



The spatial spillover effect of urban sprawl and fiscal decentralization on air pollution: evidence from 269 cities in China

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Abstract

Air pollution is an important factor affecting the quality and sustainability of the development of China's economy, and urban sprawl is also a typical by-product of the non-intensive development of urban land. At the same time, Chinese-style fiscal decentralization promotes urban sprawl through top-down yardstick competition, which has a serious impact on air pollution. Therefore, exploring the effect of fiscal decentralization and urban sprawl on air pollution is of great significance for regulating local government behavior, curbing urban sprawl, and accurately identifying the causes of air pollution. The dynamic spatial Durbin model with economic geography weight matrix is employed to analyze the direct and moderating effects of fiscal decentralization and urban sprawl on air pollution on the basis of 269 prefecture-level cities in China from 2004 to 2018. The results show that air pollution has a significant retarded time effect and space spillover effect. Both fiscal decentralization and urban sprawl have contributed significantly to air pollution. The moderating effect of urban sprawl and fiscal decentralization on air pollution is significantly positive. From the short-term effects, the coefficients of the total spillover effect, direct spillover effect, and indirect spillover effect of urban sprawl and fiscal decentralization on air pollution are significantly positive, respectively. In terms of long-term effects, the total spatial spillover effect of urban sprawl and fiscal decentralization on air pollution is significantly negative, while the direct and indirect effects of those are negative but not significant. Further research finds that there is significant regional heterogeneity in the influence of urban sprawl and fiscal decentralization on air pollution.

Keywords Urban sprawl · Fiscal decentralization · Air pollution · Heterogeneity · Spatial spillover effect

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1 Introduction

China is in the critical period of transformation from a rural society to an urban society, showing the trend of expanding urban scale, increasing urbanization rate, and improvements to the urban system. Statistics show that China's urbanization rate had increased from 17.92% in 1978 to 60.60% in 2019, and the urban built-up area has expanded from 7,438 square kilometers in 1981 to 60,312.5 square kilometers in 2019, with an increase of 8.11 times.¹ However, the speed of land urbanization is faster than that of population urbanization, which is a significant feature of China's urbanization process. The fact that the local government lacks the overall planning and strict regional comprehensive governance for land development and economic layout leads to the extremely serious phenomenon of space disordered development in many cities (Ying and Jing-qi 2011; Zhao and Kaestner 2010; Feng et al. 2019). For a long time, this development model of rapid low-density expansion and horizontal outward spread has brought about serious "urban dilemmas" and caused a series of environmental pollution problems (Ewing et al. 2003; Siedentop and Fina 2012; Feng and Wang 2020). In particular, the air pollution problem, which affects hundreds of cities and more than 1000 counties in China, is particularly prevalent (Wu et al. 2018; Yang et al., 2020a, 2020b). In 2018, only 35.8% of cities met acceptable air quality standards, and the average number of days with air quality decreased by 1.3% compared with 2017 in China (Fig. 1).² What's more, air pollution rages in North, Northeast, and Northwest China. The cities where the average concentration of PM₁₀ exceeded 100 $\mu\text{g}/\text{m}^3$ accounted for 58.4, 43.3, and 33.6%, respectively, among the 113 key cities inspected by environmental protection from 2014 to 2016.³ Although this proportion has declined, the poor quality of air pollution remains grim. According to Maji et al. (2018), the number of deaths caused by air pollution reached 964,000 in 2018, accounting for nearly one-tenth of the total number of deaths in China. Moreover, some scholars have found China's direct economic loss caused by PM_{2.5} exposure was up to about \$100 billion in 2016 (Dong et al. 2018; Fan and Xu 2020). The harm caused by air pollution is self-evident. Therefore, urban sprawl has become a phenomenon worthy of attention in the process of urbanization, and it is likewise a major practical problem that plagues the sustainable development of cities. How to solve the dilemma of urban sprawl and realize pollution control has become a common topic of concern in academic and political circles.

However, the influencing factors of air pollution are intricate; in addition to urban sprawl, one of the more important factors is fiscal decentralization. In 1994, the macro-control of financial funds by the central government has been unprecedentedly strengthened (Zhu 2016; Que et al. 2018; Zhang et al. 2020). The fiscal system had also undergone reform from a system of unified collection and allocation of funds by the state the system where local authorities take full responsibility for their finances, and

¹ See more detail: <http://www.stats.gov.cn/tjsj/ndsj/2020/indexch.htm> (accessed at 1/8/2021); <http://www.mohurd.gov.cn/xytj/tjzljxsxytjgb/jstjnj/index.html> (accessed at 1/8/2021).

² See more detail: <http://www.mee.gov.cn/hjzl/sthjzk/zghjzkgb/201905/P020190619587632630618.pdf> (accessed at 1/8/2021).

³ See more detail: <http://www.mee.gov.cn/hjzl/sthjzk/zghjzkgb/201905/P020190619587632630618.pdf> (accessed at 1/8/2021).

