



The role of governments in mitigating SO₂ pollution in China: a perspective of fiscal expenditure

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Received: 10 March 2020 / Accepted: 1 June 2020 / Published online: 15 June 2020
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Abstract

China has suffered from extensive and serious SO₂ pollution. The central and provincial governments have reinforced environmental awareness by increasing fiscal expenditure for environmental protection for years. This paper extended an environmental Kuznets curve (EKC) framework to evaluate the direct and indirect spillover effects of environmental awareness of provincial governments on SO₂ emissions, applying spatial econometric models. The empirical findings are as follows. (1) There exists an inverted U-shaped curve. Of 30 Chinese provinces, only 9 provinces, namely, 8 eastern provinces and Inner Mongolia, have passed the turning point at about 53,000 Yuan while the rest 21 provinces have not yet. (2) Expenditure for environmental protection is negatively correlated with SO₂ pollution. In other words, environmental awareness of governments contributes to substantially reducing SO₂ emissions. Besides, significant and negative spillover effects of environmental awareness are found, implying that provinces follow suit if neighboring provinces enhance environmental awareness by increasing spending on environmental protection, thereby reducing SO₂ emissions. (3) The SO₂ reduction policy implemented by the central government is found to have a negative impact on SO₂ emissions, implying that the policy effectively works. To conclude, the central and provincial governments play pivotal roles in addressing the problem of SO₂ pollution in China. Hence, more expenditure for environmental protection cannot be overstated for China's environmental quality improvements and sustainable development.

Keywords Environmental awareness · Fiscal expenditure for environmental protection · SO₂ pollution · EKC · Spatial econometric model · China

Introduction

The world had witnessed China's economic miracle and long-lasting industrial expansion since 1978 when reforms and opening up policies were implemented, making it one of the primary engines of global economic growth (Tong et al. 2016). To date, according to the latest statistics from the

International Monetary Fund, China surpassed the USA to become the world's largest economy in 2014, with a GDP of 17.6 trillion US dollars, based on the purchasing parity power principles (IMF 2014).

China's economic success and rapid economic development pattern are mainly characterized by highly resource-intensive industries. In other words, its economy is heavily dependent on various natural resources consumption, notably coal energy (He and Lin 2019). China has already become the largest coal consumer in the world since 2010 (BP 2010). Astonishingly, in 2019, China accounted for more than 50% of the world's total coal consumption (BP 2019). Consequently, varieties of pollutant emissions, for example, sulfur dioxide (SO₂) due to coal combustion, have been enormously emitted for years, leading China to be the largest emitter of pollutants in the world (Duan and Jiang 2017). Notably, over the past two decades, most Chinese cities still have suffered from the severity and extensiveness of SO₂ pollution (Yang et al. 2018). Serious SO₂ pollution problem has posed a huge threat to public health and has become a challenge for

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China's sustainable development (He et al. 2012; Zhou et al. 2017).

China has plagued with severe SO₂ pollution over the past decades, which has already triggered the Chinese governments' high attention to the issue and determination to take strict measures to mitigate SO₂ emissions. During the 11th Five-Year Plan period (2006–2010), the central government initiated a nationwide campaign to reduce various pollutants, including SO₂. For the purpose, China shut down a batch of highly polluting coal-fired power plants and energy-intensive heavy industries, for example, iron and steel, and cement. In the following 12th and 13th Five-Year Plans (2011–2015 and 2016–2020), the pollution reduction targets were strengthened again and more stringent measures for prevention and control of air pollution have been formulated (Zhang et al. 2016). Notably, to address regional air pollution and limit total emissions of pollutants, including SO₂, "Action Plan on the Prevention and Control of Air Pollution" was implemented in September 2013 (Cai et al. 2017). As a result, SO₂ emissions were reduced by 36% from 2013 to 2017. Besides, since thermal power plants in China are one of the major contributors to SO₂ pollution, strict "ultra-low emissions (ULE)" standards for innovating coal-fired power plants were put into effect on 1 July 2014, which enforced 580 million kW of existing installed capacity (about 71% of the total) to meet the standards by 2020 (Tang et al. 2019). These actions fully signaled the efforts of governments to solve the problem of SO₂ pollution.

On the other hand, several environmental protection-related laws have been further amended or enacted and have put into effect over the past decade in response to severe environmental pollution, including SO₂ pollution, which not only reflected the serious situations of environmental degradation in China that is urgently needed to be addressed, but also signaled the environmental concerns of the Chinese central government. The timeline of environmental protection-related laws amended or enacted is shown in Table 1.

Besides, to realize the goal of sustainable development, the Chinese governments have substantially reinforced pollutant emission control (Zheng and Shi 2016), by taking a series of active actions, for example, increasing fiscal expenditure for environmental protection. Specifically, over the past decade, it has increased spending on environmental protection from 3.5 billion Yuan in 2007 to 42.76 billion Yuan in 2018 (NBS 2019), which signaled the over-growing environmental awareness of the Chinese central government and its determination to cope with the problem of SO₂ pollution. Moreover, since the central government strengthened its environmental awareness through increasing expenditure for environmental protection, provincial authorities follow suit also by increasing local fiscal expenditure for environmental protection from 96 billion Yuan in 2007 to 587 billion Yuan in 2018.

Overall, the aggregated expenditure has risen more than 6-fold over the past decade.

Basically, the fiscal expenditure for environmental protection includes three aspects: environmental pollution control, ecological construction and protection, and energy resource conservation and utilization. Specifically, environmental pollution control refers to environmental protection management services, environmental monitoring and supervision, pollution prevention and control, pollution mitigation, and regulatory investigation. The expenditure for ecological construction and protection is used for ecological protection, ecological restoration, biodiversity protection, natural forest resource protection, forest protection, etc. Lastly, the expenditure for energy resource conservation and utilization is used to develop renewable energy and circular economy. To sum up, the expenditure for environmental protection aims at comprehensive improvements of environmental quality. In this sense, the more fiscal expenditure, the higher environmental awareness, the stronger abilities to improve environmental quality. Thus, a question arises as to whether environmental awareness of governments is attributed to SO₂ pollution reduction in China. Technically, the main aim of the research is to verify the assumption if increases in expenditure for environmental protection contribute to reducing SO₂ pollution in China.

