(4.7). The benchmark estimation is model (4.1), in which all explanatory variables in both two equations are included. In the other models, some control variables in Eq. (1) or/and Eq. (2) are excluded to test the consistency and robustness of the estimation results. For models (4.1)–(4.7), the coefficients of logarithmic $PM_{2.5}$ concentrations (lpm25) are consistently negative and significant at least at a significance level of 10%. In fact, except for (4.7), in all the other six models, the coefficients of lpm25 are significant at a level of 1%. These results indicate that, after taking fully into consideration the endogeneity of the bilateral causality between air pollution and economic development, haze pollution indeed has a strong negative impact on GDP per capita. Other things being equal, the increase in $PM_{2.5}$ concentrations by 1% will trigger the GDP per capita to decrease by approximately 0.3%–0.8%, depending on the particular specifications utilized. Compared with the estimates of the single Eq. (1) that are represented in Table 2, the 3SLS estimates of $PM_{2.5}$ concentrations in the SEM are considerably higher, suggesting that the actual harm of haze pollution to economic development is larger than the conventional panel data estimates, which overlook the endogeneity caused by the bilateral causality between air pollution and economic development.

According to the latest statistics of National Bureau of Statistics (NBS), China's total GDP and per capita GDP had already reached 68551 billion yuan (11006 billion U.S. dollars) and 49992 yuan (8026 U.S. dollars) by 2015. In this study, the values of China's GDP measured in U.S. dollars are calculated based on the yearly average official exchange rate of RMB against U.S. dollars in 2015. Therefore, a decrease in $PM_{2.5}$ by 1% would push up per capita GDP by approximately 150–400 yuan (24–64 U.S. dollars). Equivalently, the corresponding total GDP would be 206–548 billion yuan (33–88 billion U.S. dollars). As such, the economic cost of haze pollution is remarkably high and deserves great attention. Previous studies on the economic cost of particulate matter pollution normally focused on the negative impacts of air pollution on public health (e.g., World Bank, 2007; Huang et al., 2012). The estimation results of this study are comparable with those of the extant research. Mu and Zhang (2013) noted that the health costs dominate the total economic costs of air pollution in China. For instance, according to the World Bank's (2007) estimations, the health loss caused by PM_{10} pollution was approximately 1.2%–3.8% of national GDP in 2003. Huang et al. (2012) utilized contingent valuation (CV), amended human capital (AHC) and cost of illness (COI) methods to evaluate the economic loss of health effects caused by PM_{10} pollution in nine cities in the Pearl River Delta region. Their results indicate that the economic loss accounted for approximately 0.7%–1.35% of the total regional GDP.

As for the control variables in Eq. (1) of the SEM, the coefficients are basically consistent with the theoretical expectations. For instance, in most estimations that include trade openness (openness), the coefficients are estimated to be positive and significant,

Table 4
Estimation results for the SEM of Eqs. (1) and (2) using pooled data of all cities during the sample period.

Model	(4.1)	(4.2)	(4.3)	(4.4)	(4.5)	(4.6)	(4.7)
Dep. Var: lgdpperc							
lpm25	−0.738***	−0.816***	−0.748***	−0.839***	−0.407***	−0.283*	−0.784***
	(-4.43)	(-4.33)	(-4.49)	(-4.46)	(-2.79)	(-1.84)	(-5.04)
lfixed	0.287***	0.294***	0.274***	0.281***			0.291***
	(8.01)	(7.79)	(7.82)	(7.58)			(8.05)
lfdiperc	0.155***	0.160***	0.153***	0.160***	0.199***	0.199***	0.154***
	(9.69)	(9.72)	(9.70)	(9.79)	(13.53)	(13.95)	(9.47)
openness	0.008	0.007	0.005	0.002		0.023**	
	(0.68)	(0.53)	(0.44)	(0.19)		(2.07)	
_cons	9.392***	9.600***	9.579***	9.840***	10.81***	10.31***	9.543***
	(14.74)	(13.68)	(15.12)	(14.14)	(18.75)	(16.91)	(15.67)
Dep. Var: lpm25							
lgdpperc	128.3*	98.90**	35.42***	39.82***	97.40	78.70	130.5*
	(1.93)	(2.44)	(3.02)	(3.47)	(1.27)	(1.02)	(1.96)
lgdpperc2	−6.130*	−4.725**	−1.701***	−1.910***	−4.652	−3.758	−6.232**
	(-1.93)	(-2.45)	(-3.05)	(-3.50)	(-1.27)	(-1.02)	(-1.96)
secondratio	−1.413		0.237		−0.921	−0.543	−1.461
	(-1.06)		(0.60)		(-0.62)	(-0.37)	(-1.10)
openness	0.115	0.084*			0.076	0.057	0.116
	(1.48)	(1.66)			(0.87)	(0.65)	(1.49)
fdipergdp	4.420	3.798	2.271	2.595*	2.863	1.839	4.567
	(1.45)	(1.51)	(1.61)	(1.75)	(0.97)	(0.62)	(1.50)
lpop	0.241***	0.198***	0.152***	0.155***	0.237**	0.220**	0.240***
	(2.68)	(2.97)	(3.82)	(3.81)	(2.54)	(2.37)	(2.67)
_cons	−667.1*	−513.6**	−181.0***	−204.1***	−505.7	−408.2	−678.2*
	(-1.92)	(-2.42)	(-2.95)	(-3.40)	(-1.26)	(-1.01)	(-1.95)
RMSE- Gdpperc	0.4588	0.4791	0.4608	0.4845	0.4469	0.4323	0.4684
RMSE- lpm25	2.0592	1.6023	0.6515	0.7123	1.5726	1.2817	2.0930
N	403	407	403	407	405	405	403

Notes: t statistics in parentheses correspond to the above estimated coefficients. *, ** and *** represent significant at 10%, 5% and 1%, respectively. RMSE denotes the root mean squared errors.

which is in line with the fact that foreign trade has contributed significantly to China's enormous growth since China joined the World Trade Organization (WTO) in 2001. In addition, the results indicate that FDI indeed has a positive and significant impact on GDP per capita, similar to Li and Liu's (2005) findings for both developing and developed countries. Moreover, the coefficients of fixed asset investment (lfixed) turn out to be significant and positive, and the magnitudes of the coefficients are quite stable in the different specifications and are close to 0.3. These results also suggest that, in accordance with theoretical expectations and early estimations, such as that of Chow and Lin (2002), fixed asset investment indeed plays a vital role in China's economic development.