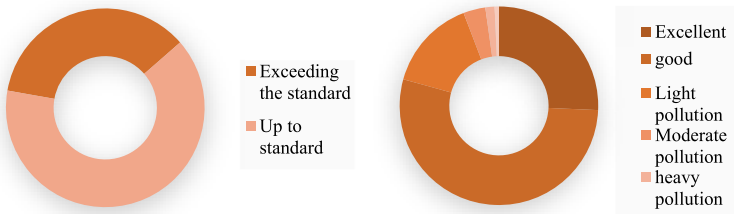


Fig.1 The air quality of 338 Chinese cities in 2018

then to the revenue-sharing system (He 2015). On the whole, the above-mentioned series of fiscal reforms are aimed at mobilizing local governments to manage their finances by expanding the financial power of local governments (Ding et al. 2019). Part of the fiscal control powers, such as debt arrangement, tax management, and budget execution, are gradually devolved from the central government to the local governments, and then the scope of fiscal revenue and expenditure between the central and local governments are defined by law (Que et al. 2018; Kuai et al. 2019). As a result, local governments are given proper budget management authority by the central government, which is known as fiscal decentralization. However, under the Chinese-style fiscal decentralization system, economic growth has emerged as a key indicator of the central government's performance assessment of local governments. Local governments, which compete fiercely around GDP growth as their primary policy assessment goal, tend to allocate more resources to high-return projects that enhance GDP, thus neglecting investments in non-economic public goods such as environmental management, ultimately exacerbating air pollution. In addition, as a "people's livelihood" public service, the spillover nature of environmental protection expenditure makes it easy for local governments to "free-riding" on environmental management, which in turn has an impact on air pollution.

Numerous scholars argue that institutional arrangement, especially the fiscal decentralization system, is an important factor affecting urban sprawl which can also explain the negative phenomena such as air pollution in the process of urban development (Milimet 2013; Que et al. 2018; Feng et al. 2015; Yuan et al. 2019; Öztürk et al. 2020). Fiscal decentralization has led local governments to face the dual pressure of growth target assessment and fiscal revenue and expenditure, which not only stimulates competition among local governments, but also forces them to seek quick channels to balance fiscal revenue and expenditure (Cheng and Zhu 2021; Kuai et al. 2019). On the one hand, the promotion incentive derived from the fiscal decentralization system makes local governments race to lower land prices and use more land for economic development to attract more investment, thus triggering spatially disorderly urban expansion and increasing urban scale, which eventually brings about urban sprawl (Ehrlich et al. 2018; Liu et al. 2018). Although the brutal urban expansion model by sacrificing resources and environment attracts a large number of industrial enterprises to invest, it will undoubtedly have a serious impact on the ecological environment. On the other hand, China's transitional fiscal decentralization model has induced serious imbalances of the fiscal structure. Since then, the income tax sharing reform in

2002 and the full implementation of “replacing business tax with value-added tax” in 2016 further exacerbated the fiscal imbalance (Kuai et al. 2019; Ahmad et al. 2021). However, China’s current financial system fails to correct the vertical fiscal imbalance and narrow down the gap in local government revenue and expenditure caused by the fiscal imbalance (Ding et al. 2019). To cope with the financial pressure, the local government’s reliance on extra-budgetary revenues mainly from land transfer fees has become an inevitable result (Kunce and Shogren 2008).⁴ The fiscal decentralization system with the land transfer as its core has laid a solid economic foundation for local governments’ urban expansion policy. At the same time, it has also become an important driving factor for local governments to be keen to engage in the city building movement (Zheng et al. 2014; Huang and Chang, 2017). The land finance under fiscal decentralization further intensifies the large-scale development of urban land, and the urban space expands rapidly. As a result, the speed of spatial urbanization has gradually exceeded the reasonable level guided by market forces, which has resulted in serious urban sprawl. However, along with urban sprawling, the industrialization process inevitably affects air quality (Bi 2015; Sun et al. 2020).

Based on the background, this paper is designed to answer the following questions: Against the backdrop of China’s in-depth promotion of high-quality economic development and gradual urban expansion, what is the mechanism of urban sprawl induced by rapid urbanization on air pollution? What kind of impact will fiscal decentralization have on air pollution? When considering China’s special decentralized system, what will be the impact of fiscal decentralization and urban sprawl on air pollution? Furthermore, is there regional heterogeneity in the above effects? The resolution of the above issues will help to clarify the deeper administrative and financial motives behind the urban expansion of local governments, to provide effective policy tools for regulating local government behavior to curb urban sprawl and combat air pollution. Meanwhile, this paper can also provide a new perspective and ideas for rational and scientific city planning and the construction of urban ecological civilization.

The marginal contribution of this paper lies in the following three aspects. First of all, fiscal decentralization, urban sprawl, and air pollution are included in the unified analysis framework on the basis of the reality of the Chinese-style decentralization system, which deeply explores the institutional causes of urban sprawl affecting air pollution and provides a new research perspective for exploring air pollution control. Secondly, given the characteristics of air pollution dynamics, uneven regional economic development, and regional factor endowment constraints, spatial econometric models were applied to examine the effect of fiscal decentralization and urban sprawl on air pollution, to provide empirical support for the implementation of differentiated decentralization system reforms and the formulation of urban policies across regions. Thirdly, the spatial spillover effects of fiscal decentralization and urban sprawl on air pollution are analyzed from the perspectives of direct, indirect, and total spillover effects using data from 269 prefecture-level cities. Therefore, this study can not only

⁴ The Budget Law of the People’s Republic of China, which was implemented by the Chinese Government in 1995, stipulates that the budgets of local governments at all levels shall be compiled in accordance with the principles of spending within means and balancing revenues. Unless otherwise stipulated by law and the State Council, local governments are not allowed to issue local government bonds, so land transfer income has become the main source of extra-budgetary income for local governments.

improve the pollution control policies and fiscal policies formulated by policymakers making them more targeted and scientific, but also give some policy reference to other developing countries in positions similar to China's economic development.

