RESEARCH ARTICLE

Fiscal decentralization, environmental regulation, and pollution: a spatial investigation

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Abstract
To investigate the effects of regulation on environmental pollution under Chinese-style fiscal decentralization, this research analyzes annual data over the period 2003 to 2017 covering 30 provinces in China with the spatial economic model. The empirical results show significant spatial agglomeration effects on the emissions of wastewater, sulfur dioxide, and solid waste. Environmental regulation helps reduce discharge of wastewater and solid waste, but does not help reduce the emission of sulfur dioxide; because there is significantly positive externality in treating pollutants with high fluidity, cost is larger than revenue for local governments. The relationship between fiscal decentralization and pollutants shapes an inverted U-shaped curve. We finally offer some implications in accordance with our empirical finding, such as the intensity of environmental regulation should be suitable for economic development, different measures should be taken based on the fluidity of pollutants, and a new evaluation system should be established.

Keywords Fiscal decentralization · Environmental regulation · Spatial economic model

JEL classifications H77 Q53

Introduction

China has achieved tremendous economic development and become the world's largest economy in 2014 (Xu 2018). Its rapid economic development has been accompanied by a large number uses of natural resources and magnanimous increases in the pollutant discharge, which may severely affect human health and do great damage to the ecosystem (Zhao et al. 2019). Thus, how to tackle the problem of economic development and environmental pollution becomes a hot topic (Wen et al. 2016). As the environmental pollutants have caused severe damage, the government of China has taken measures to reduce pollutants' discharge that have been quite effective. For example, the emissions of sulfur dioxide (SO_2) have reduced gradually from the highest value of 25.88

million tons in 2006 to 8.75 tons in 2017, and the discharges of wastewater and solid waste have both fallen continuously. However, environmental pollution is still serious in China, and thus research from different perspectives has been launched by scholars all over the world, which can be separated into three categories: the influence of fiscal decentralization on environmental pollution, the impact of environmental regulation on pollutants' discharge, and how economic growth affects environmental pollution.

The main debate on fiscal decentralization and environmental pollution is whether the former may aggravate the latter. Some scholars hold an opinion that fiscal decentralization may improve environmental quality—that is, the phenomenon of "race to the top." As a sound infrastructure can thus attract various production factors to flow in easily (Tiebout 1956), under the mechanism of "voting by foot," the public can express its preferences for public welfare, and thus local governments are confronted with a greater supply of public goods and better environmental quality (Stigler 1957; Markusen et al. 1995). Wellisch (1995) points out that if the level of regional openness is high, then local residents only get part of the profits of the enterprise, but they need to bear the total pollution costs, and so regional competition may lead to excessive environmental protection. Some scholars analyze

the relationship between fiscal decentralization and environmental pollution from the perspective of resource allocation. Oates (1972) holds the opinion that fiscal decentralization may bring better resource allocation by improving public spending efficiency and aggregate welfare. Millimet (2003) examines the impact of fiscal decentralization on environmental pollution and by the mid-1980s finds that decentralization helps local governments to improve the efficiency of resource allocation. As local governments have more financial autonomy under a decentralized system, they can provide more efficient public service (Faguet 2004; Blomquist et al. 2010). Moreover, local governments with a higher degree of fiscal decentralization have plenty of environmental governance funds and can control the discharge of pollutants (Tan and Zhang 2015). Potoski (2001) draws a similar conclusion by analyzing the environmental effects of the U.S. Clean Air Act. Mu (2018) explains the updates of an environmental target policy in China using the theoretical notion of bounded rationality and comes to a conclusion that compared with the central government, local governments have advantages in the condition of regional pollution and residents' preferences, and so they can make a strategic decision based on comprehensive information.

However, some scholars hold an opposite opinion that the effect of fiscal decentralization on environmental quality is negative—that is, the phenomenon of "race to the bottom." Supporters of this view believe that as environmental governance has a high degree of positive externality and environmental pollution can cross administrative boundaries easily, "free riding" may appear. Because an evaluation mechanism is mainly based on economic growth, local governments will pay less attention to environmental quality and more to economic development (Silva and Caplan 1997), which leads to the distortion of resource allocation and aggravation of environmental pollution (Holmstrom and Milgrom 1991). Gray and Shadbegian (2004) analyze the benefits to the surrounding population from pollution abatement and come to a conclusion that compared with the central government, local governments are more likely to choose to build up enterprises with higher pollution on the boundary. When local governments are evaluated by the growth rates of the local economy, it is more rational for them to spend money on economic growth rather than environmental pollution management (He 2015) and even sacrifice natural resources for economic and political benefits (Köllner et al. 2002). Additionally, local governments may lower environmental standards to attract foreign direct investment, and local administrations would find it difficult to strictly implement environmental policies (Dean et al. 2009). Sigman (2014) explores the relationship between fiscal decentralization and water quality, and the results suggest that when decentralization is greater, the level of water pollution is higher.

As Chinese local officials are not elected by local constituents, but appointed by upper-level officials, the central government has great power in rewarding and punishing local administrations (Blanchard and Shleifer 2001). Taking this specific national condition into consideration, Chinese fiscal decentralization has its own characteristics. Ever since China's tax sharing system reform in 1994, the intergovernmental relationship presents a framework of fiscal decentralization and political centralization. The local governments then became motivated to compete in economic growth in the following 20 years (Tian and Wang 2018). As such, scholars hold a view that the environmental problems in China mainly come from local governments' pursuit of rapid economic development (Cai et al. 2008). Central and local governments have devolved their financial power, leading to local governments facing heavy expenditure and tight fiscal revenue. The influence of the deviation between financial power and administrative power makes it difficult for local governments to invest under limited financial power in public facilities, as compared to those that have a capability to intensify economic growth (Jia et al. 2011). Ljungwall and Linde-Rahr (2005) argue that the less developed regions in China are more inclined to sacrifice environmental policies to attract foreign direct investment.

Fiscal decentralization may influence environmental policy as well. Zhang et al. (2017) find that Chinese-style fiscal decentralization leads to a green paradox. Faced with the asymmetry of financial power and administrative power, local governments have to seek various kinds of fiscal revenue beyond their normal budget as well as reduce expenditure, especially public expenditure that plays little role in promoting economic growth. Environmental protection and pollution treatment are typical public welfare projects, and presently in China the responsibility of environmental protection is always borne by local governments. A problem arises in which the responsibility of central and local governments is not clear in terms of environmental protection expenditure. Therefore, it is difficult for local governments to proactively increase financial expenditure toward environmental protection, which may eventually lead to much more serious environmental pollution.

In respect of environmental regulation, there are three points. The first opinion is that environmental regulation has little effect on the discharge of pollutants. Supporters of this point believe that though environmental regulation may reduce the discharge of pollutants theoretically, under a fiscal decentralization system, local governments just pursue economic growth, and the effect of environmental regulation on pollution is scant (Zhang et al. 2017). Smulders et al. (2012) come to a similar conclusion from the supply-side aspect. The second point is that environmental regulation can reduce the discharge of pollutants. Pickman (1998) finds that environmental regulation is conducive to environmental patent activities. Rassier and Earnhart (2011) employ a panel data model to investigate how environmental regulation influences

financial performance through both short-run and long-run effects and find that environmental regulation can indeed improve financial performance. The third point is that whether environmental regulation can reduce pollutants' discharge is uncertain. Usually, environmental regulatory competition by local governments can be efficient under certain conditions, but if the conditions cannot be met, then an environmental regulation is inefficient (Levinson 2003). Chang and Wang (2010) present that it is uncertain whether a pollution discharge permit system exists superficially in some places, and that the system is applied according to varying standards in different parts of China. Chang and Hao (2017) analyze the effect of environmental performance on economic development through panel models using panel data; their empirical results show that environmental performance positively influence on economic development. Some researchers draw a similar conclusion using province-level panel data in China (Li et al. 2018).

Based on previous studies, our goal is to test how fiscal decentralization, environmental regulation, and economic growth affect environmental pollution. Moreover, we noted that environmental pollution has spatial spillover effects that differ for various pollutants. Thus, this paper uses a panel dataset of China in province level from 2003 to 2017 to analyze the impacts of fiscal decentralization, environmental regulation, and economic development on environmental pollution.

Our research contributes to the literature in several aspects. First, we investigate the potential relationship between fiscal decentralization, environmental regulation, and environmental pollution and take into consideration the interaction effect of fiscal decentralization and environmental regulation. Second, we explore the spatial autocorrelation of environmental regulation and environmental pollution. Third, we test the spillover effects of fiscal decentralization and environmental regulation on different pollutants—i.e., wastewater discharge, sulfur dioxide, and solid waste—and analyze the reasons. Finally, we put forward targeted governance strategies on the basis of the effects on different pollutants.

The rest of this article is as follows. The "Method and regression model" section describes the method and regression model employed in the analysis. The "Data and construction of variables" section explains the data and construction of variables. The "Analysis of empirical results" section shows the empirical results. The "Conclusions and policy implications" section draws the conclusion and offers policy suggestions.

Method and regression model

In order to test whether there exist spatial effects and the influence degree of fiscal decentralization and environmental

regulation on environmental pollution, we analyze the spatial characteristics of environmental pollution first and then build the spatial econometric model.

Measuring spatial distribution

Spatial autocorrelation reflects the attributes' tendency toward clustering or concentration; it represents the interdependence of observations across space that can be attributed to their relative location (Anselin 1988). We first examine the patterns of spatial concentration of pollutant discharge by measuring spatial autocorrelation. If the spatial autocorrelation is positive, high or low values of an attribute tend to cluster in space. While if the spatial autocorrelation is negative, high or low values of opposite attribute tend to cluster in space; that is, locations are surrounded by neighbors with very dissimilar values (Anselin 1996). The methods which are widely used to test the spatial autocorrelation are global spatial autocorrelation and local spatial autocorrelation (Ord and Getis 1995; Chi and Zhu 2008; Li et al. 2014).

Global spatial autocorrelation analysis

Global Moran's I is usually used to measure global spatial autocorrelation, which reflects the overall spatial relationship across all geographic units for the entire study area (Moran 1948). Global Moran's I can be calculated by Eq. (1) (Moran 1950).

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n}w_{ij}\left(x_i-\overline{x}\right)\left(x_j-\overline{x}\right)}{\sum_{i}^{n}\sum_{j=1}^{n}w_{ij}\sum_{i=1}^{n}\left(x_i-\overline{x}\right)^2} \tag{1}$$

Here, w_{ij} means the element of row i and column j in spatial weight matrix. x_i and x_j are variables' values in two geographic units i and j, $\overline{x} = \frac{1}{n}\sum_{i=1}^{n}x_i$ means the average value of variable x, and n represents the total number of space units.

The most commonly used spatial weight matrix is the 0–1 weight matrix (Porter and Purser 2010). In order to avoid the defect of the single spatial weight matrix when describing the spatial correlation of economic affairs and to investigate the robustness of regression results, aside from the 0–1 weight matrix, we also use the geographic distance matrix and economic distance nested matrix. The specific forms of the three spatial weight matrices are as follows.

(1). 0–1 weight matrix. Let $w_{ij}=1$ if units i and j are adjacent; otherwise, $w_{ij}=0$.

(2). Geographic distance matrix. $W_d = \begin{cases} \dfrac{1}{d^2}, i\neq j \\ 0, i = j \end{cases}$

Distance d is that between the two regions (measured by the longitude and latitude of their provincial capitals).