In the environmental economics, environmental Kuznets curve (EKC) is a classical hypothesis, which dates back to Grossman and Krueger's (1991) study. It assumes a nonlinear relationship between income and pollution. Specifically, in the very first stage of economic development, environment worsens as income rises. After pollutant emissions reach the summit at a threshold of income, environmental quality becomes to improve as income continues to increase (Stern 2004; Jiang et al. 2014). The EKC hypothesis has gained huge popularity in the literature during the past decades. An extensive number of studies have been conducted for the verification of the EKC for SO₂ emissions notably in developing countries. For example, Fodha and Zaghoud (2010) focused on Tunisia, a small and open developing country, and investigated the EKC for SO₂ emissions. They observed that there was an inverted U-shaped relationship between GDP and SO₂ emissions. Miah et al. (2010) found that SO_x followed the trajectory of the EKC in most situations in Bangladesh. El Hédi Arouri et al. (2011) analyzed the relationship between SO₂ emissions and real GDP for 12 Middle East and North African countries. The results showed that no evidence for the EKC was found in 10 countries. However, the EKC was valid for two relatively industrialized countries, Egypt and Tunisia. Besides, the verification of the EKC for SO₂ in India has been conducted by Sinha (2016), and Sinha and Bhattacharya (2017). The conclusions showed that the existence of the EKC was confirmed.

On the other hand, many researchers also emphasized the verification of the EKC for developed countries. For instance,

Table 1 Environmental protection-related laws amended or enacted over the past decade

Year	Laws
2008	Law of China on prevention and control of water pollution (amendment)
2008	Circular economy promotion law of China (approval)
2009	Renewable energy law of China (amendment)
2010	Law of China on water and soil conservation (amendment)
2012	Cleaner production promotion law of China (amendment)
2014	Environmental protection law of China (amendment)
2015	Atmospheric pollution prevention and control law of China (revision)
2015	Law of China on the prevention and control of environment pollution caused by solid wastes (amendment)
2016	Marine environment protection law of China (amendment)
2016	Energy conservation law of China (amendment)
2016	Environmental impact assessment law of China (amendment)
2017	Environmental protection tax law of China (approval)
2017	Water pollution prevention and control law of China (amendment)

Kunnas and Myllyntaus (2010) paid attention to an advanced economy, Finland. They examined the linkage between per capita GDP and SO₂ emissions and concluded that a downturn in SO₂ emissions was attributed to technological development. Fosten et al. (2012) used the non-linear threshold cointegration and error correction methods and a long time series data in the UK to examine the hypothesis of the EKC. They found an inverse U shape between per capita SO₂ and income. Liddle and Messinis (2015) tested for an EKC for 25 OECD countries from 1950 to 2005 and found that 24 countries had a negative relationship between per capita SO₂ and income. Marbuah and Amuakwa-Mensah (2017) used 290 Sweden cities' data and spatial regression models to analyze the EKC. Their conclusions suggested that the EKC significantly held.

The EKC hypothesis posits that environmental degradation closely relates to income (Jiang et al. 2019). Hence, China, the most polluted country and the largest developing country in the world, is a perfect candidate for the verification of the EKC hypothesis because it not only has rapidly increased economic levels but also has suffered from serious environmental pollution (Brajer et al. 2011). Thus, over the past decade, much attention to examine if an inverted U-shaped curve phenomenon between income and pollution in China has been attracted. For example, Hao et al. (2015) used a semi-parametric panel fixed effects regression model to explore the income-SO₂ relationship in China. They found evidence in support of an inverted U-shaped curve. Zhao et al. (2017), based on data from 30 Chinese provinces from 1999 to 2017, investigated the EKC hypothesis. Then, an inverted N-shaped curve for SO₂ was found. Besides, Xu (2018) used aggregated and disaggregated data to examine the existence of the EKC in China. They found that aggregated data at national levels

supported the EKC, which may be the result of aggregation bias. When disaggregated provincial data were used, EKC did not exist.

To obtain convincing conclusions, many researchers have introduced or have developed new methods to verify the EKC hypothesis in China, since different data and econometric techniques may lead to different conclusions. For example, Yang et al. (2015) identified the sensitivity of the EKC model and applied an extreme bound analysis method to test for the EKC hypothesis. Wang et al. (2016) applied a semi-parametric panel model to examine the existence of the EKC hypothesis. Liu et al. (2019) adopted a “drivers-pressures-state-impact-response” framework to investigate the EKC for SO₂ emissions at city levels in China. Besides, since spatial spillover effects may play an important role in the verification of the EKC, spatial econometric models were also applied in Wang and Ye (2017), Hao et al. (2018), and Xie et al.'s (2019) works.

These mentioned-above empirical studies provided various insights into the verification of the EKC and draw convincing conclusions. However, to the best of our knowledge, little attention to the impact of environmental awareness of governments on SO₂ pollution in China has been received in the EKC framework, although the government plays a decisive role in solving the problem of environmental pollution. One exception is Huang (2018). However, he ignored the possible spillover effects of environmental awareness of governments. Maddison (2006) proposed controlling for the possible spatial spillovers in the models when verifying the EKC hypothesis. In this sense, we attempt to fill this gap by adding a spatially lagged term of environmental awareness of governments in spatial econometric models. Besides, to examine the role of governments in SO₂ pollution reduction, we in this study also considered environmental protection policies issued by

governments. Thus, the main contribution of this research may be threefold. One is to verify if there exists an EKC relationship between income and SO₂ pollution in China. The second is to investigate if environmental awareness of governments contributes to reducing SO₂ emissions in the framework of EKC. The last is to consider potential spillover effects and apply spatial econometric models to discover indirect effects of environmental awareness of neighboring provinces on SO₂ emissions in own province.

The rest of this research is organized as follows. The “**Models and data sources**” section presents spatial econometric models and then introduces data sources. The “**Empirical results**” section discusses the results of spatial econometric models. The “**Conclusions and policy implications**” section concludes.

Models and data sources

In this section, we firstly present spatial econometric models and variables involved in the models, and then introduce data sources.

Spatial econometric models

We first give a classical model without spatial spillover effects, namely the ordinary least squares (OLS) model, since it usually serves as a benchmark model. It is expressed as follows.

$$\begin{aligned} LnSO_{2it} = & \beta_1 LnPCGDP_{it} + \beta_2 LnPCGDP2_{it} + \beta_3 LnEnviron_{it} \\ & + \sum_{m=1}^k f_m \chi_{it} + \alpha + \mu_i + \varepsilon_{it} \end{aligned} \quad (1)$$

where Ln denotes natural logarithm. Subscript i and t refer to province i and year t , respectively. The dependent variable, SO_2 , denotes per capita SO₂ emissions. $PCGDP$ and $PCGDP2$ represent per capita GDP and the quadratic term, respectively. $Environ$ is the key variable in the model, which signals environmental awareness of governments and determination to reduce SO₂ emissions. It is defined as the share of the fiscal expenditure for environmental protection to the total. X denotes a set of exogenous variables, including foreign direct investment (FDI), trade openness ($Trade$), the share of the secondary industry ($Second$), and energy intensity (EI). Besides, α is the constant term. μ represents the individual fixed effects. ε is the error term.