The structure and main findings of this paper are as follows. Section 2 introduces the research review on the relationship among fiscal decentralization, urban sprawl, and air pollution. We find that exploring the effects of fiscal decentralization and urban sprawl on air pollution from a spatial perspective is a gap in the current research. Section 3 describes the model setting, variable selection, and data sources of this paper. Specifically, based on the database of China City Statistical Yearbook 2004–2018, we constructed the dynamic spatial Durbin model to analyze the effects of fiscal decentralization and urban sprawl on air pollution using selected 269 prefecture-level cities as the study sample. The empirical results are analyzed and discussed in Sect. 4. First, the spatial autocorrelation results reveal that air pollution is highly spatially mobile and spillover, and its distribution is characterized by a higher distribution in the northeast than in the southeast. Second, based on a non-spatial perspective, we also confirm that fiscal decentralization, urban sprawl, and the moderating effects of both contribute significantly to air pollution. Finally, we also find after decomposing the spatial spillover effects that the direct and indirect effects of fiscal decentralization and urban sprawl on air pollution are significantly positive, respectively, in the short term, but negative but not significant in the long term. The last section is the research conclusions and policy recommendations. The research framework of this paper is shown in Fig. 2.

2 Literature review

2.1. Research on urban sprawl and air pollution

Many scholars attempt to quantify the relationship between urban sprawl and air pollution from various perspectives. The existing views mainly include the following three aspects: The first view is that urban sprawl will aggravate air pollution (Shi et al. 2020; Zhang et al. 2018). For example, Johnson et al. (2001) pointed out that urban sprawl, which increases average travel time and brings about traffic congestion, is one of the major sources of urban air pollution. Etre et al. (2000) proved that the increase in vehicle flow caused by urban sprawl is closely related to the deterioration of urban environmental quality. With the continuous intensification of urban sprawl, urban residents' dependence on private transportation is also gradually increasing, while the energy consumption and air pollution caused by private transport are self-evident (Holcombe and Williams 2010). Bereitschaft and Debbage (2013) surveyed 86 metropolitan areas in the USA and found that the spread of low-density cities will cause higher air pollution. Besides, some studies have shown that the spatial division of urban land will aggravate air pollution (Novotny et al. 2011; McCarty and Kaza 2015; Dupras and Marull 2016). The second view is that urban sprawl can curb air pollution (Clark et al. 2011; Liu et al. 2018; Yuan et al. 2018). For instance, Rodríguez et al. (2016) pointed out that low-density European cities are often less vulnerable to air pollution. Some studies also believe that the urban spatial structure with low density has a lower population density, which not only results in a low concentration of air pollution over

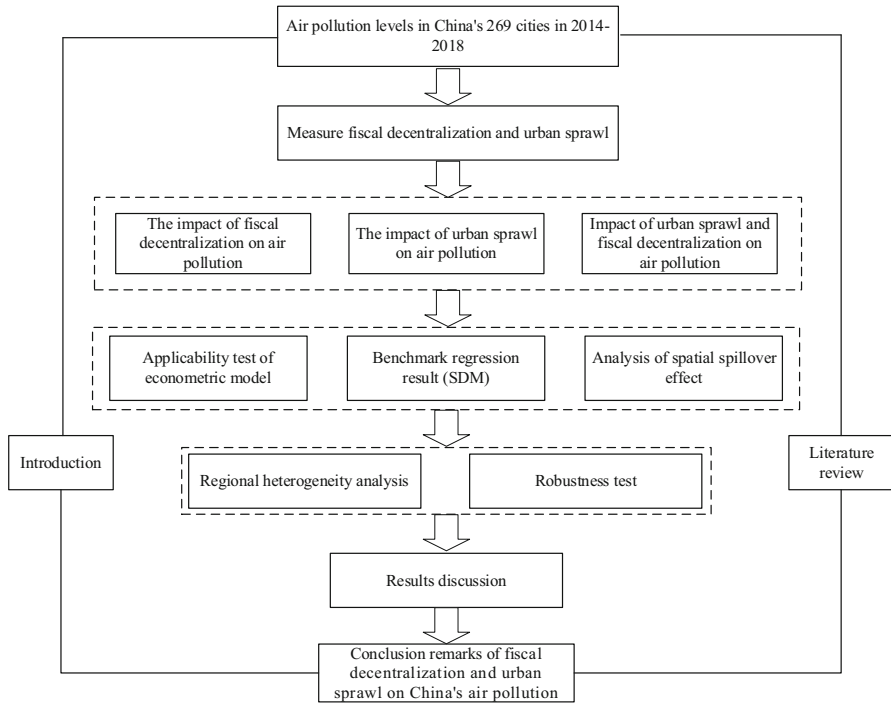


Fig. 2 Research framework

the city but also contributes to the diffusion of pollutants (De et al. 2008; Hixson et al. 2010; Kahyaoglu et al. 2009; Gordon and Richardson 1997; Buccolieri et al. 2010). The third view is that the relationship between urban sprawl and haze is not simply linear. In the early stage of urban expansion, urban sprawl promotes the deterioration of the ecological environment. However, when the city develops to the middle and later stage, the destruction of the ecological environment caused by urban sprawl can be reduced through technological innovation and structural transformation. Also, Feng and Wang (2020) argued that there was an inverted U-shaped curve relationship between air pollution and urban economic sprawl in China. Han (2020) pointed out that there was an N-type relationship between urban sprawl and air pollution.