(3). Economic distance nesting matrix.
$$W = W_d \cdot \mathrm{diag}\left(\frac{\overline{Y_1}}{\overline{Y}}, \frac{\overline{Y_2}}{\overline{Y}}, \ldots, \frac{\overline{Y_n}}{\overline{Y}}\right)$$

Weight matrix W_d covers the geographical distance, $\overline{Y_i}$ is the average GDP of region i during the research period, and $\overline{Y}$ is the average GDP of all regions during the research period. The nested matrix of economic distance reflects that if a region's economic development is much higher, then it has greater influence on the surroundings.

Local spatial autocorrelation analysis

As the study area is quite huge, the spatial autocorrelations vary along with different units. Local Moran's I is used to reflect the heterogeneity of spatial association across different geographic units within the study area (Chi and Zhu 2008). Local Moran's I can be defined as Eq. (2) (Moran 1950).

$$\text{Local Moran's } I_i = \frac{n\left(x_i - \overline{x}\right)\sum_{j=1}^{n} w_{ij}\left(x_j - \overline{x}\right)}{\sum_{j=1}^{n} w_{ij}\left(x_j - \overline{x}\right)^2} \tag{2}$$

The meanings of symbols in Eq. (2) are the same as those in Eq. (1).

Spatial econometric models

If there exists spatial autocorrelation, then the results calculated by ordinary square regression (OLS) will be biased and invalid (Anselin 1988). Spatial econometric models take spatial autocorrelation into consideration.

Basic spatial models

There are two basic spatial models, i.e., spatial lag model (SAR) and spatial error model (SEM); the major difference between the two models is how spatial dependence is set in the regression equation. In the spatial lag model, explanatory variables include a spatial lag for the dependent variable. The expression for the spatial lag model is:

$$y_{it} = \delta \sum_{j=1}^{N} w_{ij} y_{jt} + c + x_{it}\beta + \varepsilon_{it} \tag{3}$$

Here, y_{it} denotes the dependent variable of unit i at time t, w_{ij} is the element of the spatial weight matrix, and the definition of spatial weight matrix is the same as that in Eq. (1); δ is the spatial autoregressive coefficient and reflects the impact of spatial interaction in dependent variable. β is the regression coefficient of independent variables. ε_{it} is the independent disturbance term. c is the intercept constant.

The expression for the spatial error model is:

$$y_{it} = c + x_{it}\beta + \varphi_{it}, \varphi_{it} = \rho \sum_{j=1}^{N} w_{ij}\varphi_{jt} + \varepsilon_{it} \tag{4}$$

Here, φ_{it} is the spatially autoregressive error term; and ρ is the spatial autoregressive coefficient. The meanings of other symbols are the same as those in Eq. (3).

As both the spatial lag model and spatial error model have some flaws, Lesage (2008) suggests integrating the spatial lag model and spatial error model to form a comprehensive spatial Durbin model (SDM). The spatial Durbin model contains the spatial lag space of both explained variables and explanatory variables and the expression is given by Eq. (5).

$$y_{it} = \delta \sum_{j=1}^{N} w_{ij} y_{jt} + x_{it}\beta + \theta \sum_{j=1}^{N} w_{ij} x_{jt} + \varepsilon_{it} \tag{5}$$

The symbols are the same meaning as those in Eq. (3) and Eq. (4).

Fixed or random effects

The Hausman diagnostic test is used to determine whether the fixed effect model or the random effect model is more appropriate. The null hypothesis is $H_0 : h = 0$, where $h = d^T[var(d)]^{-1}d$ and $d = \widehat{\beta}_{FE} - \widehat{\beta}_{RE}$. The test statistic d should be calculated by $\left[\widehat{\beta}^T, \widehat{\delta}\right]^T_{FE} - \left[\widehat{\beta}^T, \widehat{\delta}\right]^T_{RE}$ and have a chi-square distribution (Baltagi 2008). Generally, the fixed effect model is more appropriate than the random effect model (Elhorst 2014).

Relevant tests

We test which spatial econometric model is the best for analysis using the specification tests outlined by Elhorst (2012). First, the traditional mixed panel data models are estimated and the likelihood ratio test is applied to test the fixed effects. The traditional tests of R^2 and the corrected R^2 as well as logarithm likelihood function values (LogL) are taken into consideration to compare the model fitting effects. Second, Lagrange Multiplier (LM) tests (LM_{lag} and LM_{err}) and their robustness (robust-LM_{lag} and robust-LM_{err}) are employed to test whether there exist spatial effects. Third, the likelihood ratio (LR) test is used to test which spatial panel data model is the most appropriate. The null hypothesis of the LR test is $H_0 : \theta + \beta\delta = 0$, which can determine whether the SDM model can be simplified to SLM or SEM. If the null hypotheses are rejected, then the spatial Durbin model is the most appropriate.

Data and construction of variables

We employ panel data model to conduct our research[1] and the data include 30 provinces in China[2] from 2003 to 2017.[3] The variables and related explanations are as follows.

Explained variables

There are many indicators of environmental pollution, such as carbon dioxide (Lee et al. 2008; Wei et al. 2019), and PM2.5 (Zheng et al. 2005; Dominici and Schwartz 2019). Since wastewater and sulfur dioxide cause serious injury to human beings (Zhang et al. 2014; Xia et al. 2017), we choose the emissions of wastewater, sulfur dioxide, and solid waste as the environmental pollution indicators.

Explanatory variables

Environmental regulation

(1) Calculation steps of environmental regulation

Considering that environmental regulation is multidimensional and incomplete measurement errors may occur in a single index, we construct a comprehensive index of environmental regulation using the entropy method, which can reflect environmental regulation intensity. The specific steps of the entropy method are as follows (Zou et al. 2006).

First, we normalize the original data. Suppose $\{z_{ab}(t_k)\}$ is the value of sample a's bth index at time t_k ($i = 1, 2, …, m, j = 1, 2, …, n, k = 1, 2, …, T$). The method of data normalization is given by Eq. (4).

$$z_{ab}'(t_k) = \frac{z_{ab}(t_k)_{\max} - z_{ab}(t_k)}{z_{ab}(t_k)_{\max} - z_{ab}(t_k)_{\min}} \tag{6}$$

Here, $z_{ab}'(t_k)$ is the data of the bth evaluating object on the indicator, a represents a cross-section, b represents an environmental regulation indicator, $z_{ab}(t_k)$ represents the original value of the environmental regulation indicator, and $z_{ab}(t_k)_{\max}$ and $z_{ab}(t_k)_{\min}$ denote the maximum value and minimum value of the bth indicator at time t_k respectively.

Second, we define the entropy.

$$h_a(t_k) = -k \sum_{b=1}^{n} f_{ab}(t_k) \ln f_{ab}(t_k), a = 1, 2, …, m \tag{7}$$

Here, $k = \frac{1}{\ln m}$, $f_{ab}(t_k) = \frac{x_{ab}'(t_k)}{\sum_{b=1}^{n} x_{ab}'(t_k)}$, and suppose when $f_{ab}(t_k) = 0$ that $\ln f_{ab}(t_k) = 0$. As can be seen from Eq. (7), when the contribution degree of each scheme under a certain attribute tends to be the same, the value of $h_a(t_k)$ approaches 1. Specifically, if the degrees of contribution are equal, then it is not necessary to consider the role of a target attribute in decision-making, and the weight of the attribute is 0.

Third, calculate the contribution consistency coefficient of the indicators.

$$H_a(t_k) = 1 - h_a(t_k) \tag{8}$$

Fourth, define the weight of the entropy. The weight of entropy of the ath indicator can be defined as:

$$w_a(t_k) = \frac{H_a(t_k)}{\sum_{b=1}^{n} H_a(t_k)} \tag{9}$$

Here, we can see that the higher the contribution consistency coefficient is for the ath indicator, the smaller is the weight.

Fifth, calculate the comprehensive evaluation index.

$$F_a(t_k) = \sum_{b=1}^{n} w_a(t_k) \times z_{ab}'(t_k) \tag{10}$$

The greater the value is, the better is the input-output effect for environmental protection, and the more the economic output will be per-unit pollutant discharge.

(2) Status of environmental regulation

We construct the environmental regulation index from the aspects of input costs and output effects. Labor power cost, material cost, and financial cost are employed as the input cost of environmental regulation. Labor power cost is measured by the number of administrative departments, material cost is measured by the total number of wastewater treatment facilities and waste gas treatment facilities, and financial cost is calculated by the share of environmental pollution treatment investment in GDP. The output effect indicators are indicated by the ratio of industrial added value to wastewater, waste gas, and solid waste respectively. Smaller input cost indicators are better, while bigger output effect indicators are better. Given the space limitations, Table 1 lists the environmental regulation indices for some years.

Fiscal decentralization

There are several methods to measure fiscal decentralization, such as the marginal retention rate (Lin and Liu 2000) and the ratio of provincial extra-budgetary spending to central extra-budgetary (Zhang and Zou 1998; Jin et al. 2005). As we focus

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[1] The values of these variables are from the *China Statistical Yearbook* and *China Environmental Statistics Yearbook*

[2] Tibet is not included, because of its incomplete data.

[3] The reason for the data range from 2003 to 2017 is that the statistical caliber of some indicators has changed since 2003 and the updated data in 2018 and 2019 are incomplete.

Table 1 Environmental regulation indices

	2003	2005	2007	2009	2011	2013	2015	2017
Beijing	0.0513	0.0494	0.0541	0.0551	0.0554	0.0594	0.0689	0.0483
Tianjin	0.0552	0.0402	0.0375	0.0354	0.0325	0.0338	0.033	0.0473
Hebei	0.0403	0.0381	0.0387	0.039	0.045	0.0455	0.0494	0.0371
Shanxi	0.0279	0.0293	0.0292	0.0309	0.0328	0.0348	0.0366	0.0273
Neimenggu	0.0196	0.0188	0.018	0.0185	0.0212	0.0231	0.0251	0.0176
Liaoning	0.0379	0.0328	0.0324	0.0327	0.0325	0.0331	0.0346	0.0347
Jilin	0.0314	0.0266	0.0249	0.0222	0.0194	0.0201	0.0201	0.0291
shanghai	0.0456	0.0441	0.0400	0.0364	0.0334	0.0342	0.033	0.0450
Jiangsu	0.0568	0.0528	0.052	0.0502	0.0479	0.0484	0.0514	0.0545
Zhejiang	0.0607	0.0503	0.0484	0.0468	0.0456	0.0478	0.0509	0.0541
Anhui	0.0727	0.0633	0.0536	0.0533	0.0513	0.0534	0.0546	0.0656
Fujian	0.0269	0.0252	0.0223	0.0214	0.0207	0.0237	0.025	0.0247
Jiangxi	0.0432	0.0366	0.0307	0.0271	0.0285	0.0268	0.0294	0.0385
Shandong	0.0205	0.0194	0.0177	0.0175	0.0201	0.0195	0.0219	0.0188
Henan	0.0547	0.0483	0.0454	0.044	0.0439	0.0461	0.0484	0.0499
Hubei	0.0513	0.0489	0.0450	0.0435	0.0423	0.0425	0.0470	0.0488
Hunan	0.0371	0.0317	0.0295	0.0285	0.0287	0.0235	0.0268	0.0346
Guangdong	0.0370	0.0339	0.0302	0.0295	0.0253	0.0273	0.0316	0.0344
Guangxi	0.0983	0.0797	0.0725	0.0652	0.0628	0.0646	0.0696	0.0867
Hainan	0.0205	0.0195	0.0179	0.0191	0.0169	0.0183	0.0198	0.0194
Chongqing	0.0298	0.0227	0.0214	0.0176	0.013	0.011	0.0115	0.0274
Sichuan	0.0349	0.0274	0.0228	0.0204	0.0246	0.0251	0.0238	0.0294
Guizhou	0.0304	0.0298	0.0249	0.0269	0.0271	0.0264	0.0305	0.0285
Yunnan	0.0173	0.0176	0.0167	0.0154	0.0151	0.0154	0.0161	0.0173
Xizang	0.0263	0.0246	0.0217	0.023	0.022	0.0231	0.0224	0.0248
Shanxi	0.0573	0.073	0.0899	0.0594	0.0226	0.0193	0.0107	0.0812
Gansu	0.0293	0.0246	0.0233	0.0214	0.0213	0.0208	0.0208	0.0268
Qinghai	0.0183	0.0195	0.0193	0.0187	0.0158	0.0199	0.0190	0.0187
Ningxia	0.0171	0.0115	0.0102	0.0087	0.0083	0.0089	0.0083	0.0140
Xinjiang	0.0184	0.0124	0.015	0.0106	0.0111	0.0113	0.0123	0.0156