Since the OLS model is unable to capture spatial spillover effects, we then consider a spatial lag of X model (SLX), recommended by Vega and Elhorst (2015), since it has many advantages, for example, capturing externalities of exogenous

factors. It is written as follows.

$$\begin{aligned} LnSO_{2it} = & \beta_1 LnPCGDP_{it} + \beta_2 LnPCGDP2_{it} \\ & + \beta_3 LnEnviron_{it} + \beta_4 WLnEnviron_{it} \\ & + \sum_{m=1}^k f_m \chi_{it} + \sum_{m=1}^k \theta_m w_{ij} \chi_{it} + \alpha + \mu_i + \varepsilon_{it} \end{aligned} \quad (2)$$

where W denotes a spatial weights matrix. It describes the arrangement of 30 Chinese provinces in space. In this research, we consider a widely used exogenous rook contiguity spatial weights matrix (W -Rook). Specifically, elements in the matrix are 1 if one province borders another, and otherwise 0. Furthermore, W -Rook in this study is row-standardized.

In addition, for robustness, an inverse distance spatial weights matrix (W -Dist) and an economic distance spatial weights matrix (W -Econ) are also considered in the spatial econometric models. The former is defined as reciprocals of all pair provinces of Euclidean distances while the latter is defined as follows (Lin et al. 2005).

$$W_{x_{ij}} = \begin{cases} \frac{1}{|\bar{Y}_i - \bar{Y}_j|}, & i \neq j \\ 0, & i = j \end{cases} \quad (3)$$

$$\bar{Y}_i = \frac{1}{t_1 - t_0 + 1} \sum_{t_0}^{t_1} Y_{ij} \quad (4)$$

where Y_{it} represents GDP per capita of province i in year t . Note that unlike the rook and the inverse distance matrices, W -Econ is a weakly exogenous matrix.

Besides, $WLnEnviron$ is the spatially lagged environmental awareness variable, which is used to capture spatial spillover effects of environmental awareness of governments. Thus, negative coefficients β_3 and β_4 represent direct effects and indirect spillover effects, respectively, implying that increases in expenditure for environmental protection both in own provinces and in neighboring provinces will lead to mitigating SO₂ emissions.

The SLX model ignores the spatially lagged dependent variable (W^*SO_2), which may lead to omitting spillovers of SO₂ pollution. Thus, we next consider a spatial Durbin model (LeSage and Pace 2009; Elhorst, 2010), which is widely applied in empirical studies of environmental economics. It is written as below.

$$\begin{aligned} LnSO_{2it} = & \rho \sum_{j=1}^N w_{ij} LnSO_{2jt} + \beta_1 LnPCGDP_{it} + \beta_2 LnPCGDP2_{it} \\ & + \beta_3 LnEnviron_{it} + \beta_4 WLnEnviron_{it} + \sum_{m=1}^k f_m \chi_{it} + \sum_{m=1}^k \theta_m w_{ij} \chi_{it} \\ & + \alpha + \mu_i + \varepsilon_{it} \end{aligned} \quad (5)$$

where ρ is an unknown parameter to be estimated, which is also called the spatial autoregressive coefficient.

Similarly, the spatially lagged error term may be considered in the model, since it captures spatial dependence in the stochastic errors. Then, a spatial Durbin error model (SDEM) can be expressed as follows (Elhorst 2014).

$$\begin{aligned}
 \ln SO_{2it} &= \beta_1 \ln PCGDP_{it} + \beta_2 \ln PCGDP2_{it} \\
 &+ \beta_3 \ln Environ_{it} + \beta_4 W \ln Environ_{it} \\
 &+ \sum_{m=1}^k f_m \chi_{it} + \sum_{m=1}^k \theta_m w_{ij} \chi_{it} + \alpha + \mu_i + \varepsilon_{it} \\
 \varepsilon_{it} &= \lambda \sum_{j=1}^N w_{ij} \varepsilon_{it} + \nu_{it}
 \end{aligned} \tag{6}$$

As shown in Eq. (6), SDEM is made up of two equations. The first equation is the SLX model in nature. In the second equation, λ is an unknown parameter to be estimated, which is called the spatial autocorrelation coefficient. ν is an idiosyncratic component.

Explanatory variables

Next, we introduce these explanatory variables in the models one by one.

PCGDP *PCGDP* and its quadratic term *PCGDP2* are the most important variables in the EKC model. An inverted curve is assumed. In other words, pollution aggravates as income rises and then declines as income continues to rise. This is because higher income levels push the economy towards a cleaner and quality environment. Also, public concerns on the environment, and environmental awareness significantly increase, which thus requires that governments should play a pivotal role in improving environmental quality by adding expenditure for environmental protection and implementing stricter policies. Besides, for an EKC model, if $\beta_2 < 0$ and $\beta_1 > 0$, an inverted U-shaped curve is obtained. On the contrary, if $\beta_2 > 0$ and $\beta_1 < 0$, there exists a U-shaped curve. If $\beta_2 = 0$, and $\beta_1 < 0$ or $\beta_1 > 0$, a linearly decreasing or increasing relationship is found.

FDI China has been expanding its economic cooperation with multinationals since reforms and opening up policies. Consequently, FDI flows from developed countries to China. Of developing countries in the world, China has become one of the biggest FDI recipients all over the world. In 2018, FDI flowing into China amounted to 134.97 billion US dollars (NBS 2019). Definitely, China’s economic success is

greatly attributed to a large deal of FDI inflow, since it can not only be treated as important external capital but also bring advanced technologies, managerial experience, and knowledge spillovers to China, which contributes to reducing pollution. In this study, we hypothesize that the sign of FDI on SO_2 emissions is negative.

Second The secondary industry is the largest pollutant emitter and the major source of various pollutants emissions in China, notably SO_2 emissions (Wang and Wang 2019). Thus, we expect that *Second* has a positive impact on SO_2 emissions.

Trade Trade contributes to environmental quality improvements. On the one hand, imports of a huge amount of advanced machinery and equipment immediately promote improvements of production processes and are beneficial to emission reduction (Jiang et al. 2017). On the other hand, because of trade barrier and competition in export markets, clean and environmental-friendly production inputs and techniques have to be adopted and implemented in the production processes (Miller and Upadhyay 2000), which contributes to SO_2 reduction. Hence, we expect a negative impact of *Trade* on SO_2 emissions.

EI Fossil fuel combustion, notably, coal combustion, is the main contributor to SO_2 emissions in China. Most importantly, low energy efficiency implies a large amount of energy wastes, thus leading to various pollutant emissions, including SO_2 . Thus, the governments have released a batch of campaigns and have taken active steps to save energy and reduce SO_2 emissions. The key to success is to substantially reduce energy intensity. The lower energy intensity, the more energy saved, the less SO_2 emissions, and vice versa. Thus, a positive effect of energy intensity on SO_2 emissions is hypothesized in this study.