2.2. Research on fiscal decentralization and air pollution

Relevant research on fiscal decentralization and environmental pollution is mainly divided into two views: inhibition theory and promotion theory. Researchers supporting the “inhibition theory” believe that due to the heterogeneity of public basic management services in different regions, local governments understand local information better than the central government. Therefore, local governments are responsible for most of the specific affairs of environmental governance and can take appropriate measures to address environmental problems (Oates and Portney 2003; Banzhaf and Chupp 2012; Kuai et al. 2019; Ahmad et al. 2021). Also, inter-regional

governments compete for fiscal revenue through “top-by-top competition” and “neighbor avoidance effect” caused by vertical and horizontal competition, which expands local governments’ fiscal expenditure on environmental governance and ultimately improves air quality (van et al. 2017; Wu et al. 2020a,b,c). Besides, local governments adjust environmental protection policies according to the fiscal revenue and expenditure quota while improving their financial autonomy. Through policy constraints to control enterprises that discharge pollutants, they can improve R & D and use clean corporate technology, and ultimately the cost-effectiveness of pollution control is offset by long-term technical effects (Percival et al. 2017). However, after the negative externalizations of political and economic activities caused by local governments as vested interests, the negative impact of fiscal decentralization on the environment has become increasingly pronounced. Scholars who advocate the promotion theory of decentralization believe that the fiscal competition caused by fiscal decentralization belongs to destructive competition (Abdessalam and Kamwa 2014; Cheng et al. 2021), which is easy to trigger “bottom to bottom competition” and “free-riding” among local governments, and inhibit the efficacy of air pollution controls (Levinson 2003; Konisky 2007; Zheng et al. 2014). Besides, environmental products have significant externalizations. Local governments may distort the supply structure by increasing expenditure on the production of public goods (Lihua et al. 2020; Oates and Schwab 2015) and reducing the supply of environmental public goods, resulting in the reduction in air quality (Fredriksson and Millimet 2002; Que et al. 2018).

To sum up, previous studies provide a rich theoretical framework and empirical basis for the analysis of the relationship among fiscal decentralization, urban sprawl, and air pollution. But some of the research has been ignored. First, recently most scholars mainly focus on the relationship between urban sprawl and air pollution, or explore the direct or indirect causal effect of fiscal decentralization on air pollution. However, there are few kinds of research on the relationship among fiscal decentralization, urban sprawl, and air pollution. Second, due to the huge differences in urban development patterns in China, there is also significant heterogeneity in different regions and urban characteristics. Existing studies rarely take the above heterogeneity into account to analyze the internal mechanism of air pollution caused by fiscal decentralization and urban sprawl. Third, most of the existing studies analyze air pollution based on provincial or national data. However, the spatial agglomeration and spillover effects of air pollution lead to significant spatial segmentation of regional pollution. Few scholars study the spatial effects of fiscal decentralization and urban sprawl on air pollution from the level of prefecture-level cities.

3 Methods

3.1 Econometric strategy

Since air pollution has the characteristics of spatial spillover and path dependence, the traditional measurement model cannot include spatial correlation into the research scope (Cheng et al. 2018; Hao et al. 2020a,b). Elhorst (2012) also argues that the spatial dependence of variables is not only influenced by the correlation among regions

in the previous period, but also likely affected by the non-negligible influence from the corresponding behavior among current regions.⁵ Therefore, the effects of fiscal decentralization and urban sprawl on air pollution are examined by using a spatial econometric model that can simultaneously capture the spatial heterogeneity and competitive characteristics of a region. The spatial Durbin model has a more general form than the spatial lag model and spatial error model, which can effectively analyze the externality and spillover between regions. Meanwhile, in view of the possible endogeneity among variables, the lag term of air pollution is introduced to construct the dynamic spatial Durbin model. The specific model forms are as follows:

$$\begin{aligned} Air_{it} = & \alpha_0 + \rho \sum_{j=1}^n W_{ijt} Air_{it} + \alpha_1 Air_{it-1} + \alpha_2 SPR_{it} + \alpha_3 FD_{it} \\ & + \alpha_4 \sum_{i \neq j}^N W_{ijt} SPR_{it} + \alpha_5 \sum_{i \neq j}^N W_{ijt} FD_{it} + \sum_{k=1}^5 \delta_{it} X_{it} + \mu_i + \tau_t + \varepsilon_{it} \end{aligned} \quad (1)$$