on how local governments' fiscal autonomy affects environment, fiscal decentralization is expressed as $FD = fdp/(fdp + fdf)$ based on the specific situation of China (Chen 2004), where fdp and fdf denote the per-capita fiscal expenditure and budget revenue at the provincial level and central level, respectively. If fdp and fdf represent per-capita fiscal expenditure at the provincial and central levels, then fiscal decentralization (FD) denotes fiscal expenditure decentralization (FDE). Similarly, if fdp and fdf represent per-capita budget revenue at the provincial and central levels, then FD denotes fiscal revenue decentralization (FDV) (He 2015). We employ FDV to test the robustness. Higher fiscal decentralization means more fiscal autonomy by the local governments.

Moderating and control variables

Economic aggregates (PGDP) There are many studies that investigate how economic development affects environmental pollution from different perspectives (Hettige et al. 2000; Stern and Common 2001). Grossman and Krueger (1991) note that environmental pollution increases faster than economic growth in the early stage; when the economic aggregate reaches a certain level, the environmental pollution slows down along with the improvement of GDP. This inverted U-shape relationship between pollutants and income per capita is called the environmental Kuznets curve (EKC) (Panayotou 1993). Many research studies have investigated how economic development impacts environmental quality based on the EKC hypothesis (Vukina et al. 1999; Dasgupta et al. 2002; Dinda 2004). Han et al. (2011) test the EKC hypothesis using data from 1981 to 2008 in Shandong Province, and the results show an inverted U-shape curve between SO_2 emissions and GDP per capita. Sapkota and Bastola (2017) examine the effects of income on pollution emissions and test the EKC hypothesis for Latin American countries. The empirical results indicate that the impacts of fiscal decentralization and environmental regulation on local environmental pollution vary with economic development varies. Thus, economic development is used as one of the moderating variables. We employ GDP per capita to measure the level of economic aggregates of each region.

Industrial structure (STR) Industrial structure has a great influence on environmental pollution, and environmental pollutants are mainly produced by the secondary industry (Chen et al. 2019). Thus, industrial structure is usually believed to affect environmental pollution (Jalil and Feridun 2011; Yin et al. 2015). Here, our main purpose is to investigate whether

the development of the tertiary industry helps alleviate environmental pollution. Thus, the proportion of this industry is used to indicate the industrial structure.

Foreign direct investment Foreign direct investment (FDI) can be used to reflect the market opening policy (Dong et al. 2012; Xu 2018). The actual use of FDI in a region is converted into *yuan* by the international exchange rate. We use the ratio of FDI to GDP in each province to present the status of foreign direct investment in a region.

Urbanization level (CITY) There are many specific pollutants during the process of urbanization, and thus urbanization should be taken into consideration as a factor that affects environmental pollution. Liang and Yang (2019) put forward that urbanization is positively related to environmental pollution. The ratio of urban population to total population is employed to indicate the urbanization.

The definitions and descriptive statistics of indicators are shown in Table 2.

To examine whether there are problems of multicollinearity, Table 3 presents a correlation matrix of wastewater estimation equation.[4] Moreover, we also provide variance inflation factors (VIFs).

As seen from the correlation matrices, some explanatory variables correlate with each other, but the maximum value of VIF is 8.29, which is less than 10, and thus the multicollinearity between variables can be tolerated (Schroeder et al. 1990). As the interaction terms of variables are used in the following empirical analysis, we will run the equations separately as well.

Analysis of empirical results

Spatial autocorrelation analysis

We estimate the distributions of wastewater, SO_2, solid waste, and environmental regulation in China. Table 4 summarizes the global Moran's I values of wastewater, SO_2, solid waste, and environmental regulation.[5] From Table 4, we can see that Moran's I values are significant for wastewater, SO_2, solid waste, and environmental regulation (at the 10% significance level). Moreover, the values of Moran's I are positive, indicating that there are positive spatial correlations for environmental pollutants and environmental regulation—that is, areas with serious environmental pollution are usually surrounded by heavily polluted areas and areas with less serious

environmental pollution are usually surrounded by less polluted areas. The same goes for environmental regulation.

To visually reflect variations in space, local Moran's I is used in our analysis. Moran's I scatter plots of wastewater, SO_2, solid waste, and environmental regulation are depicted in Appendix Figures 1, 2, 3, and 4.[6] From the figures, we can see that most provinces are found in quadrants I and III, which suggests that there exists fairly high stability for a positive spatial correlation.

Spatial econometric estimation results

In this paper, the explanatory variables include not only the independent variables above, but also the interaction between variables. In addition to the effects of environmental regulation on environmental pollution, we also focus on the impacts of the interaction term between environmental regulation and fiscal decentralization. As for foreign direct investment, our main concern is whether fiscal decentralization has prompted local governments to lower the criteria for foreign direct investment. Therefore, we just join the interaction term of foreign direct investment and fiscal decentralization in our analysis. In the following empirical analysis, ER*FDE means the interaction between environmental regulation and fiscal decentralization as measured by expenditure. ER*FDV means the interaction between environmental regulation and fiscal decentralization as measured by revenue. FDI*FDE means the interaction between foreign direct investment and fiscal decentralization as measured by expenditure. FDI*FDV means the interaction between foreign direct investment and fiscal decentralization as measured by revenue. Moreover, the square terms of environmental regulation and economic aggregates are also taken into consideration, because we want to test whether the impacts of environmental regulation and economic aggregates on environmental pollution exhibit quadratic non-linearity.

Panel data can distinguish the effects of differences across individuals. The fixed effects model is a panel data analysis method that changes with individuals, but not with time; the heterogeneity can be ignored since the individual effects are controlled (Wang and Ho 2010).

Based on the spatial dependence test mentioned previously, spatial dependence should be taken into consideration when analyzing the effects of how environmental regulation affects environmental pollution. According to the principles proposed by Elhorst (2003) and Elhorst (2012), OLS estimation is conducted and employ LM tests as well as their robustness tests are employed to test the spatial effects. The panel data model without spatial effects is given by:

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[4] The correlation matrices of SO_2 and solid waste estimation equation are presented in Appendix Tables 17 and 18.
[5] The Moran's I is calculated by the 0–1 weight matrix.

[6] We draw Moran's I scatter plots from 2003 to 2017. Due to space limitation, only four maps are listed.

Table 2 Descriptive statistics of variables

Variable	Indicator	Unit	Obs.	Mean	Std.
Water	Discharge of wastewater	10,000 tons	450	71,636	61,724
SO$_2$	Sulfur dioxide emission	10,000 tons	450	58.43	39.16
Solid	Discharge of solid waste	10,000 tons	450	7850	7484
ER	Environmental regulation	–	450	0.0321	0.0153
FDE	Fiscal decentralization measured by expenditure	%	450	0.8104	0.0780
FDV	Fiscal decentralization measured by revenue	%	450	0.4753	0.1412
PGDP	GDP per capita	Yuan	450	35,287	24,244
STR	Proportion of tertiary industry	%	450	0.4227	0.0870
FDI	Ratio of foreign direct investment in GDP	%	450	0.0267	0.0221
CITY	Ratio of urban population in total population	%	450	0.5145	0.1446

$$Y = \alpha_0 + \alpha_1 X + \alpha_2 Z + \varepsilon \tag{11}$$

Here, Y represents the dependent variable (i.e., wastewater, SO$_2$, and solid waste); X represents the core explanatory variables, and in the paper X denotes environmental regulation, fiscal decentralization, and the interaction effect among them; and Z represents other control variables apart from environmental regulation and fiscal decentralization, which refers to the level of economic development, industrial structure, foreign direct investment, and urbanization.

Referring to Elhorst (2012), we first estimate traditional mixed panel data models. Before conducting the estimate, we employ the F statistic to determine whether the fixed effects panel data model is suitable. The values of the F statistic in the estimations of wastewater, SO$_2$, and solid waste are 49.71, 54.73, and 114.83, respectively, and $p < 0.01$ in all estimations. The null hypothesis is rejected, and the fixed effects panel model should be used (Chang et al. 2011). Tables 5, 6, and 7 present the estimation results of non-spatial panel data models.

Table 5, Table 6, and Table 7 show the empirical results of wastewater, sulfur dioxide, and solid waste respectively. The basic assumption of the *Pooled OLS* model is that there are no individual effects, and all the data are put together for an estimate using OLS regression. The *spatial fixed effects* model refers to the individual fixed effect model, and the *time-period fixed effects* model denotes the time fixed effect model.[7]

As can be seen from Tables 5, 6, and 7, when using the robust LM tests, both the hypothesis of no spatially lagged dependent variable and the hypothesis of no spatially autocorrelated error term are rejected at the 1% significance level. These results show that there exists spatial correlation, and spatial panel models are better than the non-spatial interaction effects of traditional mixed panel data models. In

addition, we use the likelihood ratio test (LR) to examine the joint significance of spatial fixed effects and time-period fixed effects. The null hypothesis that the spatial fixed effects are jointly insignificant is rejected at the 1% significance level. The null hypothesis that the time-period fixed effects are jointly insignificant is also rejected at the 1% significance level. These results show that the two-way fixed effects model is the most appropriate (Elhorst 2012). Moreover, we use the STATA command *xtistest* to test whether there exists serial correlation (Wursten 2018). The results of Inoue-Solon Statistic (IS-stat) are shown in Appendix Table 19 and do not reject the null hypothesis of no auto-correlation of any order (Born and Breitung 2016).

Thus, we construct the spatial Durbin model as Eq. (12):

$$y_{it} = c + \delta \sum_{j=1}^{30} W_{ij} y_{jt} + \alpha_1 X_{it} + \alpha_2 Z_{it} + \alpha_1 \sum_{j=1}^{30} W_{ij} X_{it}$$
$$+ \alpha_2 \sum_{j=1}^{30} W_{ij} Z_{it} + \mu_i + \lambda_t + \varepsilon_{it} \tag{12}$$

The empirical results of the spatial Durbin models are presented in Tables 8, 9, and 10.[8]

Before the interaction terms of variables are used in the empirical analysis, we repeat the analysis by removing the interaction terms separately using the SDM model. The empirical results are shown in Appendix Tables 20, 21, 22. The coefficients of the main explanatory variables remain the same (Dreher et al. 2010).