For Eq. (2) of the SEM, the estimation results are roughly the same as those reported in Table 3 for the single equation model. For most models, there is evidence for the inverted-U shaped relationship between urban $PM_{2.5}$ concentrations and GDP per capita. This conclusion is consistent with the conventional EKC hypothesis and Hao and Liu's (2016) finding using urban data of $PM_{2.5}$ concentrations in 2013. FDI per GDP and the industrial structure are also introduced as exogenous variables in Eq. (2) of the SEM. The coefficients of these two variables are positive and significant in most specifications. The positive relation between FDI and air pollution to some extent verify the pollution haven hypothesis in China (He, 2006), and the positive association between the fraction of second industry in the GDP and $PM_{2.5}$ concentrations indicate that second industry is the main contributor to air pollution in China (Hao and Liu, 2016; Hao et al., 2016). As for trade openness, its coefficients in Eq. (2) of SEM turn out to be negative and statistically significant, suggesting that the negative effects of foreign trade on air pollution outweigh the possible positive effects, as Du et al. (2012) and Jalil and Mahmud (2009) found.

To check the robustness of the estimation results, similar estimations are conducted for panel data composed of the 73 leading cities that first reported urban $PM_{2.5}$ concentrations in 2013. Furthermore, to control for the time effect (e.g., technology progress that may have effects on $PM_{2.5}$ concentrations), time effects are introduced, and the corresponding results are presented in Table 5. Because there are in total three years (2013–2015) in the sample period, 2003 is chosen as the base year, and two time dummies are added into Eq. (2), Year2014 and Year 2015, which are dummies for the years 2014 and 2015, respectively. The time dummy is set to be 1 if the year is the corresponding year; otherwise it is set to be 0. The panel data estimation results are similar to the results from the pooled data in Table 4. The estimated coefficients of all variables using the panel data have higher statistical significance, and the coefficients of $PM_{2.5}$ concentrations are more stable in magnitude, ranging from −0.3 to −0.6. These results indicate that, for the smaller subsample of 73 cities that first reported urban $PM_{2.5}$ concentrations, the elasticity of GDP per capita with respect to $PM_{2.5}$ concentrations is approximately −0.5. In other words, an increase in $PM_{2.5}$ concentrations by 1% may lead to a decrease in per capita GDP by around −0.5%, which is a considerable wealth loss. In addition, the two time dummies turn out to be negative and statistically significant in the majority of models, suggesting that the severity of haze pollution in Chinese cities slightly lessened over time. At the meanwhile, for Eq. (2) with $PM_{2.5}$ concentrations being dependent variable, the coefficients of GDP per capita and its squared terms are significantly negative and positive, respectively. These estimation results indicate that the EKC relationship for $PM_{2.5}$ concentrations is inverted-U shaped, which is consistent with the pooled data estimation results shown in Table 4.

Moreover, to control for the time-invariant factors that affect haze pollution (e.g., climate, the habits of residents to use energy), regional dummies are introduced, and the corresponding estimation results are reported in Table 6. There could be a dummy for each province, which costs many freedoms. Instead of using provincial dummies, two regional dummies are introduced, one for the eastern region and the other for the western region (the central region is set to be the benchmark). Given the fact that provinces in the same region share many common characteristics in terms of economic and social development and because there is evidence for the club convergence among the provinces within the same region (Cai et al., 2002), introducing regional dummies is logical and reasonable. The concrete divisions of the three regions are interpreted in the notes of Table 6. Overall, the panel data fixed effects estimation results are roughly the same as the pooled estimation results, suggesting the robustness of the panel data estimation results. Interestingly, the coefficients of the eastern regional dummy are quite significant and positive (all at the significance level of at least 5% except for model 6.1). These results are roughly in line with the actual data, as the $PM_{2.5}$ concentrations in the eastern region are considerably higher than in the central region, which could as be seen intuitively in Fig. 1. Some eastern provinces and municipalities, especially Hebei and Shandong provinces and megacity of Tianjin, are relatively advanced in heavy industry and therefore consume a huge amount of coal. As a result, the combustion of coal – a relative dirty type of fossil energy – should be blamed for the poorer air quality in the eastern region of China. Comparatively, however, the air quality in western is not significantly different from that in the central region.

In summary, the panel data estimation results shown in Tables 5 and 6 are generally in line with the results for the pooled data shown in Table 4. The panel data estimates are more stable and more significant in statistical terms. Better estimation results of panel data to some degree reflect the fact that the tradeoff between air quality and economic development is more apparent in the 73 cities rather than in all county-level cities in China. One possible reason for this finding is that the 73 cities that first reported urban $PM_{2.5}$ concentrations are generally more advanced in terms of economic and social development, as many of the cities that were later required to publish air quality information are not as developed and therefore not representative enough of China's economy (Zheng et al., 2010). According to the statistics from *China City Statistical Yearbook 2015*, in 2014 the GDP of the 73 cities that first revealed $PM_{2.5}$ concentrations accounted for approximately 66.1% of total national GDP. As a result, these 73 cities could be representative of all 367 prefecture-level cities in the mainland of China. In fact, the negative relationship between $PM_{2.5}$ concentrations and GDP per capita seems very strong for the most prosperous four Chinese cities – Beijing, Shanghai, Guangzhou and Shenzhen – as shown intuitively in Fig. 3.