To further study the common influence of urban sprawl and fiscal decentralization on air pollution, the moderating term of fiscal decentralization and urban sprawl is added into the theoretical model, and the following model is constructed:

$$\begin{aligned} Air_{it} = & \alpha_0 + \rho \sum_{j=1}^n W_{ijt} Air_{it} + \alpha_1 Air_{it-1} + \alpha_2 SPR_{it} + \alpha_3 FD_{it} + \alpha_4 \sum_{i \neq j}^N W_{ijt} SPR_{it} \\ & + \alpha_5 \sum_{i \neq j}^N W_{ijt} FD_{it} + \alpha_6 \overline{SPR}_{it} \cdot \overline{FD}_{it} \\ & + \alpha_7 \sum_{i \neq j}^N W_{ijt} FD_{it} \cdot SPR_{it} + \sum_{k=1}^5 \delta_{it} X_{it} + \mu_i + \tau_t + \varepsilon_{it} \end{aligned} \quad (2)$$

where SPR denotes the urban sprawl, FD represents the fiscal decentralization, i represents the city, t represents the year. $\overline{SPR} = (SPR - \overline{SPR})$, $\overline{FD} = (FD - \overline{FD})$, \overline{SPR} , \overline{FD} represent the average value of urban sprawl and fiscal decentralization in the t year, respectively. Also, Air indicates air pollution and the first lag term of air pollution. W is the $n \times n$ order spatial weight matrix. X represents a series of control variables that affect air pollution, including the level of urban infrastructure construction (ROA), transportation (BUS); the level of financial development (FIN) and urban population density (POP). μ_i indicates the urban fixed effects. τ_t represents the time-fixed effect. ε represents the random error term.

⁵ Existing studies also indicate that there is a mutual competitive effect on environmental decision-making behavior induced by fiscal decentralization among different regions in China, and one of the mechanisms of this competitive effect is that geographically adjacent regions tend to significantly influence environmental decisions in neighboring regions, which in turn have an impact on air pollution in neighboring regions (Que et al. 2018). Moreover, Deng and Wang (2020) find evidence for the existence of spatial spillover characteristics of urban sprawl on air pollution, i.e., the urban sprawl of local regions affects air pollution in adjacent regions.

3.2 Set the spatial weight matrix

Tobler’s first law explains that things are connected and the correlation between things nearby is stronger. Therefore, most previous studies used the inverse of geographic distance to construct the spatial weight matrix (Zhai and An 2021; Wang et al. 2021). However, the differences in a geographic location only reflect the fact that air pollution is influenced by geographical correlation. In addition to geographical characteristics, economic characteristics are also crucial factors affecting air pollution. Economic competition among regions in China has driven both fiscal decentralization and urban sprawl to be highly correlated with the level of economic development. Therefore, many scholars have selected GDP per capita as a characterization variable of economic characteristics to construct a spatial weight matrix (Feng and Wang 2020; Chen et al. 2017). Based on this, referring to Yan and Qi (2017), we integrate the two most prominent geographical attributes and economic attributes among cities to construct a spatial weight matrix, so that it can more accurately portray the linkage among the spatial effects of different cities. The elements of the economic geography matrix (W) are defined as follows:

$$W_1 = \begin{cases} \frac{1}{|Y_i - Y_j|}, & i \neq j \\ 0, & i = j \end{cases}$$

$$W_2 = \begin{cases} \frac{1}{d^2}, & i \neq j \\ 0, & i = j \end{cases}$$

where d represents the distance between the geographical centers of the two regions; Y_i is the annual per capita GDP of the city i in the study period, and Y_j is the annual per capita GDP of city j in the study period; then, the economic geography matrix is: $W = W_1 \times W_2$.

3.3 Spatial autocorrelation test

To explain the spatial correlation of fiscal decentralization, urban sprawl, and air pollution, the spatial correlation degree needs to be calculated based on the above spatial matrix. This paper uses global *Moran’s I* index and Geary’s *c* index to verify the spatial correlation. The formula is as follows:

$$Moran's I = \frac{\sum_{i=1}^n \sum_{j=1}^n W_{ij} (M_i - \bar{M})(M_j - \bar{M})}{S^2 \sum_{i=1}^n \sum_{j=1}^n W_{ij}}; (-1 \leq Moran's I \leq 1) \quad (3)$$

$$Geary's c = \frac{(n - 1) \sum_{i=1}^n \sum_{j \neq 1}^n W_{ij} (M_i - M_j)^2}{2n S^2 \sum_{i=1}^n \sum_{j \neq 1}^n W_{ij}} \quad (4)$$

where $S^2 = \frac{1}{n} \sum_{i=1}^n (M_i - \bar{M})^2$, $\bar{M} = \frac{1}{n} \sum_{i=1}^n M_i$, W_{ij} is the elements of the spatial weights matrix, M represents air pollution level at location i . When *Moran’s I* > 0, air

pollution has a positive spillover effect among prefecture-level cities. If $Moran's I < 0$, air pollution has a negative spillover effect among prefecture-level cities. When $Moran's I = 0$, there is no spatial autocorrelation of air pollution among prefecture-level cities. The value of Geary's C is significantly lower than 1, it indicates that air pollution shows a significant positive spatial autocorrelation. The value of Geary's C is equal to 1, which means that air pollution has no spatial autocorrelation. The value of Geary's C is significantly higher than 1, revealing that air pollution shows a significant negative spatial autocorrelation.