The first columns in Tables 8, 9, and 10 show the results calculated by the 0–1 rook matrix, the second columns represent the results calculated by the geographic distance matrix, and the third columns denote the results calculated by the economic distance nesting matrix.

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[7] In this part, the panel data models are used to examine whether there exist spatial effects and which spatial panel model is the most appropriate. Please see **Econometric Analysis** (Greene 2007, Prentice Hall press) for the details of the fixed panel effects models.

[8] The values of the Hausman tests in the estimations of wastewater, SO$_2$, and solid waste are 12.1931, 13.4328, and 13.7143, respectively, and $p < 0.01$ in all estimations, indicating that the random effects model must be rejected and the spatial fixed model is more suitable. Thus, we only show the results of SDM with fixed effects.

Table 3   Correlation coefficient matrix and VIF test

	VIF	Water	ER	FDE	PGDP	STR	CITY	FDI
Water		1.000						
ER	8.29	0.483***	1.000					
FDE	5.76	− 0.379***	0.030	1.000				
PGDP	5.19	0.044	0.367***	0.621***	1.000			
STR	2.30	− 0.351***	0.360***	0.518***	0.534***	1.000		
CITY	2.22	− 0.066	0.515***	0.718***	0.629***	0.714***	1.000	
FDI	1.57	0.118**	0.329***	0.080*	0.183***	0.162***	0.427***	1.000

The product terms of the explained and explanatory variables and the spatial weights matrix W in the SDM reflect how the explained and explanatory variables in the adjacent regions affect the regions' discharge of wastewater, SO_2, and solid waste.

The coefficients of W*Water, W*SO_2, and W*Solid are positive and significant at 10% or above significant level in most models, further proving that SDM model is much more suitable in this analysis. The spatial lag terms of pollutants calculated by three weight matrices are all significant, indicating that the spatial lag effects of environmental pollution not only depend on the distance or whether they are bounded by each other, but also depend on the relative development level.

According to Table 8, the findings are as follows.

Analyzing the empirical results of the spatial Durbin model with three kinds of a spatial matrix, the coefficients of environmental regulation's square term are positive at the 10% significance level in all three case, indicating that the relationship between environmental regulation and discharge of wastewater presents a conic illustration with a positive coefficient of the quadratic term. When the intensity of environmental regulation is low, the discharge of wastewater drops when environmental regulation intensity increases. If the intensity of environmental regulation reaches a certain degree, then the discharge of wastewater will increase when environmental regulation intensity continues to rise. When the intensity of environmental regulation is low, enterprises will try their best to meet the requirements of environmental protection and reduce pollution discharge within the scope of what costs they can bear. However, if environmental regulation reaches a certain degree and becomes too high, then enterprises will not be able to bear the cost of emission reduction and will face production stoppage or even ignore environmental regulation. The coefficients' signs of W*ER and W*ER^2 are the same as the coefficients' signs of environmental regulation (ER) and ER^2, but they are non-significant, indicating that the spatial effects of neighboring provinces' environmental regulation on wastewater are consistent with the effects of environmental regulation in local provinces, but these effects are non-significant.

Table 4   Global Moran's I of environmental pollutants and environmental regulation

	Water		SO_2		Solid		ER	
	Moran's I	P value	Moran's I	P value	Moran's I	P value	Moran's I	P value
2003	0.173	0.055	0.091	0.061	0.199	0.033	0.141	0.099
2004	0.177	0.051	0.106	0.021	0.226	0.010	0.129	0.127
2005	0.152	0.084	0.128	0.048	0.287	0.002	0.143	0.073
2006	0.174	0.054	0.126	0.052	0.290	0.003	0.131	0.095
2007	0.203	0.031	0.143	0.041	0.299	0.002	0.164	0.070
2008	0.199	0.035	0.130	0.043	0.314	0.001	0.171	0.064
2009	0.244	0.012	0.114	0.085	0.326	0.001	0.170	0.066
2010	0.249	0.010	0.126	0.052	0.298	0.001	0.142	0.100
2011	0.293	0.003	0.223	0.020	0.215	0.001	0.195	0.040
2012	0.272	0.005	0.208	0.029	0.311	0.001	0.190	0.043
2013	0.305	0.002	0.199	0.036	0.300	0.001	0.181	0.053
2014	0.283	0.004	0.185	0.048	0.343	0.000	0.160	0.080
2015	0.313	0.001	0.156	0.086	0.331	0.001	0.183	0.049
2016	0.327	0.001	0.086	0.084	0.342	0.001	0.137	0.101
2017	0.328	0.001	0.072	0.095	0.317	0.001	0.144	0.099

Table 5 Estimation results of panel data models without spatial interaction effects (dependent variable: water)

	Pooled OLS	Spatial fixed effects	Time-period fixed effects	Spatial and time-period fixed effects
ER	0.3620* (1.7143)	−0.6207***(−3.7792)	0.4434**(2.1763)	−0.4535***(−3.0957)
ER^2	0.1748*(1.9286)	0.0474(0.5985)	0.1745**(1.9526)	0.1361*(1.8650)
FDE	−9.0910***(−13.2016)	−0.9965(−1.6201)	−9.3228***(−12.6184)	−2.4747***(−4.1696)
ER*FDE	0.5049(1.7248)	−0.2910*(−1.8861)	0.1675(0.5762)	−0.3429**(−2.3762)
PGDP	8.6939***(7.3592)	1.8164**(2.4373)	7.1595***(5.5982)	1.7867**(2.4012)
$PGDP^2$	−0.3706***(−10.1326)	−0.0893***(−2.6062)	−0.3022***(−5.0213)	−0.0663*(−1.7974)
STR	−2.1053***(−10.1326)	−0.8725***(−5.7932)	−1.8280***(−7.9076)	−0.0575(−0.3072)
CITY	−2.2247*(−1.7249)	1.2573*(1.8480)	−0.7374(−0.5763)	1.5070**(2.3671)
FDE*FDI	−0.2301(−0.8556)	0.1562(0.6723)	0.0806(0.2605)	0.5125**(2.4339)
constant	7.9431*(1.7618)			
σ^2	0.2855	0.0508	0.2601	0.0392
R^2	0.7068	0.2991	0.7252	0.1263
LogL	−351.3899	−336.4393	−330.9371	−371.4281
LM_{lag}	10.2796***	21.8053***	1.7344	3.7234*
LM_{error}	84.2160***	13.5293***	55.3205***	1.3341
robust LM_{lag}	17.9484***	12.3087***	23.5589***	9.0618***
robust LM_{error}	91.8848***	4.0327**	77.1450***	6.6724***
LR test	Spatial fixed effects		851.4639	Prob = 0.0000
	Time-period fixed effects		116.7110	Prob = 0.0000

T-values are in parentheses. ***$p < 0.01$, **$p<0.05$, and *$p < 0.1$

The coefficients of fiscal decentralization affecting wastewater in the local unit are positive at the 5% significance level, and the coefficients of fiscal decentralization in adjacent areas are also positive, but they are not significant, which indicates that fiscal decentralization in the local region plays a significant role in exacerbating wastewater discharge and confirms

Table 6 Estimation results of panel data models without spatial interaction effects (Dependent variable: SO₂)

	Pooled OLS	Spatial fixed effects	Time-period fixed effects	Spatial and time-period fixed effects
ER	1.0356***(3.7356)	−0.8199***(−3.6020)	1.1753***(4.5863)	0.4247***(2.9745)
ER^2	−0.0822(−0.6949)	−0.0339(−0.3085)	−0.1835(−1.6329)	−0.1311*(1.8432)
FDE	−2.1479**(−2.2016)	0.6087(0.7141)	−2.991***(−3.2193)	−2.5689***(−4.4404)
ER*FDE	1.3036***(3.4114)	0.2625(0.2625)	0.7921**(2.1670)	0.2049(1.4568)
PGDP	6.0112***(3.8969)	4.1258***(3.9947)	5.1904***(3.2272)	4.4304***(6.1084)
$PGDP^2$	−0.2787***(−3.7362)	−0.2180***(−4.5890)	−0.2235***(−2.9535)	−0.1887***(−5.2428)
STR	−2.9504***(−10.3858)	−1.6425***(−7.8694)	−2.3614***(−8.1229)	0.1107(0.6065)
CITY	−5.8581***(−3.4793)	−1.1955(−1.2679)	−3.6486**(−2.2672)	−0.9014(−1.4526)
FDE*FDI	−0.9063**(−2.5823)	−0.5368*(−1.6669)	−1.1503***(−2.9576)	0.2189(1.0665)
constant	−5.3971(−0.7754)			
σ^2	0.4860	0.0976	0.4113	
R^2	0.5196	0.5545	0.5081	0.1844
LogL	−471.1142	−110.3932	−434.0705	−106.3060
LM_{lag}	17.4800***	27.7447***	10.2601***	10.2622***
LM_{error}	8.8609***	20.3610***	8.3680***	8.3681***
robust LM_{lag}	9.8321***	29.3610***	7.0868***	12.3750***
robust LM_{error}	2.2130***	4.0856***	5.2010***	15.2103***
LR test	Spatial fixed effects		1080.7530	Prob = 0.0000
	Time-period fixed effects		433.3984	Prob = 0.0000

T-values are in parentheses. ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$

Table 7 Estimation results of panel data models without spatial interaction effects (dependent variable: solid)

	Pooled OLS	Spatial fixed effects	Time-period fixed effects	Spatial and time-period fixed effects
ER	1.3062***(4.3025)	− 0.9324***(− 5.3490)	− 1.2793***(− 4.3291)	− 0.8204***(− 4.8728)
ER^2	0.4786***(3.6919)	0.1304(1.5503)	0.3262**(2.5164)	0.1968**(2.3462)
FDE	− 3.9359***(− 3.6839)	− 0.0665(− 0.1018)	− 3.6075***(− 3.3669)	− 1.7312**(− 2.5381)
ER*FDE	0.0699(0.1672)	− 1.1727***(− 7.1617)	0.0851(0.2019)	− 1.0635***(− 6.4111)
PGDP	7.8004***(4.6177)	1.4297*(1.8077)	5.2348***(2.8225)	2.4562***(2.8722)
$PGDP^2$	− 0.3091***(− 3.7834)	− 0.0423(− 1.1625)	− 0.2322***(− 2.6602)	− 0.0931**(− 2.1933)
STR	− 2.0999***(− 6.7502)	− 0.5813***(− 3.6372)	− 2.5466***(− 7.5962)	− 0.2044(− 0.9497)
CITY	− 0.5892(− 0.3195)	4.9965***(6.9197)	− 0.6231(− 0.3358)	4.5255***(6.1850)
FDE*FDI	− 1.6295***(− 4.2394)	0.4999**(2.0272)	− 0.3774(− 0.8416)	0.8260***(3.4128)
constant	− 7.8792			
σ^2	0.5828	0.0572	0.5469	0.0518
R^2	0.4813	0.7452	0.4411	0.3624
LogL	− 511.9808	− 91.6820	− 498.2040	− 32.1819
LM_{lag}	27.3926***	43.6711***	20.0920***	15.2256***
LM_{error}	0.3173	14.1867***	1.4820	1.6991
robust LM_{lag}	91.0916***	39.5587***	53.7849***	32.5679***
robust LM_{error}	6.0164***	10.0743***	35.1749***	19.0414***
LR test	Spatial fixed effects		1060.7718	Prob = 0.0000
	Time-period fixed effects		44.9997	Prob = 0.0001

T-values are in parentheses. ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$

the hypothesis of "race to bottom." These results are in line with the findings of He (2015).