Furthermore, to intuitively exhibit the potential economic gains of cleaning up air pollution in various cities, the incurred boost in GDP per capita due to the reduction in $PM_{2.5}$ concentrations are calculated. On the basis of previous estimation results that a decrease in $PM_{2.5}$ concentrations by 1% would lead to an increase in GDP per capita by 0.5%, the percentage and absolute amount of increase in GDP per capita if the safety threshold of $PM_{2.5}$ concentrations (25 $\mu g/m^3$) is reached are estimated for the 73 Chinese major cities. According to the estimation results shown in Table 7, the economic gains to reduce $PM_{2.5}$ concentrations are remarkable for the majority of cities. If the $PM_{2.5}$ concentrations could be reduced to the WHO guidelines, the city of Xingtai in the middle of Hebei province that relies heavily on the heavy industry may see the largest increase in the percentages of per capita GDP (40.4%), while the rich eastern city Wuxi would benefit most in terms of the absolute amount of GDP per capita (26,823 yuan, at constant 2000 prices).

Table 5
3SLS estimation results for the SEM of Eqs. (1) and (2) using balanced panel data of 73 cities during the sample period when time fixed effects are controlled.

Model Dep. Var.	Panel data of 73 cities during the whole sample period							
	(5.1)		(5.2)		(5.3)		(5.4)	
	lgdpperc	lpm25	lgdpperc	lpm25	lgdpperc	lpm25	lgdpperc	lpm25
lpm25	−0.313***		−0.571***		−0.457***		−0.577***	
	(-2.62)		(-6.10)		(-3.20)		(-5.59)	
lfixed	0.441***		0.409***					
	(7.34)		(6.18)					
lfdiperc	0.125***		0.129***		0.167***		0.166***	
	(6.68)		(6.42)		(8.20)		(8.00)	
openness	0.0695***	−0.033		−0.027	0.032	−0.111***		−0.112***
	(2.94)	(-0.85)		(-0.72)	(1.15)	(-5.78)		(-6.14)
lgdpperc		68.70***		71.26***		417.0***		452.2***
		(3.03)		(3.37)		(2.62)		(2.86)
lgdpperc2		−3.254***		−3.377***		−19.65***		−21.30***
		(-3.05)		(-3.39)		(-2.63)		(-2.86)
secondratio		0.421		0.311		0.490*		0.442*
		(1.18)		(0.94)		(1.81)		(1.70)
fdipergdp		0.450		1.537		2.026		2.363*
		(0.26)		(0.94)		(1.57)		(1.89)
lpop		0.333***		0.295***		0.232***		0.214***
		(5.16)		(4.86)		(5.73)		(5.61)
year2014		−0.097		−0.070		−0.098**		−0.090*
		(-1.52)		(-1.19)		(-1.98)		(-1.90)
year2015		−0.185***		−0.141**		−0.185***		−0.172***
		(-2.63)		(-2.16)		(-3.39)		(-3.30)
_cons	6.343***	−212.7***	7.757***	−237.8***	11.37***		11.89***	
	(7.42)	(-2.71)	(9.73)	(-3.12)	(18.52)		(25.29)	
RMSE- Gdpperc	0.2977	0.5557	0.3382	0.6031	0.35294	0.3351	0.3708	0.3403
RMSE- lpm25	0.5205	−0.8682	0.3810	−1.2005	0.3299	0.3174	0.2604	0.2962
N	198		198		200		200	
Cities	73		73		73		73	

Notes: t statistics in parentheses correspond to the above estimated coefficients. *, ** and *** represent significant at 10%, 5% and 1%, respectively. RMSE denotes the root mean squared errors. Year2014 and Year2015 are time dummies for the year 2014 and 2015, respectively.

Table 6
3SLS estimation results for the SEM of Eqs. (1) and (2) using balanced panel data of 73 cities during the sample period when regional fixed effects are controlled.

Model Dep. Var.	Panel data of 73 cities during the whole sample period							
	(6.1)		(6.2)		(6.3)		(6.4)	
	lgdpperc	lpm25	lgdpperc	lpm25	lgdpperc	lpm25	lgdpperc	lpm25
lpm25	−0.402***		−0.641***		−0.527***		−0.605***	
	(-2.79)		(-6.46)		(-3.37)		(-5.59)	
lfixed	0.458***		0.440***					
	(7.39)		(6.62)					
lfdiperc	0.115***		0.106***		0.177***		0.179***	
	(6.25)		(5.71)		(8.17)		(8.09)	
openness	0.061**	0.011		0.012	0.020	0.624**		0.685**
	(2.29)	(0.23)		(0.30)	(0.67)	(2.23)		(2.46)
lgdpperc		68.70***		71.26***		417.0***		452.2***
		(3.03)		(3.37)		(2.62)		(2.86)
lgdpperc2		−3.254***		−3.377***		−19.65***		−21.30***
		(-3.05)		(-3.39)		(-2.63)		(-2.86)
lpop		0.343***		0.313***		1.089***		1.150***
		(5.24)		(5.51)		(3.19)		(3.39)
dummyeast		0.272		0.292**		2.632**		2.873***
		(1.62)		(2.00)		(2.50)		(2.75)
dummywest		−0.082		−0.051		0.303		0.352*
		(-0.81)		(-0.61)		(1.43)		(1.69)
secondratio				0.160		−2.169*		−2.438**
				(0.56)		(-1.93)		(-2.20)
_cons	6.612***	−360.3***	7.876***	−373.5***	11.59***	−2213.1***	11.91***	−2400.1***
	(6.92)	(-2.98)	(9.55)	(-3.32)	(17.28)	(-2.62)	(24.07)	(-2.85)
RMSE- Gdpperc	0.3093	0.7915	0.3524	0.8103	0.3623	3.9999	0.37489	4.3296
RMSE- lpm25	0.4899	−2.8260	0.3279	−2.9715	0.2938	−96.2548	0.2440	−112.9480
N	200		198		200		200	
Cities	73		73		73		73	

Notes: t statistics in parentheses correspond to the above estimated coefficients. *, ** and *** represent significant at 10%, 5% and 1%, respectively. RMSE denotes the root mean squared errors. Dummyeast and Dummywest represent the dummies for the eastern and western regions, respectively. In this study, the eastern region includes Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Guangxi and Hainan; the central region includes Shanxi, Inner Mongolia, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei and Hunan; and the western region includes Sichuan, Chongqing, Guizhou, Yunnan, Tibet, Shaanxi, Gansu, Ningxia, Qinghai, Qinghai and Xinjiang.