Policy China has long been suffering from the problem of serious SO_2 pollution in recent years. In order to address the ever-worsening SO_2 pollution, a series of regulations, laws, and programs had put into effect ever since environmental quality declined. Notably, in the 11th, 12th, and 13th Five-Year Plans, binding and quantitative targets for each province to reduce its aggregated SO_2 emissions were implemented. The required reduction percentage of each province is mainly dependent on its industrial structure, technological levels, development patterns, economic levels, etc. For example, eastern provinces with higher technological levels are required to reduce more SO_2 emissions than western provinces. Thus, the reduction targets describe environmental regulations of the central government for provincial governments. In this study, we consider the *Policy* variable. In addition, we also introduce a time dummy variable when the policy started to implement. Thus, we consider the interaction term of the policy reduction

variable and the year dummy variable in order to test for whether the reduction policy effectively works.

Data sources

Data for SO₂ emissions, per capita GDP, fiscal expenditure for environmental protection, and the share of the second industry in this study are available from China Statistical Yearbooks (2008–2018). Data for energy consumption are collected from China Energy Statistical Yearbooks (2008–2018). Data for FDI and trade are obtained from the Wind database.

Empirical results

We first geo-visualized the spatial distribution of per capita SO₂ emissions of 31 Chinese provinces, followed by the estimation results of spatial econometric models.

Spatial distribution of per capita SO₂ emissions

The spatial distribution of average provincial per capita SO₂ emissions in China over the period of 2007–2016 is plotted in Fig. 1.

By geo-visualizing provincial average per capita SO₂ emissions, it can be found that provinces with high per capita SO₂

emissions are clustered in North China, including Qinghai, Xinjiang, Inner Mongolia, Shanxi, Shaanxi, Gansu, Hebei, Henan, and Shandong. Moreover, two southern provinces, namely Chongqing and Guizhou, also have high per capita SO₂ emissions. In contrast, most of the southeastern provinces are mainly characterized by low per capita SO₂ emissions. Notably, three northeastern provinces, viz. Liaoning, Jilin, and Heilongjiang, are also found to have higher per capita SO₂ emissions.

We also observe from Fig. 1 that provincial per capita SO₂ emissions are likely to exhibit a positive spatial autocorrelation. In other words, per capita SO₂ emissions of a province are similar to those of its neighboring provinces, which may violate an assumption of independence of data. Hence, we conducted a Moran test to examine if there is positive spatial dependence among provincial per capita SO₂ emissions. Technically, Moran’s *I* statistic for provincial per capita SO₂ emissions was calculated. The test results indicate that Moran’s *I* (Moran’s *I* = 0.2826) is significant and positive, indicating a positive spatial autocorrelation. Besides, the Moran scatterplot is given in Fig. 2.

Expenditure for environmental protection

Since China’s environment has worsened in recent years, the Chinese central government and provincial governments have

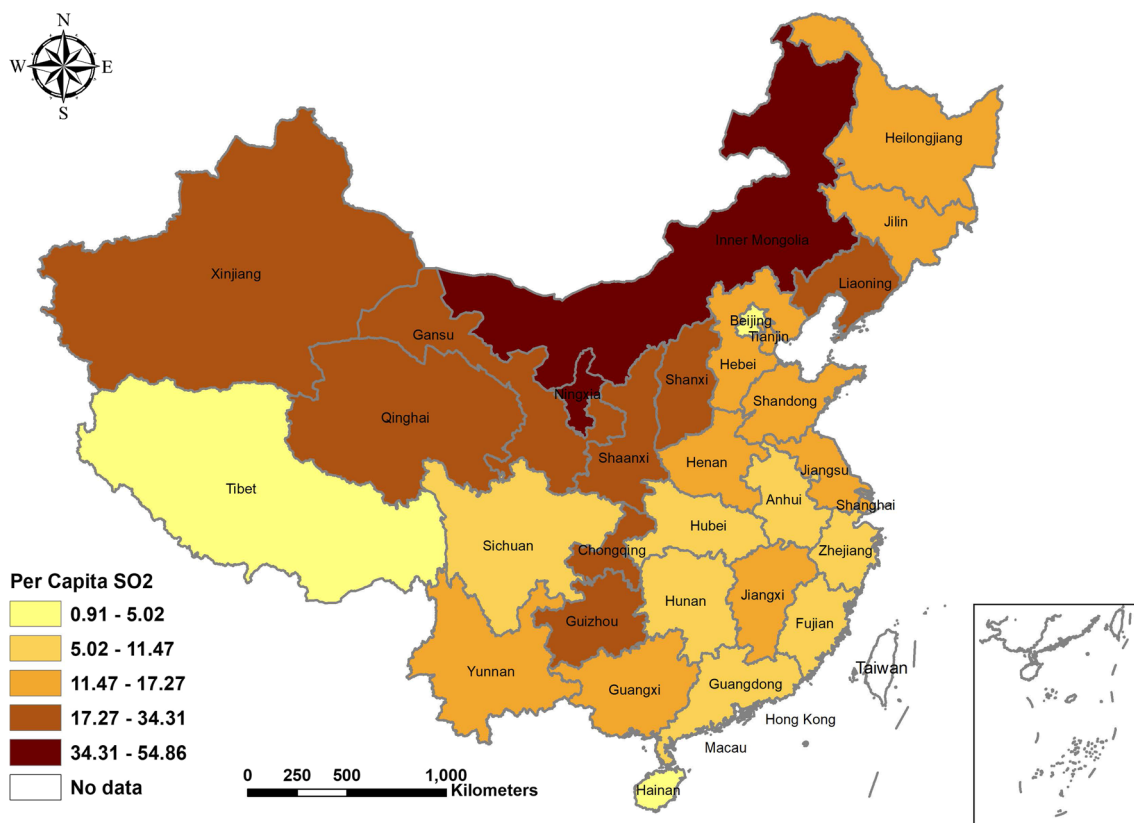
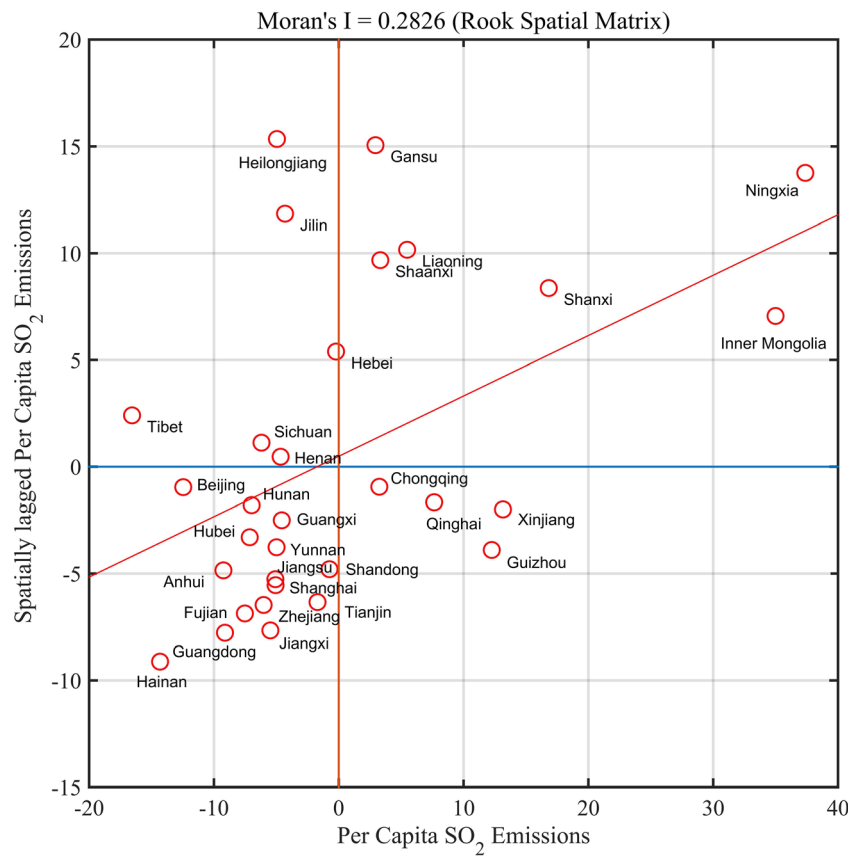