The coefficients of GDP per capita are positive, while the coefficients of its square term are negative. All of the

Table 8 Estimation results of the SDM model (dependent variable: water)

	0–1 rook matrix	Geographic distance matrix	Economic distance nesting matrix
W*Water	0.177* (0.104)	0.221*(0.115)	0.398***(0.099)
ER	− 4.758(4.805)	− 6.217(4.811)	− 4.360(5.162)
ER^2	0.193*(0.113)	0.246*(0.126)	0.174*(0.103)
FDE	5.357**(2.221)	5.801***(2.076)	4.998**(2.443)
ER*FDE	0.936(1.052)	1.242(1.050)	0.864(1.132)
PGDP	6.399***(2.311)	6.974***(1.662)	6.153***(1.916)
$PGDP^2$	− 0.279***(0.105)	− 0.304***(0.078)	− 0.267***(0.086)
STR	− 0.663***(0.158)	− 0.437***(0.156)	− 0.323***(0.103)
CITY	0.331(0.920)	0.252(0.966)	− 0.032(1.115)
FDE*FDI	− 0.006(0.008)	− 0.016(0.010)	− 0.009(0.011)
W*ER	− 2.636(6.338)	− 16.75*(9.281)	− 5.352(13.06)
$W*ER^2$	0.186(0.243)	0.450*(0.263)	− 0.426(0.605)
W*FDE	4.031(2.535)	2.045(2.877)	3.227(3.921)
W*ER*FDE	0.442(1.410)	3.561*(2.000)	1.502(2.753)
W*PGDP	− 6.311**(3.009)	− 9.030***(2.901)	− 8.815***(3.310)
$W*PGDP^2$	0.268*(0.139)	0.392***(0.130)	0.388***(0.150)
W*STR	− 2.522**(1.019)	− 3.364***(1.140)	− 3.470**(1.427)
W*CITY	0.476(1.689)	0.636(1.823)	0.841(2.339)
W*FDE*FDI	− 0.027(0.019)	− 0.040*(0.023)	− 0.008(0.024)
R^2	0.280	0.461	0.362

Robust standard errors are in parentheses. ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$

Table 9 Estimation results of the SDM model (dependent variable: SO_2)

	0–1 rook matrix	Geographic distance matrix	Economic distance nesting matrix
$W*SO_2$	0.585***(0.074)	0.657***(0.068)	0.742***(0.055)
ER	−4.463(4.986)	−2.432(5.062)	−1.553(4.400)
ER^2	0.110(0.161)	0.140(0.165)	0.109(0.145)
FDE	3.502*(1.500)	2.849***(1.086)	2.402**(1.190)
ER*FDE	0.878(1.087)	0.420(1.094)	0.230(0.957)
PGDP	5.481***(2.115)	4.209*(1.821)	3.823**(1.697)
$PGDP^2$	−0.233**(0.093)	−0.174**(0.082)	−0.161**(0.078)
STR	−0.018***(0.005)	−0.152***(0.026)	−0.280**(0.107)
CITY	2.195**(0.903)	1.533*(0.801)	1.538**(0.781)
FDE*FDI	−0.002(0.009)	−0.004(0.010)	−0.001(0.011)
W*ER	−1.099(6.790)	−14.77*(8.119)	−9.400(11.31)
$W*ER^2$	0.189(0.232)	0.502**(0.222)	0.0299(0.464)
W*FDE	2.424(3.118)	−0.389(2.738)	−0.902(3.633)
W*ER*FDE	0.170(1.485)	3.276*(1.737)	2.345(2.422)
W*PGDP	−3.794(3.013)	−1.418(2.601)	−0.102(2.272)
$W*PGDP^2$	0.159(0.134)	0.0485(0.110)	0.005(0.097)
W*STR	−2.701***(0.925)	−2.753**(1.357)	−2.792**(1.161)
W*CITY	4.936***(1.392)	5.009***(1.667)	5.626**(2.616)
W*FDE*FDI	−0.043**(0.021)	−0.033(0.026)	−0.038(0.025)
R^2	0.301	0.721	0.732

Robust standard errors are in parentheses. ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$

coefficients are at the 1% significance level, thus confirming that the relationship is inverted U-shaped between economic development and its square term. At the same time, the coefficients of GDP per capita and its squared term in adjacent

Table 10 Estimation results of the SDM model (dependent variable: solid)

	0–1 rook matrix	Geographic distance matrix	Economic distance nesting matrix
W*Solid	0.394***(0.070)	0.290***(0.103)	0.369***(0.094)
ER	−2.374(4.463)	−4.324(4.356)	−3.549(4.504)
ER^2	0.288**(0.140)	0.274*(0.140)	0.281*(0.150)
FDE	2.038(1.580)	3.471*(1.797)	3.478**(1.727)
ER*FDE	0.317(0.985)	0.780(0.953)	0.593(0.984)
PGDP	2.872(2.709)	4.194(2.863)	4.782*(2.736)
$PGDP^2$	−0.119(0.123)	−0.181(0.129)	−0.212*(0.120)
STR	−1.560(1.078)	−1.900*(1.018)	−1.854*(0.992)
CITY	1.462(0.959)	1.403*(0.840)	1.504(0.917)
FDE*FDI	−0.042(0.026)	−0.0376(0.0270)	−0.038(0.025)
W*ER	1.225(6.147)	0.0083(8.708)	4.296(11.56)
$W*ER^2$	0.216(0.176)	0.234(0.254)	0.500(0.533)
W*FDE	1.125(2.841)	1.979(3.363)	3.805(3.726)
W*ER*FDE	−0.332(1.341)	0.007(1.900)	−1.172(2.548)
W*PGDP	1.596(3.381)	1.059(4.264)	−0.129(4.338)
$W*PGDP^2$	−0.087(0.155)	−0.049(0.196)	−0.006(0.198)
W*STR	0.654(1.566)	0.997(1.726)	0.436(1.787)
W*CITY	0.244(2.113)	−2.251(2.047)	0.938(2.183)
W*FDE*FDI	−0.018(0.021)	−0.018(0.028)	−0.032(0.036)
R^2	0.7511	0.7422	0.7382

Robust standard errors are in parentheses. ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$

areas have the same attribute as those in the local unit, showing that economic development in adjacent areas significantly impacts environmental pollution in the local unit.

The coefficients of industrial structure affecting wastewater in the local unit are negative at the 1% significance level. At the same time, the coefficients of industrial structure in adjacent areas influencing wastewater in the local unit are negative at the 1% significance level, too. Which means that the tertiary industry of both the local unit and adjacent areas plays a significant role in reducing wastewater discharge, which may be due to the fluidity of wastewater and the scale effect of the tertiary industry. The level of tertiary industry development in a unit is much higher; it is easier to attract the tertiary industry of adjacent units, which will reduce wastewater discharge in adjacent units.

The coefficients of urbanization, the product terms of environmental regulation and fiscal decentralization, and the product terms of fiscal decentralization and foreign direct investment are not significant. This indicates that fiscal decentralization does not significantly affect the discharge of wastewater through environmental regulation and foreign direct investment.

As can be seen from Table 9, the coefficients of environmental regulation and its square term affecting sulfur dioxide emissions are not significant, which is different from those on wastewater discharge. The reason for this is that sulfur dioxide flows strongly, and the emissions in one region quickly flow to another region. This negative externality leads to the local government's lack of incentives to reduce local sulfur dioxide emissions. The influences of fiscal decentralization, industrial structure, and economic development on sulfur dioxide emissions are consistent with that on wastewater discharge. The coefficients of urbanization that affect sulfur dioxide in the local unit are positive at the 10% significance level. At the same time, the coefficients of urbanization in adjacent areas influencing sulfur dioxide in the local unit are positive at the 5% significance level, too. It indicates that the process of urbanization does increase sulfur dioxide emissions, and that urbanization in adjacent areas also increase sulfur dioxide emissions in the local unit. In addition, the product terms of environmental regulation and fiscal decentralization and the product terms of fiscal decentralization and foreign direct investment are not significant, indicating that fiscal decentralization does not significantly affect sulfur dioxide emissions through environmental regulation and foreign direct investment.

As seen from Table 10, the impact that environmental regulation affects the discharge of solid waste is similar to that on wastewater. The coefficients of environmental regulation square term are positive at the 10% significance level in all three case, indicating that the relationship between environmental regulation and discharge of solid waste presents a conic illustration with a positive coefficient of quadratic term. The

reasons are the same as that in the spatial Durbin models of wastewater. The coefficients of W*ER and W*ER^2 are not significant, meaning that the environmental regulation of adjacent units has little effect on the local unit. The influences of fiscal decentralization, urbanization, and economic development on solid waste discharge are consistent with that on wastewater discharge. The coefficients of industrial structure affecting solid waste in the local unit are negative at the 10% significance level, while the coefficients of industrial structure in adjacent areas influencing solid waste in the local unit are not significant. This reveals that improvement of the tertiary industry will reduce the discharge of solid waste in the local unit, while it has little impact on the adjacent units, because there is no fluidity of solid waste, and solid waste in one region can only affect local areas. In addition, the product terms of environmental regulation and fiscal decentralization and the product terms of fiscal decentralization and foreign direct investment are not significant, indicating that fiscal decentralization does not significantly affect the discharge of solid waste through environmental regulation and foreign direct investment.

When there exist spatial effects, they are biased for estimating the data using the non-spatial panel model. How much is the bias? Parameters estimated in the non-spatial panel model reflect the marginal impact of dependent variables when the explanatory variables change, while the independent variables in the spatial Durbin model directly affect the local dependent variables and also indirectly affect the local dependent variables through the adjacent areas. Hence, comparing the differences of coefficients between the spatial Durbin model and non-spatial panel model is invalid (Elhorst 2010). Elhorst (2014) puts forward a method to estimate the effects of explanatory variables on local dependent variables and the adjacent dependent variables, which are called direct effect and indirect effect, respectively. The estimation results are shown in Tables 11, 12, and 13.

The significances of the coefficients are the same with those in Tables 6, 7, and 8, further proving the reliability of the results estimated by SDM. Due to the feedback effect, the coefficients of variables in Tables 8, 9, and 10 are slightly different than those in Tables 11, 12, and 13.