Table 7
The economic gains of cleaning up $PM_{2.5}$ pollutions for the 73 Chinese major cities and the whole nation.

City	$RDPM_{2.5}$ (%)	IIGDPr (%)	IIGDPy (yuan)	City	$RDPM_{2.5}$ (%)	IIGDPr (%)	IIGDPy (yuan)
Hefei	−67.6	33.8	15,004.4	Nantong	−60.4	30.2	15,441.3
Beijing	−70.7	35.3	21,171.1	Suzhou	−60.7	30.4	26,195.5
Fuzhou	−17.9	8.9	4734.1	Taizhou	−65.2	32.6	15,652.9
Xiamen	−20.3	10.1	6616.6	Wuxi	−63.5	31.7	26,823.4
Lanzhou	−56.6	28.3	10,193.2	Suqian	−62.6	31.3	10,299.8
Dongguan	−29.8	14.9	8173.6	Xuzhou	−63.9	32.0	12,084.1
Foshan	−44.9	22.5	17,067.9	Yancheng	−57.3	28.7	10,128.1
Guangzhou	−46.1	23.1	21,746.1	Yangzhou	−61.1	30.6	16,690.6
Huizhou	−24.6	12.3	5669.6	Zhenjiang	−62.4	31.2	21,082.3
Jiangmen	−40.8	20.4	7081.3	Nanchang	−54.1	27.0	11,857.6
Shenzhen	−27.0	13.5	14,642.0	Dalian	−42.3	21.1	18,829.3
Zhaoqing	−49.1	24.6	8231.3	Shenyang	−64.9	32.5	21,423.0
Zhongshan	−36.9	18.5	12,123.9	Hohhot	−48.6	24.3	15,137.0
Zhuhai	−27.3	13.6	11,589.6	Yinchuan	−45.5	22.8	7254.9
Nanning	−48.2	24.1	6711.8	Xining	−65.2	32.6	8796.7
Guiyang	−47.6	23.8	6982.3	Jinan	−74.9	37.4	21,050.1
Haikou	8.3	−4.1	−1292.0	Qingdao	−55.6	27.8	18,613.1
Baoding	−79.4	39.7	7795.0	Taiyuan	−63.2	31.6	12,280.7
Cangzhou	−70.2	35.1	10,323.1	Xi'an	−68.9	34.5	12,206.6
Chengde	−48.8	24.4	6277.7	Shanghai	−55.0	27.5	21,666.7
Handan	−77.6	38.8	8390.9	Chengdu	−66.4	33.2	15,884.6
Hengshui	−77.2	38.6	7049.2	Tianjin	−70.3	35.1	26,350.1
Langfang	−74.9	37.4	12,939.3	Urumqi	−65.5	32.8	14,561.1
Qinhuangdao	−56.4	28.2	8000.8	Kunming	−22.1	11.1	4014.5
Shijiazhuang	−79.4	39.7	13,845.6	Hangzhou	−59.2	29.6	20,689.7
Tangshan	−75.0	37.5	21,859.2	Huzhou	−61.2	30.6	14,846.1
Xingtai	−80.8	40.4	6573.1	Jiaxing	−57.4	28.7	14,210.3
Zhangjiakou	−32.6	16.3	3506.1	Jinhua	−60.0	30.0	13,651.9
Zhengzhou	−73.9	37.0	17,855.1	Lishui	−42.3	21.1	5648.0
Haerbin	−66.2	33.1	15,828.2	Ningbo	−46.6	23.3	15,507.7
Wuhan	−69.1	34.5	20,623.5	Quzhou	−55.1	27.5	9719.5
Changsha	−65.1	32.6	21,898.1	Shaoxing	−59.4	29.7	17,193.6
Changchun	−63.0	31.5	15,192.4	Taizhou	−47.1	23.5	8966.6
Changzhou	−63.0	31.5	21,603.7	Wenzhou	−49.0	24.5	8497.6
Huaian	−64.2	32.1	10,776.4	Zhoushan	−17.2	8.6	5510.9
Lianyungang	−59.3	29.6	8719.9	Chongqing	−56.9	28.4	9520.4
Nanjing	−63.7	31.9	22,818.5	**National**	−60.6	30.3	14,923.5

Notes: RDPM2.5 represents required decrease in $PM_{2.5}$ concentrations in percentage to meet the WHO guidelines, IIGDPr represents the incurred increase in GDP per capita in percentage caused by the reduction in $PM_{2.5}$ concentrations, IIGDPy represents the incurred increase in GDP per capita in absolute amount (constant 2000 Chinese yuan). The safety threshold value for $PM_{2.5}$ concentrations is 25 $\mu g/m^3$, and an increase in $PM_{2.5}$ by 1% would cause an incurred increase in GDP per capita by approximately 0.5%. Haikou's average level of $PM_{2.5}$ concentrations between 2013 and 2015 was already lower than the threshold level of 25 $\mu g/m^3$.