Fig. 1 Spatial distribution of provincial average per capita SO₂ emissions

Fig. 2 Moran scatterplot for provincial per capita SO₂ emissions

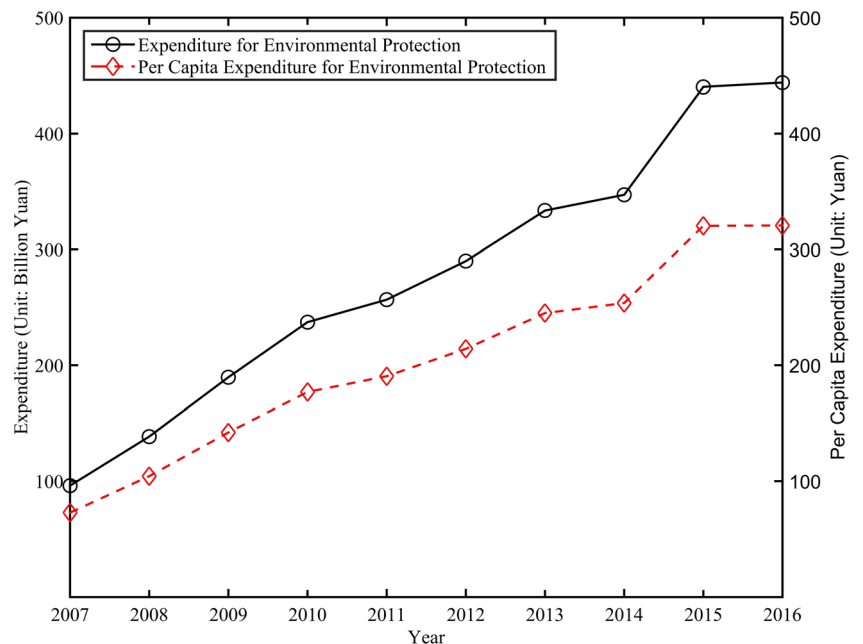


been aware of the importance of environmental quality and thus have substantially increased fiscal expenditure for environmental protection in a bid to mitigate pollution and realize the goal of sustainable development. Then, we plot the yearly

aggregated and per capita expenditure for environmental protection in China from 2007 to 2016 (Fig. 3).

Figure 3 shows that the aggregated fiscal expenditure for environmental protection continuously and significantly increased over the past decade. It clearly presents an upward

Fig. 3 Aggregated and per capita expenditure for environmental protection



trend over the sample period. On the other hand, per capita expenditure exhibits a similar trend to that of the aggregated expenditure, fully indicating that the Chinese governments have increased environmental awareness and have signaled determination to reduce SO₂ pollution by expanding expenditure for environmental protection.

Results of spatial econometric models

Before spatial econometric models, we present the results of the OLS, the fixed effects, and the random effects models without spatial spillovers considered. The estimation results are summarized in Table 2.

As shown in Table 2, it can be found that in model (1), *LnPCGDP* is negative but highly insignificant while *LnPCGDP2* is highly significant and positive, indicating that there exists no evidence of EKC. This is because the OLS model does not control for the fixed effects, which may lead to biased results. Then, we performed the estimation of the fixed effects model, namely, model (2). We observe that *LnPCGDP2* is significant and negative while *LnPCGDP* is significant and positive, indicating that there is an inverted U-shaped curve. In other words, income firstly drives SO₂ emissions up. However, as income levels continue to rise, SO₂ emission goes down. Thus, we obtain a turning point at 28,073 Yuan. Based on the calculated turning point, it is computed that most of 30 provinces have already passed it. Obviously, the conclusion is counterintuitive since the turning

point is fairly low. China has not yet been an industrialized country, having lower income per capita than that of advanced economies. Hence, we conclude that it is underestimated.

Moreover, we also presented the fixed effects model controlling for *Policy*Time* and *Time* variables in a bid to compare the two fixed effects models. It can be found that an inverted U-shaped curve is also confirmed in model (3), similar to that of model (2). However, it is calculated that a turning point at 50,304 Yuan in model (3) is larger than that in the model (2). We can draw a robust conclusion that model (2) is greatly underestimated. On the other hand, we also estimated the random effects model. The results are shown in model (4). Similarly, an inverted U-shaped curve is obtained. However, it has a turning point at 143,636 Yuan. Obviously, it is overestimated. It is of more interest in comparing the fixed and random effects models. We conducted a Hausman test to examine the fixed effects model against the random effects model. The results show that the null hypothesis of “difference in coefficients not systematic” can be strongly rejected. In other words, the test results are in favor of the fixed effects model.