According to Table 11, we take the 0–1 weight matrix as an example to analyze the direct effect, indirect effect, and total effect. The direct effect coefficient of environmental regulation affecting wastewater discharge is − 4.790, while the coefficient of environmental regulation affecting wastewater discharge in the spatial Durbin model is − 4.758, and the feedback effect of environmental regulation is 0.032 and accounts for 0.67% of the direct effects. The direct effect coefficient of the environmental regulation square term affecting wastewater discharge is 0.199, while the coefficient of the environmental regulation square term affecting wastewater discharge in the spatial Durbin model is

Table 11 Direct and indirect effects of the spatial Durbin model (dependent variable: water)

	0–1 rook matrix			Geographic distance matrix			Economic distance nesting matrix		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
ER	−4.790	−4.003	−8.794	−6.636	−22.10*	−28.74**	−4.528	−10.93	−15.46
	(4.842)	(7.720)	(7.776)	(4.889)	(11.30)	(11.91)	(5.161)	(20.68)	(20.49)
ER^2	0.199*	0.265	0.464	0.257**	0.622*	0.878**	0.116	−0.625	−0.509
	(0.115)	(0.320)	(0.360)	(0.128)	(0.355)	(0.395)	(0.128)	(1.039)	(1.081)
FDE	5.104**	−3.689	1.415	5.629***	−1.004	4.625	4.749**	−2.181	2.568
	(2.196)	(2.905)	(2.342)	(2.039)	(3.609)	(2.991)	(2.380)	(5.770)	(5.226)
ER*FDE	0.935	0.693	1.628	1.331	4.680*	6.011**	0.917	2.883	3.800
	(1.060)	(1.691)	(1.673)	(1.066)	(2.442)	(2.543)	(1.130)	(4.304)	(4.225)
PGDP	6.103***	−6.057*	0.0461	6.642***	−9.259***	−2.618	5.711***	−10.23**	−4.518
	(2.110)	(3.101)	(1.840)	(1.512)	(3.194)	(2.521)	(1.704)	(4.346)	(3.548)
PGDP^2	−0.267***	0.255*	−0.012	−0.289***	0.401***	0.111	−0.248***	0.451**	0.203
	(0.0954)	(0.143)	(0.086)	(0.0707)	(0.143)	(0.115)	(0.0764)	(0.198)	(0.166)
STR	−0.776*	−3.035**	−3.811***	−0.553	−4.353***	−4.906***	−0.509	−5.696**	−6.204***
	(0.469)	(1.210)	(1.230)	(0.592)	(1.628)	(1.820)	(0.471)	(2.355)	(2.339)
CITY	0.313	0.720	1.033	0.237	0.994	1.231	−0.0295	1.335	1.305
	(0.938)	(1.912)	(2.134)	(0.959)	(2.251)	(2.313)	(1.104)	(3.336)	(3.372)
FDE*FDI	−0.0075	−0.0327	−0.0401	−0.0171*	−0.0537*	−0.0708**	−0.0095	−0.0193	−0.0287
	(0.008)	(0.0232)	(0.0262)	(0.0101)	(0.0275)	(0.0316)	(0.0115)	(0.0421)	(0.0499)

Robust standard errors are in parentheses. ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$

0.193, and thus the feedback effect of the environmental regulation square term is 0.006 and accounts for 3.01% of the direct effects. The direct effect coefficient of fiscal decentralization affecting wastewater discharge is 5.104,

while the coefficient of fiscal decentralization affecting wastewater discharge in the spatial Durbin model is 5.357, and thus the value of feedback effect that fiscal decentralization affects wastewater is −0.253 and accounts

Table 12 Direct and indirect effects of the spatial Durbin model (dependent variable: SO₂)

	0–1 rook matrix			Geographic distance matrix			Economic distance nesting matrix		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
ER	−5.255	−10.45	−15.71	−4.743	−45.38*	−50.12*	−3.200	−41.66	−44.86
	(5.237)	(15.99)	(17.88)	(5.630)	(25.26)	(28.12)	(4.221)	(40.61)	(40.98)
ER^2	0.159	0.625	0.784	0.219	1.600*	1.819*	0.117	0.365	0.481
	(0.187)	(0.674)	(0.795)	(0.195)	(0.824)	(0.970)	(0.189)	(1.965)	(2.100)
FDE	−3.336	0.151	−3.186	−3.046	−6.529	−9.575	−2.736	−11.20	−13.93
	(2.349)	(5.445)	(5.327)	(2.504)	(7.444)	(8.034)	(2.025)	(11.86)	(11.57)
ER*FDE	1.025	1.987	3.011	0.925	9.882*	10.81*	0.628	9.937	10.56
	(1.128)	(3.362)	(3.726)	(1.203)	(5.374)	(5.942)	(0.897)	(8.615)	(8.634)
PGDP	5.276***	−1.079	4.197	4.349***	4.109	8.458	4.238***	10.90	15.14*
	(1.782)	(4.894)	(4.370)	(1.666)	(6.822)	(7.019)	(1.597)	(8.023)	(8.408)
PGDP^2	−0.224***	0.0390	−0.185	−0.181**	−0.198	−0.378	−0.178**	−0.461	−0.639*
	(0.0786)	(0.225)	(0.207)	(0.0767)	(0.294)	(0.312)	(0.0748)	(0.350)	(0.374)
STR	−0.543	−6.057***	−6.600***	−0.570	−7.846***	−8.416**	−0.771	−11.59**	−12.37**
	(0.620)	(1.604)	(1.788)	(0.859)	(3.029)	(3.375)	(0.811)	(4.572)	(4.967)
CITY	1.413	−8.144***	−6.731*	0.868	−11.54**	−10.67*	0.801	−16.57*	−15.77
	(1.023)	(3.155)	(3.800)	(0.881)	(5.563)	(6.161)	(0.932)	(9.776)	(10.43)
FDE*FDI	−0.0109	−0.106*	−0.117*	−0.0095	−0.100	−0.110	−0.0082	−0.152	−0.160
	(0.0119)	(0.0606)	(0.0697)	(0.0121)	(0.0717)	(0.0795)	(0.0154)	(0.116)	(0.130)

Robust standard errors are in parentheses. ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$

Table 13 Direct and indirect effects of the spatial Durbin model (dependent variable: solid)

	0–1 rook matrix			Geographic distance matrix			Economic distance nesting matrix		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
ER	−2.177	0.513	−1.663	−4.233	−1.611	−5.844	−3.207	4.898	1.690
	(4.734)	(9.386)	(11.65)	(4.579)	(12.37)	(14.30)	(4.784)	(18.57)	(20.62)
ER^2	0.317**	0.502	0.819*	0.283*	0.425	0.708	0.301*	0.899	1.200
	(0.152)	(0.322)	(0.435)	(0.147)	(0.415)	(0.512)	(0.162)	(0.853)	(0.951)
FDE	1.851*	−0.591	1.260	3.271*	−1.283	1.988	3.198*	−4.003	−0.804
	(1.104)	(3.979)	(4.013)	(1.687)	(4.538)	(4.332)	(1.634)	(5.475)	(5.435)
ER*FDE	0.258	−0.335	−0.0771	0.758	0.289	1.047	0.504	−1.527	−1.023
	(1.041)	(2.030)	(2.509)	(0.999)	(2.680)	(3.074)	(1.045)	(4.132)	(4.572)
PGDP	3.031*	4.093	7.124**	4.133*	2.984	7.117*	4.723*	2.227	6.950
	(1.626)	(4.010)	(3.560)	(2.502)	(5.151)	(4.236)	(2.411)	(5.426)	(4.772)
$PGDP^2$	−0.128**	−0.203	−0.330*	−0.177	−0.132	−0.309	−0.210*	−0.116	−0.325
	(0.007)	(0.188)	(0.173)	(0.113)	(0.238)	(0.201)	(0.107)	(0.254)	(0.233)
STR	−1.544	0.145	−1.399	−1.891**	0.685	−1.206	−1.856**	−0.222	−2.078
	(1.003)	(2.018)	(1.970)	(0.953)	(2.183)	(1.969)	(0.927)	(2.314)	(2.059)
CITY	1.558*	1.312	2.869	1.298	−2.521	−1.223	1.579*	2.168	3.746
	(0.920)	(3.300)	(3.539)	(0.838)	(2.952)	(3.350)	(0.901)	(3.556)	(3.962)
FDE*FDI	−0.0452	−0.0545	−0.0997*	−0.0379	−0.0416	−0.0795	−0.0400	−0.0706	−0.111
	(0.0275)	(0.0362)	(0.0566)	(0.0278)	(0.0499)	(0.0697)	(0.0271)	(0.0684)	(0.0920)

Robust standard errors are in parentheses. ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$

for 4.96% of the direct effects. The negative feedback effect of fiscal decentralization indicates that the directions of the feedback effect and direct effect are opposite. The direct effect coefficient of industrial structure affecting wastewater discharge is −0.776, while the coefficient of industrial structure affecting wastewater discharge in the spatial

Table 14 Estimation results of the SDM model

	Water	SO_2	Solid
W*Dep	0.138(0.115)	0.578***(0.086)	0.381***(0.074)
ER	−1.269(1.447)	−1.255(1.435)	−3.446(2.283)
ER^2	0.149*(0.084)	0.037(0.119)	0.329***(0.123)
FDE	0.370***(0.027)	0.649(0.413)	1.335*(0.733)
ER*FDV	−0.475(0.353)	−0.452(0.350)	−1.151*(0.593)
PGDP	1.189(1.869)	1.755(1.309)	−0.107(2.017)
$PGDP^2$	−0.048(0.087)	−0.073(0.063)	0.006(0.095)
STR	−0.317(0.554)	0.251(0.685)	−1.390(1.075)
CITY	−0.278(1.022)	1.921**(0.878)	1.442(1.013)
FDV*FDI	−0.009(0.010)	0.001(0.011)	−0.041(0.028)
W*ER	−4.812(3.257)	−0.264(3.326)	0.469(2.526)
$W*ER^2$	0.069(0.263)	0.183(0.192)	0.268*(0.149)
W*FDV	−0.664(0.941)	0.195(0.846)	−0.009(0.690)
W*ER*FDV	1.117(0.899)	−0.0391(0.837)	−0.209(0.650)
W*PGDP	−1.295(2.293)	−0.724(1.664)	3.932(2.512)
$W*PGDP^2$	0.044(0.105)	0.0277(0.0777)	−0.185(0.118)
W*STR	−2.902***(1.010)	−2.705***(0.998)	0.726(1.604)
W*CITY	1.211(1.476)	−4.751***(1.174)	−0.004(2.023)
W*FDV*FDI	−0.025(0.021)	−0.0283(0.022)	−0.005(0.025)
R^2	0.306	0.740	0.751

Robust standard errors are in parentheses. ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$

Durbin model is -0.663, and thus the feedback effect of industrial structure is 0.113 and accounts for 17.04% of the direct effects.

Similarly, as can be seen from Table 12, the direct effect coefficient of environmental regulation affecting SO_2 emissions is -5.255, while the coefficient of environmental regulation affecting SO_2 emissions in the spatial Durbin model is -4.463, and the feedback effect of environmental regulation is 0.792 and accounts for 15.07% of the direct effects. The direct effect coefficient of the environmental regulation square term affecting SO_2 emissions is 0.159, while the coefficient of the environmental regulation square term affecting SO_2 emissions in the spatial Durbin model is 0.110, and thus the feedback effect of the environmental regulation square term is -0.049 and accounts for 30.81% of the direct effects. The direct effect coefficient of fiscal decentralization affecting SO_2 emissions is 3.336, while the coefficient of fiscal decentralization affecting SO_2 emissions in the spatial Durbin model is 3.502, and thus the value of the feedback effect as fiscal decentralization impacts SO_2 emissions is 0.166 and accounts for 4.97% of the direct effects.