5. Conclusions and policy implications

This paper investigates the economic cost of haze pollution in China using city-level panel data established on the basis of newly published urban $PM_{2.5}$ concentrations. To address the endogeneity that may be caused by the bilateral causality between economic development and air pollution, a carefully designed SEM that contains a pollution equation and a growth equation is utilized, and the 3SLS method is employed to conduct the estimations. To ensure the stability and robustness of the estimation results, pooled data containing all cities with available information and panel data of the 73 cities that first reported $PM_{2.5}$ concentrations are used. In addition, to control for the regional and time fixed effects, a series of time dummies and regional dummies are introduced in the panel data analysis. The estimation results indicate that haze pollution indeed has negative impacts on China's economic development. On average, other things being equal, an increase in $PM_{2.5}$ concentrations by 1% will cause a decrease in GDP per capita of approximately 0.5%. Specifically, as of 2015, the average level of $PM_{2.5}$ concentrations for all sample cities was 49.9 $\mu g/m^3$, while national GDP per capita was 49992 yuan. As a result, the estimation results indicate that when all other conditions are held unchanged, an increase in $PM_{2.5}$ by 10% (from 49.9 $\mu g/m^3$ to 54.9 $\mu g/m^3$) would cause GDP per capita to decrease by roughly 5% (from 49992 yuan to 47,492 yuan). Moreover, the estimation results of the SEM are more stable and reasonable than conventional OLS estimations without considering endogeneity. The SEM results also suggest that there is evidence of an inverted-U shaped relationship between $PM_{2.5}$ concentrations and GDP per capita. For the cities with a relatively high level of economic development, urban $PM_{2.5}$ concentrations will decrease as GDP per capita continues to increase.

According to the main findings of this study, some policy implications can be presented in a straightforward manner.

First, given the considerable economic loss caused by air pollution, it is economically beneficial for Chinese central and local governments to pay more attention and money to curbing haze pollution. It is worth necessary investment and financial support to improve air quality because the economic benefits will be probably sufficient and far more than the input. It should be noted that this conclusion seems to be counter-intuitive. According to the conventional wisdom, the investment in improving air quality means stricter regulations and large financial investment in air pollution prevention, which might lower the interest of industries, especially second-hand industry. However, the conventional wisdom did not account for the potential huge economic gains of reducing pollution levels and improving environmental quality. These potential economic benefits may come from better public health and the possible booming of environment-friendly industries (Hoque and Clarke, 2013; Chen et al., 2017). Moreover, the latest studies have found that the environmental regulation may be beneficial to economic growth, possibly through its positive impacts on innovation (Zhu et al., 2014; Wang et al., 2016b). Besides, stricter environmental regulations and targeted financial support may lead to the booming of environmental friendly enterprises and the innovations in industries, as the "Potter hypothesis" suggested. In this regard, the appropriate environmental regulations could help to accelerate China's industrial upgrading and economic transition to a more sustainable style. China has vowed to cut $PM_{2.5}$ concentrations by 25% during the 13th "Five-year Plan" period (2016–2020).[7] According to our estimations, if China can achieve this ambitious goal, the GDP per capita would be boosted by as much as 15% merely due to the improvement of air quality. As a result, the Chinese government, at various levels, should arrange for specific financial resources to invest in environmental protection, especially the improvement of air quality.

Second, contrarily to the conventional idea that curbing air pollution is at the cost of economic development, the estimation results indicate that economic development may lead to the improvement of air quality. However, due to the different stages of economic development, differentiated policies should be designed for different cities. For some economically prosperous megacities, such as Beijing, Shanghai and Shenzhen, there is already a decreasing trend in $PM_{2.5}$ concentrations. Therefore, in these cities, the loop between the improvement of air quality and economic development is positive: the increase in GDP per capita may lead to lower $PM_{2.5}$ concentrations, which in turn could bring about economic revenue. Hence, for these cities, the policies should maintain and strengthen this positive feedback. However, for some economically backward cities, a tradeoff between economic development and environmental pollution is apparent. Correspondingly, relatively tight environmental regulations should be applied to reduce the detrimental impacts of surging air pollution on economic growth. One caveat should be noted: even for Beijing and other prosperous cities, the decrease in $PM_{2.5}$ concentrations may not automatically occur alongside economic growth. Instead, the strong pollution control policy is still needed even when there is a clear downward trend of $PM_{2.5}$ concentrations. In fact, given that the importance of the secondary industry has dramatically decreased in the prosperous cities of Beijing and Shanghai, the negative effect of strict environmental regulations on the economic growth is limited, if any. In other words, the relatively high level of economic and social development and reasonable industrial structure in the economically developed cities ensure that the strong pollution control policy could be implemented with low resistance and costs.

Third, environmental policies should be adjusted according to cities' specific features of geological location and industrial structure. For instance, in some eastern provinces or municipalities, such as Hebei, Shandong and Tianjin, where heavy industry dominates the economy, the combustion of coal contributes most to the severe haze pollution. For the cities in this region, technology progress in improving the efficiency and decreasing the pollution of coal combustion (especially green coal technology) should be strongly advocated and promoted. In addition, for some cities located in the basin area, where the diffusion of air pollution is not rapid or smooth (e.g., Beijing, Shijiazhuang and Jinan), the energy- and pollution-intensive industries, including steel and iron and cement production, should be strictly limited or even prohibited.

[7] For more information, one can refer to https://www.chinadialogue.net/article/show/single/en/8696-13th-Five-Year-Plan-is-the-first-to-include-PM2-5-targets (accessed at 07/08/2017).

Acknowledgements

The authors acknowledge financial support from the National Natural Science Foundation of China (71403015, 71521002), Beijing Natural Science Foundation (9162013), the National Key Research and Development Program of China (2016YFA0602801, 2016YFA0602603), the Joint Development Program of Beijing Municipal Commission of Education. The authors are also very grateful to three anonymous reviewers and Co-Editor-in-Chief Prof. Dr. Yutao Wang for their insightful comments that help us sufficiently improve the quality of this paper. The usual disclaimer applies.