Next, we present the result of the fixed effects SLX models. Instead of the spatial lag model and the spatial error model, we opt for the SLX model due to two reasons. One is that there are no theoretical grounds that per capita SO₂ emissions in one province is directly affected by per capita SO₂ emissions in its neighboring provinces. In other words, SO₂ emissions generated in a specific province is merely dependent on its own

Table 2 Results of OLS, fixed effects, and random effects models

Variables	Model (1) OLS	Model (2) Fixed effects	Model (3) Fixed effects	Model (4) Random effects
<i>LnEnviron</i>	− 0.0869 (0.0574)	− 0.0824 (0.0582)	− 0.1641*** (0.0403)	− 0.1641*** (0.0413)
<i>LnFDI</i>	− 0.0050 (0.0239)	− 0.0192 (0.0311)	− 0.0302 (0.0214)	− 0.0108 (0.0210)
<i>LnTrade</i>	0.0361 (0.0229)	− 0.0333 (0.0518)	− 0.2122*** (0.0373)	− 0.1543*** (0.0314)
<i>LnSecond</i>	1.1447*** (0.0997)	0.7614*** (0.1811)	0.2600** (0.1273)	0.4236*** (0.1212)
<i>LnEI</i>	1.3743*** (0.0736)	1.0694*** (0.1894)	0.5864*** (0.1337)	0.8540*** (0.1083)
<i>LnPCGDP</i>	− 0.0847 (0.1366)	0.3780** (0.1531)	0.5735*** (0.1087)	0.4967*** (0.0975)
<i>LnPCGDP2</i>	0.1797*** (0.0567)	− 0.1831*** (0.0627)	− 0.1775*** (0.0432)	− 0.0932** (0.0424)
<i>Policy*Time</i>			− 0.5995* (0.3405)	− 0.5946* (0.3561)
<i>Time</i>			− 0.4905*** (0.0633)	− 0.4601*** (0.0661)
Constant	− 4.5845*** (0.4410)	− 2.0457** (0.7916)	2.4702*** (0.6055)	0.9270* (0.5626)
Curve	U-shaped	Inverted U-shaped	Inverted U-shaped	Inverted U-shaped
Turning point	No turning point	28,073	50,304	143,636
Observations	300	300	300	300
R-squared	0.798	0.589	0.809	

Standard errors in parentheses

**p* < 0.10

***p* < 0.05

****p* < 0.01

industrial size, industrial structure, energy type consumed, technological levels, etc., rather than SO₂ emissions generated in its neighboring provinces. Technically, if we use SO₂ concentrations in this study, then the SO₂ pollution of a province is deeply affected by that of its neighbors. In this sense, the spatial lag model could be more appropriate since it can capture spatial spillovers of SO₂ concentrations. Instead, we consider SO₂ emissions in this study. Technically, the spatially lagged SO₂ emissions are unnecessarily considered and the SLX model may be more appropriate. The second reason that we do not consider the spatial error model is that the SLX model does not cause biased estimates, though little loss of estimation efficiency. What’s more, the SLX model can be estimated fast and its coefficients can be interpreted easily and directly.

Note that only the spatial lag of the *Environ* variable is considered in the SLX models, since we assume that spillovers of environmental awareness of governments play a decisive role in SO₂ pollution reduction. Besides, three types of spatial weights matrices, namely, W-Rook, W-Dist, and W-Econ, are adopted. The estimation results are summarized in Table 3.

From models (5)–(7) shown in Table 3, the estimation results of the SLX models with three types of spatial weights matrices are presented. Regarding the key variable, *Environ*, we find that it is also significant and negative, implying that an increase in expenditure for environmental protection in own province contributes to mitigating SO₂ emission. In other words, the direct effect of environmental awareness works. On the other hand, its spatial lag in each SLX model is also found to be negative and significant, implying that increases in expenditure for environmental protection in neighboring provinces will drive down SO₂ emissions in own province. In other words, the indirect spillover effects of environmental awareness of governments play important roles in reducing SO₂ emissions. One possible interpretation is that one follows suit if its neighboring provinces enhance environmental awareness by expanding fiscal expenditure for environmental protection, thereby reducing its own SO₂ emissions and improving environmental quality. In other words, the demonstration effect works. Another possible explanation may be a competition effect. Specifically, a province with high environmental awareness increases its fiscal expenditure to reduce SO₂ emissions, which contributes to political prestige and promotion of local provincial officials. In turn, it may enforce neighboring polluting provinces to pay more attention to environmental quality improvements by adding more expenditure for environmental protection, thus contributing to mitigating SO₂ emissions. To conclude, environmental awareness of governments is of utmost importance for SO₂ emission reduction in China.

Besides, it is worth noting that an inverted U-shaped curve is found for each model. However, different spatial weights

matrices lead to different turning points. Table 3 displays that model (5) has a similar turning point with model (7) at above 53,101 Yuan, slightly higher than that (50,304) of model (3). However, model (6) with W-Econ has a higher turning point at 70,107 that may be overestimated. One possible interpretation is that W-Econ cannot be taken to be exogenous relative to the strong exogenous W-Rook and W-Dist.

Since the results of model (5) are similar to those of model (7), we will discuss the estimated coefficients of explanatory variables based on model (5). *FDI* is found to be significant and negative, as expected, indicating that the more FDI inflows, the more advanced technologies, the less SO₂ emissions, the better environmental quality. In other words, it shows the supportive evidence of the “pollution halo” effect. Hence, deeper reform to widen channels to attract more FDI inflows into China should be highly encouraged. Similarly, The *Trade* variables has a significant and negative impact on SO₂ emissions, indicating that the expansion of trade openness to the international community may enhance environmental standards and contribute to SO₂ emission reduction. The impact of the *Second* variable is found to be significant and positive, in line with our expectations, indicating that an expansion of the secondary industry will definitely increase SO₂ emissions. Since the secondary industry is the main contributor to environmental pollutants, including SO₂ emissions, the optimization of the industrial structure by lowering the share of the secondary industry should be urgently needed. Similarly, the energy intensity variable (*EI*) also has a significant and positive impact on SO₂ emissions, indicating that the higher energy intensity, the lower energy technology, the more SO₂ emissions. Besides, the interaction term, *Policy*Time*, is verified to be negative and significant, implying that the SO₂ reduction policy effectively works. Again, it fully implies that the role of governments in mitigating SO₂ emissions cannot be overstated in China.

It is of great significance to disclose which provinces have already passed the turning point. It is calculated that 8 eastern provinces, namely, Beijing, Tianjin, Shandong, Shanghai, Jiangsu, Zhejiang, Fujian, Guangdong, and a western province, Inner Mongolia, have already passed. In contrast, the rest 21 provinces have not yet. Then, we estimated the number of years to approach the turning point for these 21 provinces (Jiang et al. 2014).

$$Turning = PCGDP_i \times (1 + \theta_i)^{N_i} \tag{7}$$

where the turning point *Turning* in the left hand of Eq. (7) is taken 53,101 Yuan. *PCGDP_i* denotes the current GDP per capita of province *i*. θ is the average growth rate of GDP per capita. *N_i* for each province can be easily obtained after natural log transformation. The years to pass the turning point at 53,101 of 30 Chinese provinces are summarized in Table 4.