3.4 Variable definition and data description

(1) Dependent variable

Air pollution (*Air*). The components of air pollution in China are mainly substances such as sulfur dioxide, industrial soot, and nitrogen oxides, most of which are less than or equal to 2.5 microns in diameter. Therefore, $PM_{2.5}$ is a suitable proxy variable for air pollution, and larger values of the $PM_{2.5}$ variable indicate more serious air pollution. Referring to Zhang et al. (2020) and Ma et al. (2015), the real values of $PM_{2.5}$ ($\mu\text{g}/\text{m}^3$) concentrations in 269 prefecture-level cities in China are analyzed using ArcGIS software to characterize air pollution (*Air*) from the raster data of global average $PM_{2.5}$ ($\mu\text{g}/\text{m}^3$) concentrations based on satellite monitoring published by the Center for Socioeconomic Data and Applications at Columbia University.

(2) Core explanatory variable.

Urban sprawl (*SPR*). Many scholars have measured urban sprawl from different angles, such as population density (Burke 2002), the scale of land urbanization (Kolankiewicz and Beck 2001), and night light data (Ch et al. 2020). However, it is too one-sided to measure urban sprawl using only population density or the scale of construction land, and night light data acquisition is also greatly affected by the weather. According to Hong and Zhang (2013), urban sprawl (*SPR*) is estimated as follows:

$$SPR_i = 1 - \left(\frac{\Delta P_i}{P_{io}} / \frac{\Delta A_i}{A_{io}} \right) \quad (5)$$

where SPR_i is the urban sprawl index of prefecture-level cities. P_{io} is the base period population of the prefecture-level city. ΔP_i is the added value of the population compared with the base period of prefecture-level cities. A_{io} is the base period of the built-up area of the prefecture-level city; ΔA_i is the added value of built-up area compared with the base period of prefecture-level cities.

Fiscal decentralization (*FD*). For the measurement of fiscal decentralization indicators, there are mainly three proxy variables: fiscal expenditure decentralization, fiscal revenue decentralization, and financial freedom. The central government gives local financial autonomy, which is the catalyst of local economic development, and enables local governments to obtain greater financial freedom. In this context, local governments will increase the financial intervention of their local environmental protection departments. Therefore, fiscal autonomy is adopted as

the proxy indicator of fiscal decentralization, which is measured by the combination of local fiscal general budget expenditure and local fiscal general budget revenue (He, 2015).

- (3) Given that there are many factors affecting air pollution, this paper introduces a series of control variables to control the influence of other factors on air pollution (Sun et al. 2019; Zhao et al. 2020; Yang et al. 2020a,2020 b; Feng et al. 2021). Among them, the level of urban infrastructure construction (*ROA*) is measured by the per capita road area of prefecture-level cities. Transportation (*BUS*) is represented by the number of buses per capita in the city. The level of financial development (*FIN*) is expressed by the ratio of the year-end deposit and loan balance of financial institutions to the total GDP. Urban population density (*POP*) is measured by the ratio of the population at the end of the year and the administrative area of the prefecture-level city.

3.5 Data sources and descriptive statistics

Balanced panel data for 269 prefecture-level cities in China from 2004 to 2018 were selected for this study. The original data for the selected indicators were obtained from the China Statistical Yearbook of Science and Technology, the China Financial Statistics Yearbook, and the China Urban Statistics Yearbook. The definitions and descriptive statistics of the variables selected for this paper are given in Table 1.

4 Analysis and discussions

4.1 Analysis of spatial correlation results

Before testing the spatial correlation of the green development efficiency of each city, this paper uses Stata 15 software to draw the quartile map of air pollution and observe the spatial dynamic evolution trend and spatial distribution characteristics of air pollution (Fig. 3). Figure 3 implies that air pollution in coastal areas is higher than that in inland areas in 2004, and air pollution levels are generally low. Air pollution is mainly concentrated in eastern and central China. Since then, air pollution concentration has

Table 1 Statistical description of variables

Variables	N	Mean	Sd	Min	Max
<i>Air</i>	4,035	3.522	0.500	1.466	4.754
<i>SPR</i>	4,035	0.230	0.254	- 3.490	0.868
<i>FD</i>	4,035	0.487	0.224	0.056	1.541
<i>ROA</i>	4,035	2.593	0.469	0.942	4.096
<i>BUS</i>	4,035	3.159	6.441	0.035	115.000
<i>FIN</i>	4,035	2.087	0.991	0.508	12.390
<i>POP</i>	4,035	7.894	0.848	3.296	9.908