From Table 13, we can see that the direct effect coefficient of environmental regulation affecting the discharge of solid waste is -2.177, while the coefficient of environmental regulation affecting the discharge of solid waste in the spatial Durbin model is -2.374, and the feedback effect of environmental regulation is -0.197 and accounts for 9.04% of the direct effects. The direct effect coefficient of the environmental regulation square term affecting the discharge of solid waste is 0.317, while the coefficient of the environmental regulation square term affecting the discharge of solid waste in the spatial Durbin model is 0.288, and thus the feedback effect of the environmental regulation square term is -0.029 and accounts for 9.14% of the direct effects. The direct effect coefficient of fiscal decentralization affecting the discharge of solid waste is 1.851, while the coefficient of fiscal decentralization affecting the discharge of solid waste in the spatial Durbin model is 2.038, and thus the value of the feedback effect when fiscal decentralization impacts the discharge of solid waste is 0.178 and accounts for 9.80% of the direct effects.

Robustness tests

To verify our analysis on fiscal decentralization and environmental pollution, we re-estimate Eq. (12) with fiscal revenue decentralization. In order to save space, we only present the results calculated by the 0–1 spatial weight matrix. The results calculated by revenue decentralization are reported in Tables 14 and 15.

According to Tables 14 and 15, the effect of fiscal decentralizations measured by expenditure and revenue on environmental pollution is similar. What is more, the empirical results of other variables also support our main findings.

In order to verify our analysis on regulations and environmental pollution, we construct another environmental regulation index that is measured by the total pollution governance (Chen et al. 2019) and we explore this issue via the panel

Table 15 Direct and indirect effects of the spatial Durbin model

	Water			SO$_2$			Solid		
	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect	Direct effect	Indirect effect	Total effect
ER	1.177	-5.069	-3.891	1.364	0.743	2.107	3.717	2.739	6.456
	(1.507)	(3.716)	(4.319)	(1.836)	(8.035)	(9.334)	(2.355)	(3.570)	(4.430)
ER^2	0.150*	0.0988	0.249	0.0715	0.448	0.519	0.369***	0.603**	0.972***
	(0.0824)	(0.295)	(0.318)	(0.129)	(0.443)	(0.520)	(0.124)	(0.241)	(0.296)
FDV	0.421***	-0.655	-0.234	0.797*	1.157	1.954	1.455**	0.778	2.233*
	(0.101)	(1.046)	(1.142)	(0.421)	(1.772)	(1.950)	(0.736)	(1.001)	(1.294)
ER*FDV	-0.454	1.141	0.687	-0.515	-0.604	-1.118	$-1.241**$	-0.998	$-2.239**$
	(0.369)	(1.011)	(1.142)	(0.442)	(1.957)	(2.260)	(0.611)	(0.909)	(1.127)
PGDP	1.015	-1.119	-0.104	1.711	0.495	2.206	0.305	6.053**	6.359**
	(1.742)	(2.239)	(1.296)	(1.270)	(3.183)	(3.785)	(1.785)	(2.988)	(2.882)
PGDP^2	-0.0408	0.035	-0.006	-0.0704	-0.0233	-0.0937	-0.014	$-0.286**$	$-0.300**$
	(0.0817)	(0.103)	(0.063)	(0.063)	(0.156)	(0.187)	(0.086)	(0.145)	(0.145)
STR	-0.395	$-3.301***$	$-3.696***$	-0.204	$-5.586***$	$-5.790***$	-1.345	0.339	-1.006
	(0.564)	(1.134)	(1.093)	(0.677)	(1.616)	(1.738)	(0.982)	(2.004)	(1.877)
CITY	-0.249	1.225	0.975	1.178	$-8.085***$	$-6.907*$	1.485	1.110	2.596
	(1.032)	(1.686)	(2.002)	(1.026)	(2.852)	(3.540)	(0.965)	(3.029)	(3.318)
FDV*FDI	-0.0098	-0.0295	-0.0393	-0.0036	-0.0642	-0.0678	-0.0432	-0.0295	-0.0727
	(0.0108)	(0.025)	(0.028)	(0.013)	(0.0617)	(0.072)	(0.028)	(0.039)	(0.0585)

Robust standard errors are in parentheses. ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$

GMM model (Sui et al. 2018). The results calculated by the panel dynamic model are presented in Table 16.

According to Table 16, the effect of environmental regulation measured by the total pollution governance is similar to our analysis above and the empirical results of other variables also support our main findings, too. Which indicate that both fiscal decentralization and environmental regulation have a robust impact on environmental pollution.

Discussions

With the improvement of living conditions, one's living environment is being paid more and more attention both at home and abroad. Many scholars hold the point that a fiscal system, especially fiscal decentralization, may influence environmental pollution through a sound infrastructure or lowering environmental criteria (Tiebout 1956; Köllner et al. 2002). Our results demonstrate that the phenomenon of "race to the top" does not appear in China, because local governments of China are motivated to compete in economic growth (Tian and Wang 2018).

Comparing Tables 8, 9, and 10, we can see that environmental regulation can reduce wastewater and solid waste discharge, but cannot significantly reduce sulfur dioxide emissions. Our results demonstrate that the effects of environmental regulation on the discharge of pollutants are related to the fluidity of pollutants. The stronger the fluidity of pollutants is, the greater the positive externality of governing is. Thus, the cost is larger than the revenue for local government managing pollution. This view is different from previous studies.

There is an inverted U-shape curve between GDP per capita and wastewater, SO_2, and solid waste, respectively. Proving the hypothesis of environmental Kuznets curve (EKC), this result is consistent with those of many relevant researchers (Panayotou 1993; Dinda 2004; Xu 2018).

Due to data limitations, this study only analyzes data at the provincial level and ignores differences between cities within a province. As the economic development and environmental quality of different cities in the same province differ greatly, the overall value of a province does not reflect the situation of specific cities accurately. This is the limitation of this research. Next, we will collect data at prefecture level to do further research.

Conclusions and policy implications

Conclusions

We investigate the impact of fiscal decentralization and environmental regulation on environmental pollution using provincial data from 2003 to 2017 in China. As environmental pollution has the characteristic of spatial spillover, the traditional panel data model will lead to a biased estimation. Compared with the non-spatial panel data model, the spatial panel data model takes spatial effects into consideration and can avoid bias. The spatial Durbin model offers a means to explore whether the local discharge of pollutants depends on the neighboring provinces. The main findings are robust, as indicated by a robustness test.

According to our empirical results, four main conclusions can be drawn. In the beginning, spatial agglomeration effects are significant on the discharges of wastewater, SO_2, and solid waste. Hence, environmental regulation can reduce wastewater and solid waste discharge, but environmental regulations cannot significantly reduce sulfur dioxide emissions. The main reason is that sulfur dioxide flows strongly, and this negative externality leads to the local government's lack of incentives to reduce local sulfur dioxide emissions. Then, fiscal decentralization increases the discharge of wastewater,

Table 16 Estimation results of the dynamic panel model

	Water	SO_2	Solid
L. Dep	0.987***(0.071)	0.861***(0.0189)	0.494***(0.035)
ER	−5.540(7.719)	−0.179(3.733)	−2.882**(1.044)
ER^2	0.538**(0.239)	0.181***(0.059)	0.157*(0.086)
FDE	2.583**(1.061)	3.166***(1.054)	4.966***(1.053)
ER*FDE	−0.161(1.752)	−0.360(0.911)	4.326**(1.734)
PGDP	1.334*(0.803)	2.148***(0.831)	2.697(1.734)
$PGDP^2$	−1.706**(0.968)	0.084***(0.041)	−0.124(0.085)
STR	0.926(0.784)	−1.466***(0.244)	−1.887***(0.638)
CITY	−0.078(0.623)	1.059***(0.212)	−0.726(0.530)
FDE*FDI	−0.011(0.008)	−0.007***(0.002)	−0.020***(0.006)
AR(1) P value	0.0014	0.0002	0.0333
AR(2) P value	0.2250	0.0849	0.4271
Sargan	0.7485	0.5670	0.1929

Robust standard errors are in parentheses. ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$

SO$_2$, and solid waste and confirms the hypothesis of "race to the bottom." Furthermore, the product terms of environmental regulation and fiscal decentralization are not significant, indicating that fiscal decentralization does not significantly affect the discharge of wastewater, sulfur dioxide, and solid waste through environmental regulation. Finally, the relationship between economic development and discharge of pollutants is an inverted U-shape curve, which proves the EKC hypothesis.

Policy implications

From the main conclusions above, we can draw two policy recommendations.

Firstly, the intensity of environmental regulations should be adapted to the characteristics of economic development. Appropriate environmental regulations are conducive to reducing the level of environmental pollution, and any environmental regulation should be carried out step by step. An excessively high level of environmental regulation will place dual pressures on the local government's economy and the environment, which will not help the government's active energy conservation and emission reduction. Environmental pollution has the distinct characteristics of spatial agglomeration and overflow. The environmental regulation of a region has significantly positive external effects on its adjacent space units. Therefore, the central government must make overall plans that give some subsidies to local governments for pollution control when coordinating environmental regulations and policies, coordinate the responsibilities with the authorities of local governments, and avoid the "free-rider" psychology of some local governments.

Second, the pollutants with high fluidity should be treated by the central government. There is significantly positive externality in treating pollutants with high fluidity, and the cost is larger than the revenue for local governments. Therefore, local governments have no incentive to control this kind of pollutant.

Finally, a new evaluation system based on green GDP should be established. Our results show that fiscal decentralization increases the discharge of local pollutants, which is a main reason that the central government has great power in rewarding and punishing local administrations, and hence local governments are motivated to compete in economic growth (Blanchard and Shleifer 2001; Cai et al. 2008; Tian and Wang 2018). If green GDP is considered an assessment indicator of government performance, then environmental quality will be sacrificed less for economic growth.
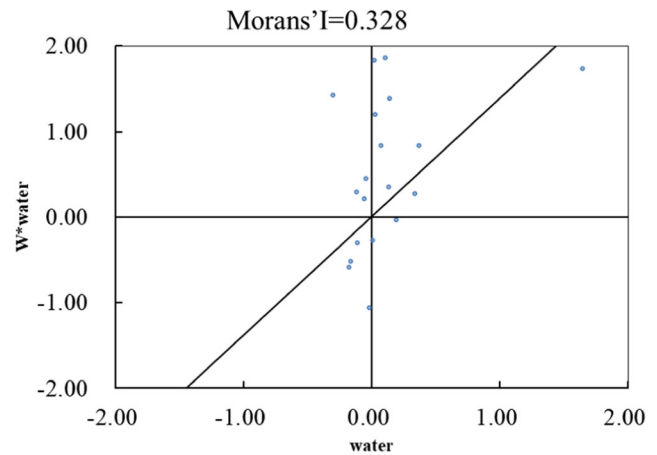
Appendix

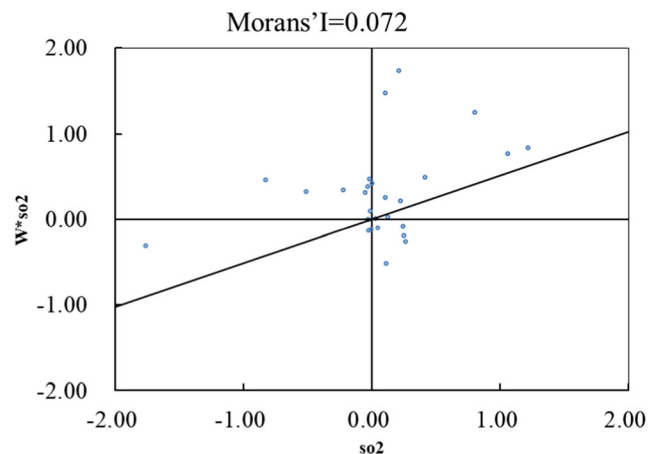**Fig. 1** Moran's *I* scatter plot for wastewater