Table 3 Results of SLX models with different spatial weights matrices

Variables	Model (5) W-Rook	Model (6) W-Econ	Model (7) W-Dist	Model (8) W-Rook	Model (9) W-Econ	Model (10) W-Dist
<i>LnEnviron</i>	-0.0728 (0.0471)	-0.1195*** (0.0404)	-0.1205*** (0.0445)	-0.1087** (0.0472)	-0.1430*** (0.0398)	-0.1898*** (0.0431)
<i>LnFDI</i>	-0.0222 (0.0210)	-0.0285 (0.0207)	-0.0265 (0.0213)	-0.0038 (0.0209)	-0.0165 (0.0204)	-0.0067 (0.0215)
<i>LnTrade</i>	-0.2332*** (0.0369)	-0.2520*** (0.0373)	-0.2424*** (0.0394)	-0.2211*** (0.0377)	-0.2499*** (0.0377)	-0.2165*** (0.0403)
<i>LnSecond</i>	0.2961** (0.1249)	0.3095** (0.1238)	0.2645** (0.1263)	0.4141*** (0.1237)	0.3955*** (0.1208)	0.3992*** (0.1268)
<i>LnEI</i>	0.5406*** (0.1314)	0.5151*** (0.1305)	0.5614*** (0.1331)	0.6728*** (0.1296)	0.5941*** (0.1285)	0.7340*** (0.1316)
<i>LnPCGDP</i>	0.5286*** (0.1071)	0.4557*** (0.1088)	0.6366*** (0.1115)	0.2760*** (0.0847)	0.2660*** (0.0828)	0.3236*** (0.0888)
<i>LnPCGDP2</i>	-0.1583*** (0.0426)	-0.1170*** (0.0442)	-0.1904*** (0.0433)			
<i>Policy*Time</i>	-0.5589* (0.3334)	-0.6426* (0.3300)	-0.5648* (0.3383)	-0.7058** (0.3391)	-0.7538** (0.3310)	-0.7569** (0.3471)
<i>Time</i>	-0.5055*** (0.0620)	-0.5132*** (0.0615)	-0.5073*** (0.0632)	-0.4829*** (0.0632)	-0.5012*** (0.0620)	-0.4735*** (0.0649)
<i>W*LnEnviron</i> (W-Rook)	-0.2627*** (0.0740)			-0.2976*** (0.0751)		
<i>W*LnEnviron</i> (W-Econ)		-0.3406*** (0.0797)			-0.4083*** (0.0764)	
<i>W*LnEnviron</i> (W-Dist)			-0.2636** (0.1182)			-0.1941 (0.1211)
Constant	2.8422*** (0.6016)	3.2304*** (0.6128)	3.0806*** (0.6603)	2.3185*** (0.5990)	2.9953*** (0.6133)	2.2313*** (0.6532)
Curve	Inverted U-shaped	Inverted U-shaped	Inverted U-shaped	Linear	Linear	Linear
Turning point	53,101	70,107	53,214			
Observations	300	300	300	300	300	300
<i>R</i> -squared	0.818	0.822	0.813	0.808	0.817	0.799

Standard errors in parentheses

* $p < 0.10$

** $p < 0.05$

*** $p < 0.01$

From Table 4, we find that 21 provinces have not yet passed the turning point. Of 21 provinces, 17 provinces will pass the turning point within no more than 5.5 years while four provinces, namely, Shanxi, Guizhou, Yunnan, and Gansu, will pass within approximately 8 years. Moreover, the average of years to pass the turning point for these 21 provinces is 4.25 that is very close to the median value (4.32). Besides, the average years to pass the turning point for four regions, namely, East, Northeast, Middle, and West, are also given in Table 4.

The SLX is an appropriate model in this study. However, to verify if $W*SO_2$ or $W*\varepsilon$ should be considered, that is to say, SDM or SDEM, we may apply a Lagrange multiplier (LM) test, suggested by Anselin et al. (1996). However, the LM test is sensitive to the spatial weights matrix used in the models, and different matrices may lead to conflicting conclusions.

Hence, we directly reported the results of SDM and SDEM with three matrices.

Besides, it is computed that 21 Chinese provinces had not reached the turning point. In other words, most provinces are in the left hand of the inverted U curve, implying that there is a monotonically increasing relationship between income and per capita SO_2 emissions. In what follows, we took a reduced form of SDM and SDEM, namely, a linear model, to re-examine the role of governments in mitigating SO_2 pollution in China. One big advantage is that it may avoid the potential problem of multicollinearity that EKC models usually suffer due to the quadratic term of income. Lastly, the results of SDM and SDEM are summarized in Table 5.

As shown from columns 2 to 4 in Table 5, the results of SDM are sensitive to spatial weights matrices, judging

Table 4 Years to approach the turning point

East		Northeast		Middle		West	
Province	Years	Province	Years	Province	Years	Province	Years
Beijing	Passed	Liaoning	0.04	Shanxi	7.18	Inner Mongolia	Passed
Tianjin	Passed	Jilin	0.91	Anhui	4.93	Guangxi	5.31
Hebei	3.73	Heilongjiang	2.79	Jiangxi	4.68	Chongqing	0.89
Shanghai	Passed			Henan	3.55	Sichuan	4.32
Jiangsu	Passed			Hubei	2.20	Guizhou	7.35
Zhejiang	Passed			Hunan	3.79	Yunnan	7.41
Fujian	Passed					Shaanxi	2.24
Shandong	Passed					Gansu	7.92
Guangdong	Passed					Qinghai	4.28
Hainan	5.36					Ningxia	5.09
						Xinjiang	5.15
Mean	4.54	Mean	1.25	Mean	4.39	Mean	5.00

from the estimated spatial autoregressive coefficients (ρ) of models (11) to (13). The estimated ρ of model (11) with the rook matrix is only found to be significant. Similarly, the estimated spatial autocorrelation coefficients (λ) of model (14) and model (16) have different values. Model (14) has a significant and positive coefficient λ while model (16) has a negative one. To conclude, spatial weights matrix determines the results of spatial econometric models. However, it can also be found that each coefficient of the explanatory variables in models (11) to (16) slightly varies. Besides, we observe that in these models $LnEnviron$, its spatial lag ($W*LnEnviron$), $Policy*Time$, and $Time$ all have significant and negative effects on SO_2 emissions. To conclude, the Chinese governments have played a pivotal role in the SO_2 emission reduction through increasing fiscal expenditure for environmental protection and implementing strict environmental policies during the past decade.

Conclusions and policy implications

The main aim of this study is to examine the role of the Chinese governments in SO_2 emission reduction and then evaluate potential spatial spillovers of environmental awareness of governments. To this end, we adopted spatial econometric models to verify the impact of governments' fiscal expenditure for environmental protection on SO_2 emissions in the EKC framework using panel data of China's 30 provinces. The main findings and relevant policy implications are as follows.