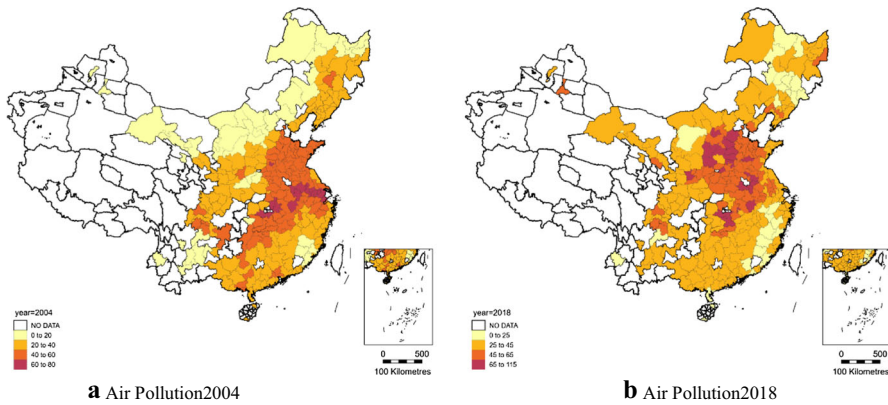


Fig. 3 China's air pollution in 2004 and 2018

shown an upward trend on the whole, and the coastal areas and northern areas are generally higher than the southern regions. Areas of air pollution gradually shifted from the Yangtze River Delta to the North China Plain, while the air pollution in the South gradually improved.

Table 2 shows the test results of spatial correlation by introducing the global Moran's I index method and Geary's C index into the economic geography matrix. Under the economic geography weight matrix, the global Moran's I index value and Geary's C index value of air pollution are significantly positive at the level of 1%, which indicates

Table 2 The values of Moran's I and Geary's C index

Year	Moran's I	Z	<i>p</i> value	Geary's C	Z	<i>p</i> value
2004	0.828	11.190	0.000	0.153	- 9.767	0.000
2005	0.842	11.375	0.000	0.118	- 10.205	0.000
2006	0.834	11.257	0.000	0.112	- 10.408	0.000
2007	0.853	11.513	0.000	0.103	- 10.631	0.000
2008	0.840	11.338	0.000	0.117	- 10.477	0.000
2009	0.823	11.122	0.000	0.125	- 10.175	0.000
2010	0.839	11.328	0.000	0.117	- 10.339	0.000
2011	0.855	11.553	0.000	0.105	- 10.386	0.000
2012	0.865	11.677	0.000	0.106	- 10.548	0.000
2013	0.834	11.258	0.000	0.122	- 10.333	0.000
2014	0.830	11.207	0.000	0.125	- 10.163	0.000
2015	0.877	11.819	0.000	0.098	- 10.855	0.000
2016	0.860	11.597	0.000	0.109	- 10.856	0.000
2017	0.741	9.999	0.000	0.245	- 9.169	0.000
2018	0.738	10.039	0.000	0.281	- 7.266	0.000

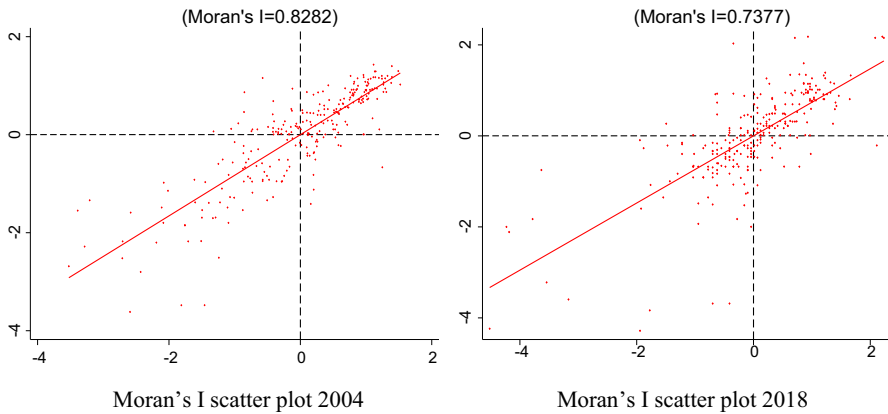


Fig. 4 Air pollution Moran index scatter plot in 2004–2018

that air pollution has significant spatial positive correlation and certain spatial cluster distribution characteristics in the whole region.

The local Moran scatter plot is used to describe the spatial agglomeration of urban air pollution, to further show the spatial agglomeration characteristics of air pollution (Fig. 4). Figure 4 shows that under the economic geography matrix, the scatter points are mainly distributed in the first quadrant (High–High) cluster and third quadrant (Low–Low) cluster. And as time goes on, the air pollution cluster trend mainly shifted from the first quadrant (High–High) to the third quadrant (Low–Low). It also shows that the joint governance of air in various regions of China has achieved certain results.

4.2 Applicability analysis of the econometric model

In order to verify the validity of the above spatial model setting, a series of tests should be performed on the spatial panel data. Table 3 shows the results of the pooled OLS test, LM test, Hausman test, LR test, and Wald test. Among them, Moran's I test is significant at the level of 1%, which indicates that the spatial setting of panel data is

Table 3 Model applicability test

Test	Statistic	<i>p</i> value
Moran's I	40.391	0.000
LM-Spatial error	1627.821	0.000
RobustLM-Spatial error	32.502	0.000
LM-Spatial lag	1787.790	0.000
RobustLM-Spatial lag	192.471	0.000
WALD-Spatial error	429.37	0.000
WALD-Spatial lag	254.08	0.000
Hausman	75.26	0.000

reasonable. Besides, the statistical values of the LM error test, LM error (Robust) test, LM lag test, and LM lag (Robust) test are significantly positive at the level of 1%, which means that the spatial error and spatial lag characteristics of the model should be considered at the same time. The spatial Durbin model is reasonable (Anselin 1995). The results of the Hausman test show that the two-way fixed effect of urban individuals and time should be considered in the model set. Finally, the statistical values of the LR test and Wald test are significantly positive, indicating that the spatial Durbin model will not degenerate into the spatial lag model and spatial error model (LeSage and Pace 2009). Therefore, this paper selects the time and individual two-way fixed spatial Durbin model for regression analysis.