References

Alfaro, L., Chanda, A., Kalemli-Ozcan, S., Sayek, S., 2004. FDI and economic growth: the role of local financial markets. J. Int. Econ. 64 (1), 89–112.
Ang, J.B., 2007. CO_2 emissions, energy consumption, and output in France. Energy Policy 35 (10), 4772–4778.
Ang, J.B., 2009. CO_2 emissions, research and technology transfer in China. Ecol. Econ. 68 (10), 2658–2665.
Auffhammer, M., Carson, R.T., 2008. Forecasting the path of China's CO_2 emissions using province-level information. J. Environ. Econ. Manag. 55 (3), 229–247.
Azam, M., 2016. Does environmental degradation shackle economic growth? A panel data investigation on 11 Asian countries. Renew. Sustain. Energy Rev. 65, 175–182.
Barbier, E.B., 1994. Natural capital and the economics of environment and development. Invest. Nat. Cap. Ecol. Econ. approach Sustain. 291–322.
Barrett, S., Graddy, K., 2000. Freedom, growth, and the environment. Environ. Dev. Econ. 5 (4), 433–456.
Basmann, R.L., 1957. A generalized classical method of linear estimation of coefficients in a structural equation. Econ. J. Econ. Soc. 25 (1), 77–83.
Baumol, W.J., Oates, W.E., 1988. The Theory of Environmental Policy. Cambridge university press.
Borensztein, E., De Gregorio, J., Lee, J.W., 1998. How does foreign direct investment affect economic growth? J. Int. Econ. 45 (1), 115–135.
Brock, W.A., Taylor, M.S., 2005. Economic growth and the environment: a review of theory and empirics. Handb. Econ. Growth 1, 1749–1821.
Brock, W.A., Taylor, M.S., 2010. The green Solow model. J. Econ. Growth 15 (2), 127–153.
Cai, F., Wang, D., Du, Y., 2002. Regional disparity and economic growth in China: the impact of labor market distortions. China Econ. Rev. 13 (2), 197–212.
Chen, X., Shao, S., Tian, Z., Xie, Z., Yin, P., 2017. Impacts of air pollution and its spatial spillover effect on public health based on China's big data sample. J. Clean. Prod. 142, 915–925.
Chow, G.C., 1993. Capital formation and economic growth in China. Q. J. Econ. 108 (3), 809–842.
Chow, G., Lin, A.L., 2002. Accounting for economic growth in Taiwan and Mainland China: a comparative analysis. J. Comp. Econ. 30 (3), 507–530.
Copeland, B.R., Taylor, M.S., 1995. Trade and the environment: a partial synthesis. Am. J. Agric. Econ. 77 (3), 765–771.
Din, S.A.M., Yahya, N.N.H.N., Abdullah, A., 2013. Fine particulates matter (PM2. 5) from coal-fired power plant in Manjung and its health impacts. Proc. Soc. Behav. Sci. 85, 92–99.
Dockery, D.W., Pope, C.A., 1994. Acute respiratory effects of particulate air pollution. Annu. Rev. Public Health 15 (1), 107–132.
Dockery, D.W., Pope, C.A., Xu, X., Spengler, J.D., Ware, J.H., Fay, M.E., Ferris, B.J., Speizer, F.E., 1993. An association between air pollution and mortality in six US cities. N. Engl. J. Med. 329 (24), 1753–1759.
Du, L., Wei, C., Cai, S., 2012. Economic development and carbon dioxide emissions in China: provincial panel data analysis. China Econ. Rev. 23 (2), 371–384.
Eskeland, G.S., Harrison, A.E., 2003. Moving to greener pastures? Multinationals and the pollution haven hypothesis. J. Dev. Econ. 70 (1), 1–23.
Frankel, J.A., Romer, D., 1999. Does trade cause growth? Am. Econ. Rev. 379–399.
Friedl, B., Getzner, M., 2003. Determinants of CO_2 emissions in a small open economy. Ecol. Econ. 45 (1), 133–148.
Galeotti, M., Lanza, A., Pauli, F., 2006. Reassessing the environmental Kuznets curve for CO_2 emissions: a robustness exercise. Ecol. Econ. 57 (1), 152–163.
Graff Zivin, J., Neidell, M., 2012. The impact of pollution on worker productivity. Am. Econ. Rev. 102 (7), 3652–3673.
Graff Zivin, J., Neidell, M., 2013. Environment, health, and human capital. J. Econ. Lit. 51 (3), 689–730.
Grossman, G.M., Krueger, A.B., 1991. Environmental Impacts of a North American Free Trade Agreement (No. w3914). National Bureau of Economic Research.
Grossman, G.M., Krueger, A.B., 1995. Economic growth and the environment. Q. J. Econ. 110 (2), 353–377.
Hanna, R., Oliva, P., 2015. The effect of pollution on labor supply: evidence from a natural experiment in Mexico City. J. Public Econ. 122, 68–79.
Hao, Y., Liu, Y.M., 2016. The influential factors of urban $PM_{2.5}$ concentrations in China: a spatial econometric analysis. J. Clean. Prod. 112, 1443–1453.