Firstly, an inverted U-shaped curve was verified. Notably, 8 economically developed eastern coastal

provinces and one western province have already passed the turning point at about 53,000 Yuan, while the rest 21 provinces have not yet. Due to high technological levels, most of the eastern provinces have reduced substantial SO_2 emissions. However, we observe that the eastern Hebei province has still been suffering from the problem of SO_2 pollution. This is because its economy is mainly characterized by heavy industries, notable steel, which leads it to the most polluted province in China. Hence, the Chinese central government should pay much more attention to Hebei province since it strongly determines the air quality of the North China Plain. Besides, more preferential policies to upgrade and optimize the industrial structure by lowering the share of heavy industries should be urgently needed.

Secondly, both the $Environ$ variable and its spatial lag are found to be highly significant and negative, indicating that increases in fiscal expenditure for environmental protection both in own province and in neighboring provinces contribute to SO_2 pollution reduction. In addition, indirect spatial spillovers of environmental awareness of provincial governments effectively work. Technically, the demonstration effect exhibits. This is because economic growth is not a sole indicator to evaluate the political performance of provincial governments. They have faced a new challenge as of how to balance the nexus between economic growth and environmental quality. As a result, provincial fiscal expenditure for environmental protection has been increasing in recent years. It also indicates that environmental awareness of governments has become prominent. Because of the demonstration effects, provinces tend to follow suits if neighboring provinces achieve the trade-off between local economy and environmental

Table 5 Results of spatial Durbin models and spatial Durbin error models

	SDM			SDEM		
	Model (11) W_Rook	Model (12) W_Econ	Model (13) W_Dist	Model (14) W_Rook	Model (15) W_Econ	Model (16) W_Dist
<i>LnEnviron</i>	- 0.0989** (0.0422)	- 0.1058*** (0.0372)	- 0.1516*** (0.0397)	- 0.1093*** (0.0400)	- 0.1113*** (0.0362)	- 0.1522*** (0.0397)
<i>LnFDI</i>	- 0.0135 (0.0195)	- 0.0380** (0.0187)	- 0.0229 (0.0195)	- 0.0132 (0.0201)	- 0.0398** (0.0186)	- 0.0227 (0.0193)
<i>LnTrade</i>	- 0.1905*** (0.0374)	- 0.2446*** (0.0348)	- 0.2106*** (0.0380)	- 0.1977*** (0.0365)	- 0.2437*** (0.0347)	- 0.2164*** (0.0378)
<i>LnSecond</i>	0.3130*** (0.1231)	- 0.0572 (0.1469)	0.0664 (0.1490)	0.3140*** (0.1237)	- 0.0490 (0.1460)	0.0203 (0.1502)
<i>LnEI</i>	0.5184*** (0.1483)	0.4489*** (0.1246)	0.6955*** (0.1314)	0.4978*** (0.1446)	0.4480*** (0.1244)	0.6966*** (0.1317)
<i>LnGDP</i>	0.6629*** (0.1157)	0.9604*** (0.1779)	1.1659*** (0.1952)	0.6682*** (0.1134)	0.9457*** (0.1756)	1.2271*** (0.1969)
<i>W*LnEnviron</i>	- 0.3123*** (0.0711)	- 0.4665*** (0.0798)	- 0.2065 (0.1473)	- 0.3640*** (0.0702)	- 0.4857*** (0.0747)	- 0.1278 (0.1145)
<i>W*LnFDI</i>	- 0.0436 (0.0447)	- 0.1986*** (0.0493)	- 0.0816 (0.1457)	- 0.0363 (0.0470)	- 0.2024*** (0.0494)	- 0.0543 (0.1350)
<i>W*LnTrade</i>	- 0.0440 (0.0630)	0.0427 (0.0718)	0.0643 (0.1138)	- 0.0763 (0.0675)	0.0335 (0.0715)	0.1068 (0.0898)
<i>W*LnSecond</i>	0.5263** (0.2175)	0.4697** (0.2475)	0.7625** (0.3970)	0.6593*** (0.2310)	0.4846** (0.2500)	0.6927*** (0.3162)
<i>W*LnEI</i>	- 0.4897** (0.2338)	0.0757 (0.2189)	- 0.7695** (0.3788)	- 0.3204 (0.2456)	0.1051 (0.2172)	- 0.7976*** (0.3019)
<i>W*LnGDP</i>	- 0.6226*** (0.1659)	- 0.8820*** (0.2100)	- 1.4256*** (0.2832)	- 0.5482*** (0.1795)	- 0.8643*** (0.2091)	- 1.4764*** (0.2537)
<i>Policy*Time</i>	- 0.7034** (0.3036)	- 0.6237** (0.2943)	- 0.7174** (0.3154)	- 0.7905** (0.3368)	- 0.6182** (0.2959)	- 0.6822** (0.2974)
<i>Time</i>	- 0.3915*** (0.0665)	- 0.4732*** (0.0812)	- 0.5721*** (0.1242)	- 0.4669*** (0.0660)	- 0.5099*** (0.0603)	- 0.4572*** (0.0566)
ρ	0.1600* (0.0722)	0.0620 (0.0972)	- 0.2000 (0.1917)			
λ				0.2340* (0.0749)	0.0400 (0.1014)	- 0.3520* (0.2100)
Observations	300	300	300	300	300	300
R-squared	0.8248	0.8368	0.8165	0.8253	0.8367	0.8169

Standard errors in parentheses

* $p < 0.10$ ** $p < 0.05$ *** $p < 0.01$

quality by increasing expenditure for environmental protection. Besides, regarding the SO₂ reduction policy issued by the central government, it has been confirmed to be valid. Thus, we conclude that the Chinese central governments definitely play decisive roles in reducing SO₂ pollution. To sum up, the role of governments in mitigating SO₂ emissions cannot be overstated. Thus, to improve the environmental quality in China, gradually increasing fiscal expenditure for environmental protection should be highly encouraged.

Lastly, regarding other explanatory variables, the share of the secondary industry and energy intensity has positive impacts on SO₂ emissions, indicating that they are the main contributors to SO₂ pollution. The secondary industry is the biggest energy consumer in China, accounting for more than 60% of the total energy use, which is responsible for high energy intensity and SO₂ pollution in

China. Hence, industrial upgrading and optimization are urgently needed. China has been experiencing a transition towards the tertiary industry-dominated economy, featured by high value-added and low pollution. However, compared with advanced countries, serious environmental pollution still remains the largest threat to China's sustainable development. An effective solution is to promote technological progress. From the estimation results, we find that trade openness and foreign direct investment have negative impacts. This is because they bring advanced technologies. Thus, the Chinese government should further deepen economic reforms and widen the channels of foreign capital into China because not only they stimulate economic growth but also advanced technologies flowing into China can create positive externalities, which contributes to reducing the environmental pollution.

Funding information The authors are grateful for the financial supports provided by the Ministry of Education of Humanities and Social Science project of China (17YJC790061), the Natural Science Foundation of Zhejiang Province (LY19G030013), and the National Natural Science Foundation of China (41761021).

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