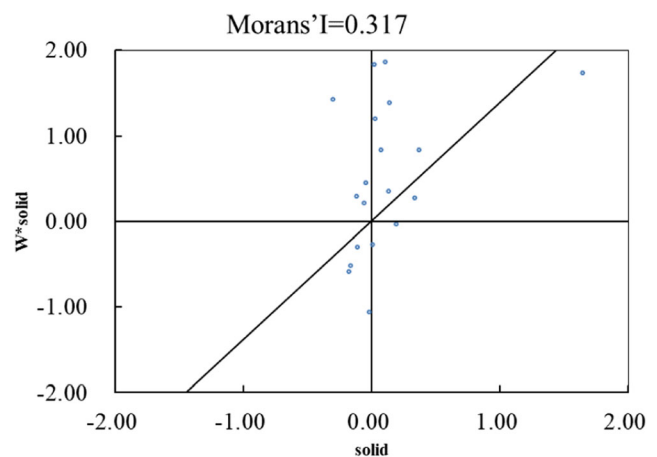**Fig. 2** Moran's *I* scatter plot for sulfur dioxide emissions

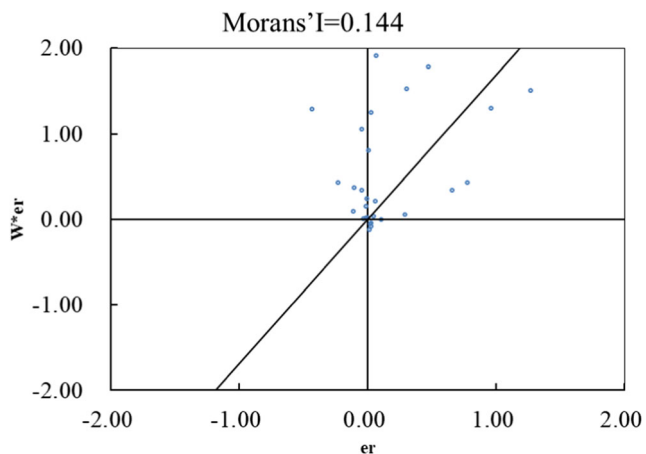**Fig. 3** Moran's *I* scatter plot for solid waste

Fig. 4 Moran's *I* scatter plot for environmental regulation

Table 17 Correlation coefficient matrix in SO₂ estimation equation

	SO$_2$	ER	FDE	PGDP	STR	CITY	FDI
SO$_2$	1.000						
ER	0.122***	1.000					
FDE	− 0.419***	0.030	1.000				
PGDP	− 0.257***	0.367***	0.621***	1.000			
STR	− 0.582***	0.360***	0.518***	0.534***	1.000		
CITY	− 0.386***	0.515***	0.718***	0.629***	0.714***	1.000	
FDI	− 0.144***	0.329***	0.080*	0.183***	0.162***	0.427***	1.000

Robust standard errors are in parentheses. ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$

Table 18 Correlation coefficient matrix in Solid estimation equation

	Solid	ER	FDE	PGDP	STR	CITY	FDI
Solid	1.000						
ER	− 0.002	1.000					
FDE	− 0.053	0.030	1.000				
PGDP	0.141***	0.367***	0.621***	1.000			
STR	− 0.362***	0.360***	0.518***	0.534***	1.000		
CITY	− 0.190***	0.515***	0.718***	0.629***	0.714***	1.000	
FDI	− 0.330***	0.329***	0.080*	0.183***	0.162***	0.427***	1.000

Robust standard errors are in parentheses. ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$

Table 19 IS statistic for serial correlation

	IS-stat	*P* value
Water	29.88	0.319
SO$_2$	29.84	0.322
Solid	29.65	0.328

Table 20 Estimation results of the SDM model (dependent variable: water)

	(1)	(2)	(3)	(4)	(5)
W*Water	0.233**(0.112)	0.234**(0.112)	0.235**(0.112)	0.233**(0.110)	0.177* (0.104)
ER	− 0.297**(0.148)	− 0.494***(0.153)	− 1.964(4.342)	− 3.570(4.932)	− 4.758(4.805)
ER^2		0.107(0.073)		0.149(0.104)	0.193*(0.113)
FDE	3.952***(0.824)	3.907***(0.815)	4.552**(2.038)	5.019**(2.239)	5.357**(2.221)
ER*FDE			0.373(0.373)	0.678(1.084)	0.936(1.052)
PGDP	5.507***(1.489)	5.368***(1.526)	6.103***(2.312)	6.242***(2.306)	6.399***(2.311)
PGDP^2	− 0.240***(0.072)	− 0.234***(0.073)	− 2.662**(0.105)	− 0.272***(0.104)	− 0.279***(0.105)
STR	− 0.199(0.223)	− 0.199(0.218)	− 0.216(0.226)	− 0.233(0.211)	− 0.663***(0.158)
CITY	0.399(0.983)	0.504(0.945)	0.425(0.963)	0.469(0.937)	0.331(0.920)
FDE*FDI					− 0.006(0.008)
W*ER	− 0.236(0.341)	− 0.548(0.661)	2.458(6.538)	0.985(6.479)	− 2.636(6.338)
W*ER^2		0.115(0.225)		0.106(0.214)	0.186(0.243)
W*FDE	4.336***(1.550)	4.318***(1.559)	5.306**(2.446)	4.853*(2.486)	4.031(2.535)
W*ER*FDE				− 0.347(1.487)	0.442(1.410)
W*PGDP	− 5.907**(2.405)	− 5.943**(2.358)	− 6.856**(3.165)	− 6.678**(3.157)	− 6.311**(3.009)
W*PGDP^2	0.253**(0.112)	0.254**(0.111)	0.296**(0.146)	0.287*(3.157)	0.268*(0.139)
W*STR	− 0.833(0.396)	− 0.819**(0.411)	− 0.775*(0.446)	− 0.805*(0.447)	− 2.522**(1.019)
W*CITY	− 0.033(1.622)	0.202(1.661)	− 0.136(1.705)	0.145(1.735)	0.476(1.689)
W*FDE*FDI					− 0.0267(0.0194)

Robust standard errors are in parentheses. ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$

Table 21 Estimation results of the SDM model (dependent variable: SO$_2$)

	(1)	(2)	(3)	(4)	(5)
W*SO$_2$	0.623***(0.076)	0.624***(0.077)	0.627***(0.074)	0.626***(0.074)	0.585***(0.0738)
ER	− 0.389***(0.134)	− 0.446**(0.227)	− 2.601(4.590)	− 3.006(5.377)	− 4.463(4.986)
ER^2		0.015(0.115)		0.040(0.151)	0.110(0.161)
FDE	1.955*(1.004)	1.902*(1.039)	2.738*(1.639)	2.827*(1.627)	3.502*(1.500)
ER*FDE			0.495(1.029)	0.567(1.178)	0.878(1.087)
PGDP	4.255***(1.458)	4.305***(1.418)	5.087**(2.358)	5.125**(2.361)	5.481***(2.115)
PGDP^2	− 0.179**(0.069)	− 0.182***(0.066)	− 0.216**(0.104)	− 0.218**(0.272)	− 0.233***(0.0926)
STR	0.142(0.284)	0.133(0.276)	0.125(0.283)	0.113(0.272)	− 0.018***(0.005)
CITY	2.078**(0.818)	2.199***(0.812)	2.147***(0.825)	2.202***(0.811)	2.195**(0.903)
FDE*FDI					− 0.0015(0.0087)
W*ER	0.070(0.346)	− 0.331(0.666)	4.908(6.595)	3.494(6.981)	− 1.099(6.790)
W*ER^2		0.165(0.205)		0.117(0.210)	0.189(0.232)
W*FDE	1.828(1.979)	1.745(1.977)	3.568(2.749)	3.106(3.065)	2.424(3.118)
W*ER*FDE			− 1.110(1.541)	− 0.852(1.577)	0.170(1.485)
W*PGDP	− 2.787(2.974)	− 3.032(2.788)	− 4.384(3.316)	− 4.257(3.325)	− 3.794(3.013)
W*PGDP^2	0.119(0.135)	0.131(0.126)	0.191(0.149)	0.186(0.149)	0.159(0.134)
W*STR	− 0.941**(0.417)	− 0.905**(0.417)	− 0.830**(0.365)	− 0.838**(0.362)	− 2.701***(0.925)
W*CITY	− 5.195***(1.405)	5.037***(1.428)	5.356***(1.511)	5.186***(1.518)	4.936***(1.392)
W*FDE*FDI					− 0.0434**(0.0207)

Robust standard errors are in parentheses. ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$

Table 22 Estimation results of the SDM model (dependent variable: solid)

	(1)	(2)	(3)	(4)	(5)
W*Solid	0.057***(0.022)	0.413***(0.068)	0.407***(0.065)	0.408***(0.065)	0.394***(0.070)
ER	−0.522***(0.146)	−1.024***(0.222)	−4.330(6.442)	1.644(6.077)	−2.374(4.463)
ER^2		0.302**(0.127)		0.243**(1.551)	0.288**(0.140)
FDE	2.654(2.085)	2.603(1.937)	0.780(1.746)	1.627(1.558)	2.038(1.580)
ER*FDE			−1.102(1.465)	−0.582(1.361)	0.317(0.985)
PGDP	2.842(2.815)	2.323(2.693)	1.551(3.104)	1.782(2.957)	2.872(2.709)
$PGDP^2$	−0.102(0.121)	−0.079(0.116)	−0.047(0.406)	−0.055(0.131)	−0.119(0.123)
STR	−0.350(0.463)	−0.334(0.423)	−0.279(0.406)	−0.290(0.391)	−1.560(1.078)
CITY	1.687*(0.936)	1.803*(0.957)	1.944**(0.920)	1.918**(0.939)	1.462(0.959)
FDE*FDI					−0.042(0.026)
W*ER	0.311(0.274)	0.046(0.304)	5.239(5.121)	5.087(5.916)	1.225(6.147)
$W*ER^2$		0.067(0.094)		−0.024(0.143)	0.216(0.176)
W*FDE	0.247(1.786)	0.310(1.808)	2.106(2.602)	2.131(2.772)	1.125(2.841)
W*ER*FDE			−1.141(1.158)	−1.109(1.285)	−0.332(1.341)
W*PGDP	2.385(0.140)	2.721(3.065)	1.730(3.831)	1.840(3.747)	1.596(3.381)
$W*PGDP^2$	−0.128(0.726)	−0.146(0.144)	−0.097(0.175)	−0.105(0.172)	−0.087(0.155)
W*STR	−0.010(0.726)	−0.037(0.694)	0.114(0.714)	0.067(0.696)	0.654(1.566)
W*CITY	0.427(1.811)	0.010(1.848)	−0.499(1.874)	−0.246(1.873)	0.244(2.113)
W*FDE*FDI					−0.018(0.021)

Robust standard errors are in parentheses. ***$p < 0.01$, **$p < 0.05$, and *$p < 0.1$

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