Hao, Y., Wei, Y.M., 2015. When does the turning point in China's CO_2 emissions occur? Results based on the Green Solow model. Environ. Dev. Econ. 20 (6), 723–745.
Hao, Y., Zhang, Z.Y., Liao, H., Wei, Y.M., 2015. China's farewell to coal: a forecast of coal consumption through 2020. Energy Policy 86, 444–455.
Hao, Y., Chen, H., Zhang, Q., 2016. Will income inequality affect environmental quality? Analysis based on China's provincial panel data. Ecol. Indic. 67, 533–542.
Harrison, A., 1996. Openness and growth: a time-series, cross-country analysis for developing countries. J. Dev. Econ. 48 (2), 419–447.
He, J., 2006. Pollution haven hypothesis and environmental impacts of foreign direct investment: the case of industrial emission of sulfur dioxide (SO_2) in Chinese provinces. Ecol. Econ. 60 (1), 228–245.
He, J., 2009. China's industrial SO_2 emissions and its economic determinants: EKC's reduced vs. structural model and the role of international trade. Environ. Dev. Econ. 14 (02), 227–262.
HEI International Oversight Committee, 2004. Health Effects of Outdoor Air Pollution in Developing Countries of Asia: a Literature Review. Health Effects Institute, Boston, USA.
Hering, L., Poncet, S., 2014. Environmental policy and exports: evidence from Chinese cities. J. Environ. Econ. Manag. 68 (2), 296–318.
Holtz-Eakin, D., Selden, T.M., 1995. Stoking the fires? CO_2 emissions and economic growth. J. Public Econ. 57 (1), 85–101.
Hoque, A., Clarke, A., 2013. Greening of industries in Bangladesh: pollution prevention practices. J. Clean. Prod. 51, 47–56.
Hou, Q., An, X.Q., Wang, Y., Guo, J.P., 2010. An evaluation of resident exposure to respirable particulate matter and health economic loss in Beijing during Beijing 2008 Olympic Games. Sci. Total Environ. 408 (19), 4026–4032.
Huang, D., Xu, J., Zhang, S., 2012. Valuing the health risks of particulate air pollution in the Pearl River Delta, China. Environ. Sci. Policy 15 (1), 38–47.
Hung, M.F., Shaw, D., 2004. Economic growth and the environmental Kuznets curve in Taiwan: a simultaneity model analysis. In: Human Capital, Trade, and Public Policy in Rapidly Growing Economies: from Theory to Empirics, pp. 269–290.
Jalil, A., Mahmud, S.F., 2009. Environment Kuznets curve for CO_2 emissions: a cointegration analysis for China. Energy Policy 37 (12), 5167–5172.
Jerrett, M., Burnett, R.T., Ma, R., Pope III, C.A., Krewski, D., Newbold, K.B., Thurston, G., Shi, Y., Finkelstein, N., Calle, E.E., Thun, M.J., 2005. Spatial analysis of air pollution and mortality in Los Angeles. Epidemiology 16 (6), 727–736.
Kaika, D., Zervas, E., 2013. The Environmental Kuznets Curve (EKC) theory—Part A: concept, causes and the CO_2 emissions case. Energy Policy 62 (5), 1392–1402.
Kang, Y.Q., Zhao, T., Yang, Y.Y., 2016. Environmental Kuznets curve for CO_2 emissions in China: a spatial panel data approach. Ecol. Indic. 63, 231–239.
Katsouyanni, K., Touloumi, G., Samoli, E., Gryparis, A., Le Tertre, A., Monopolis, Y., Rossi, G., Zmirou, D., Ballester, F., Boumghar, A., Anderson, H.R., Wojtyniak, B., Paldy, A., Braunstein, R., Pekkanen, J., Schindler, C., Schwartz, J., 2001. Confounding and effect modification in the short-term effects of ambient particles on total mortality: results from 29 European cities within the APHEA2 project. Epidemiology 12 (5), 521–531.
Kennedy, P., 2011. A guide to econometrics (6e). Blackwell, Malden.
Letchumanan, R., Kodama, F., 2000. Reconciling the conflict between the pollution-haven'hypothesis and an emerging trajectory of international technology transfer. Res. policy 29 (1), 59–79.
Li, X., Liu, X., 2005. Foreign direct investment and economic growth: an increasingly endogenous relationship. World Dev. 33 (3), 393–407.
Li, M., Zhang, L., 2014. Haze in China: current and future challenges. Environ. Pollut. 189 (12), 85–86.
Li, X., Qiao, Y., Zhu, J., Shi, L., Wang, Y., 2017. The "APEC blue" endeavor: causal effects of air pollution regulation on air quality in China. J. Clean. Prod. 168, 1381–1388.
Liao, X., Tu, H., Maddock, J.E., Fan, S., Lan, G., Wu, Y., Zhao, K.Y., Lu, Y., 2015. Residents' perception of air quality, pollution sources, and air pollution control in Nanchang, China. Atmos. Pollut. Res. 6 (5), 835–841.
Liu, X., Burridge, P., Sinclair, P.J., 2002. Relationships between economic growth, foreign direct investment and trade: evidence from China. Appl. Econ. 34 (11), 1433–1440.
Lopez, R., 1994. The environment as a factor of production: the effects of economic growth and trade liberalization. J. Environ. Econ. Manag. 27 (2), 163–184.
Ma, Y.R., Ji, Q., Fan, Y., 2016. Spatial linkage analysis of the impact of regional economic activities on $PM_{2.5}$ pollution in China. J. Clean. Prod. 139, 1157–1167.
Mankiw, N.G., Romer, D., Weil, D.N., 1992. A contribution to the empirics of economic growth. Q. J. Econ. 107 (2), 407–437.
Matus, K., Nam, K.M., Selin, N.E., Lamsal, L.N., Reilly, J.M., Paltsev, S., 2012. Health damages from air pollution in China. Glob. Environ. Change 22 (1), 55–66.
Mu, Q., Zhang, S.Q., 2013. An evaluation of the economic loss due to the heavy haze during January 2013 in China. China Environ. Sci. 33 (11), 2087–2094 (in Chinese).
Mu, Q., Zhang, S.Q., 2015. Assessment of the trend of heavy $PM_{2.5}$ pollution days and economic loss of health effects during 2001–2013. Acta Sci. Nat. Univ. Pekin. 51 (4), 694–706 (in Chinese).
Neidell, M.J., 2004. Air pollution, health, and socio-economic status: the effect of outdoor air quality on childhood asthma. J. Health Econ. 23 (6), 1209–1236.
Omri, A., 2013. CO_2 emissions, energy consumption and economic growth nexus in MENA countries: evidence from simultaneous equations models. Energy Econ. 40, 657–664.
Pao, H.T., Tsai, C.M., 2010. CO_2 emissions, energy consumption and economic growth in BRIC countries. Energy Policy 38 (12), 7850–7860.
Pearce, D.W., Warford, J.J., 1993. World without End: Economics, Environment, and Sustainable Development. Oxford University Press.
Pope, C.A., Thun, M.J., Namboodiri, M.M., Dockery, D.W., Evans, J.S., Speizer, F.E., Heath, C.W., 1995. Particulate air pollution as a predictor of mortality in a prospective study of US adults. Am. J. Respir. Crit. Care Med. 151 (3), 669–674.
Pope, C.A., Burnett, R.T., Thun, M.J., Calle, E.E., Krewski, D., Ito, K., Thurston, G.D., 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. Jama 287 (9), 1132–1141.
Samet, J.M., Zeger, S.L., Dominici, F., Curriero, F., Coursac, I., Dockery, D.W., Schwartz, J., Zanobetti, A., 2000. The national morbidity, mortality, and air pollution study. In: Part II: Morbidity and Mortality from Air Pollution in the United States Res Rep Health Eff Inst, 94(pt 2), pp. 5–79.
Selden, T.M., Song, D., 1994. Environmental quality and development: is there a Kuznets curve for air pollution emissions? J. Environ. Econ. Manag. 27 (2), 147–162.
Shafik, N., Bandyopadhyay, S., 1992. Economic Growth and Environmental Quality: Time-series and Cross-country Evidence, vol. 904. World Bank Publications.
Smith, J.P., 1999. Healthy bodies and thick wallets: the dual relation between health and economic status. J. Econ. Perspect. A J. Am. Econ. Assoc. 13 (2), 144–166.
Solow, R.M., 1956. A contribution to the theory of economic growth. Q. J. Econ. 70 (1), 65–94.
Song, T., Zheng, T., Tong, L., 2008. An empirical test of the environmental Kuznets curve in China: a panel cointegration approach. China Econ. Rev. 19 (3), 381–392.
Stern, D.I., 2004. The rise and fall of the environmental Kuznets curve. World Dev. 32 (8), 1419–1439.
Stern, D.I., Zha, D., 2016. Economic growth and particulate pollution concentrations in China. Environ. Econ. Policy Stud. 18 (3), 327–338.
Sun, Y., Zhuang, G., Tang, A., Wang, Y., An, Z., 2006. Chemical characteristics of $PM_{2.5}$ and PM_{10} in haze-fog episodes in Beijing. Environ. Sci. Technol. 40 (10), 3148–3155.
Sun, C., Yuan, X., Xu, M., 2016. The public perceptions and willingness to pay: from the perspective of the smog crisis in China. J. Clean. Prod. 112, 1635–1644.
Suri, V., Chapman, D., 1998. Economic growth, trade and energy: implications for the environmental Kuznets curve. Ecol. Econ. 25 (2), 195–208.
Tang, S., Selvanathan, E.A., Selvanathan, S., 2008. Foreign direct investment, domestic investment and economic growth in China: a time series analysis. World Econ. 31 (10), 1292–1309.
Theil, H., 1953. Estimation and Simultaneous Correlation in Complete Equation Systems. Central Planning Bureau, The Hague, Netherlands. Unpublished manuscript.
Tiba, S., Omri, A., 2017. Literature survey on the relationships between energy, environment and economic growth. Renew. Sustain. Energy Rev. 69, 1129–1146.
Tie, X., Wu, D., Brasseur, G., 2009. Lung cancer mortality and exposure to atmospheric aerosol particles in Guangzhou, China. Atmos. Environ. 43 (14), 2375–2377.
Torras, M., Boyce, J.K., 1998. Income, inequality, and pollution: a reassessment of the environmental Kuznets curve. Ecol. Econ. 25 (2), 147–160.
Wang, X., Bi, X., Sheng, G., Fu, J., 2006. Chemical composition and sources of PM_{10} and $PM_{2.5}$ aerosols in Guangzhou, China. Environ. Monit. Assess. 119 (1–3), 425–439.
Wang, Y., Sun, M., Yang, X., Yuan, X., 2016a. Public awareness and willingness to pay for tackling smog pollution in China: a case study. J. Clean. Prod. 112, 1627–1634.
Wang, Z., Zhang, B., Zeng, H., 2016b. The effect of environmental regulation on external trade: empirical evidences from Chinese economy. J. Clean. Prod. 114, 55–61.
Wooldridge, J.M., 2016. Introductory Econometrics: A Modern Approach (6e). South-Western Cengage Learning, USA, Mason.
World Health Organization (WHO), 2006. Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide. Global update 2005. http://apps.who.int/iris/bitstream/10665/69477/1/WHO_SDE_PHE_OEH_06.02_eng.pdf (Accessed 07 August 2017).
Xu, B., Lin, B., 2016. Regional differences of pollution emissions in China: contributing factors and mitigation strategies. J. Clean. Prod. 112, 1454–1463.
Yang, T., Gbaguidi, A., Yan, P., Zhang, W., Zhu, L., Yao, X., Wang, Z., Chen, H., 2017. Model elucidating the sources and formation mechanisms of severe haze pollution over Northeast mega-city cluster in China. Environ. Pollut. 230, 692–700.
Yanikkaya, H., 2003. Trade openness and economic growth: a cross-country empirical investigation. J. Dev. Econ. 72 (1), 57–89.
Yao, S., 2006. On economic growth, FDI and exports in China. Appl. Econ. 38 (3), 339–351.
Zellner, A., Theil, H., 1962. Three-stage least squares: simultaneous estimation of simultaneous equations. Econ. J. Econ. Soc. 54–78.
Zhang, M., Song, Y., Cai, X., 2007. A health-based assessment of particulate air pollution in urban areas of Beijing in 2000–2004. Sci. Total Environ. 376 (1), 100–108.
Zheng, M., Salmon, L.G., Schauer, J.J., Zeng, L., Kiang, C.S., Zhang, Y., Cass, G.R., 2005. Seasonal trends in PM2. 5 source contributions in Beijing, China. Atmos. Environ. 39 (22), 3967–3976.
Zheng, S., Kahn, M.E., Liu, H., 2010. Towards a system of open cities in China: home

prices, FDI flows and air quality in 35 major cities. Regional Sci. Urban Econ. 40 (1), 1–10.
Zhu, S., He, C., Liu, Y., 2014. Going green or going away: environmental regulation, economic geography and firms' strategies in China's pollution-intensive industries. Geoforum 55, 53–65.
World Bank, China SEPA, 2007. Cost of pollution in China: Economic estimates of physical damages. http://siteresources.worldbank.org/INTEAPREGTOPENVIRONMENT/Resources/China_Cost_of_Pollution.pdf (Accessed 07 August 2017).