4.3 Analysis of benchmark regression results

The regression results of urban sprawl and fiscal decentralization on air pollution are shown in Table 4. In columns (1)–(4), the lag term of air pollution is significantly positive at the level of 1%, which indicates that air pollution has significant time lag characteristics, and the early residual air pollution may have an impact on the ecological environment in the later stage. In terms of the specific impact of non-spatial variables on air pollution solely, the coefficients of *SPR* in column (1) and column (3) are significantly positive at the level of 1%, indicating that urban sprawl (*SPR*) promotes air pollution. This is consistent with the findings of Shi et al. (2020), Berentschaft and Debbage (2013), and Dupras and Marull (2016). In the process of rapid urban sprawl, local governments erode the nearby cultivated land, wetlands, woodland, and green space by establishing supporting facilities such as factories, residential areas, and schools, to reduce the carrying capacity and self-purification capacity of the ecosystem (Navamuel et al. 2018). Additionally, urban sprawl will increase the proportion of urban construction land, which will not only cause a large number of activities such as housing construction, real estate investment and development, as well as factory demolition and construction, but also induce the emission of pollutants mainly comprising smoke and dust and cause air pollution. (Ouyang et al. 2019; Wu et al. 2020a,b,c). Moreover, urban sprawl leads to relatively dispersed public service facilities and low-density transportation network, which separates people's living areas from other functional areas (work, shopping, school, etc.), resulting in an increased commuting distance and driving residents to rely heavily on private transportation (Etre et al. 2000; Pucher et al. 2007; Holcombe and Williams 2010). This not only brings about serious traffic congestion, but also results in a surge in vehicle exhaust emissions, which in turn increases air pollution in the area (Burke 2002; Zhao 2020).

In columns (2) and (3), the coefficients of *FD* are significantly positive at the level of 1%, which indicates that the significant contribution of fiscal decentralization to air pollution. This is similar to the view proposed by Que et al. (2018). Under the influence of Chinese-style fiscal decentralization and various government policies, governments at all levels, to accelerate economic growth, tend to relax environmental regulation and attract industrial enterprises' investment in resources and the environment. This phenomenon of inferior competition will aggravate environmental deterioration (van

Table 4 Results of benchmark regression

Variables	(1)	(2)	(3)	(4)
<i>L.Air</i>	0.6609*** (46.69)	0.6864*** (48.58)	0.6460*** (45.64)	0.6939*** (49.00)
<i>SPR</i>	0.0949*** (5.90)		0.0950*** (5.91)	0.0157 (0.49)
<i>FD</i>		0.2462*** (8.03)	0.2488*** (8.12)	0.2214*** (6.92)
<i>SPR • FD</i>				0.1333*** (2.98)
<i>ROA</i>	0.0228** (2.32)	0.0340*** (3.53)	0.0214** (2.17)	0.0210** (2.11)
<i>BUS</i>	- 0.0011 (- 1.00)	- 0.0015 (- 1.40)	- 0.0007 (- 0.59)	- 0.0011 (- 0.97)
<i>FIN</i>	0.0112* (1.91)	0.0040 (0.71)	0.0194*** (3.33)	0.0173*** (2.96)
<i>POP</i>	0.0022 (0.49)	0.0120*** (2.67)	0.0027 (0.59)	0.0027 (0.60)
<i>W • SPR</i>	0.1013*** (6.00)		0.1042*** (6.18)	0.0402 (1.20)
<i>W • FD</i>		0.4497*** (13.96)	0.4468*** (13.87)	0.4603*** (12.70)
<i>W • FD • SPR</i>				0.1036** (2.27)
ρ	0.5172*** (53.33)	0.5203*** (53.68)	0.5050*** (52.10)	0.5183*** (53.44)
σ^2	0.0146*** (43.78)	0.0145*** (43.70)	0.0147*** (44.12)	0.0145*** (43.76)
Individual effect	Yes	Yes	Yes	Yes
Year effect	Yes	Yes	Yes	Yes
Other variables	Yes	Yes	Yes	Yes
N	3766	3766	3766	3766
R^2	0.7965	0.7006	0.6752	0.6913

***, **, and * indicate that the estimated coefficients are significant at 1, 5, and 10% levels, respectively. The value in parentheses () represents the value of Z. $\alpha_1 \dots \alpha_5$ denote the coefficients of *L.Air*, *SPR*, *FD*, *W • SPR*, and *W • FD*, respectively

et al. 2017; Wu et al. 2020a,b,c). As a result, fiscal decentralization transforms the fiscal expenditure structure of local governments from a “helping hand” to a “grabbing hand,” which makes local governments ignore environmental protection expenditure. Moreover, the existence of spillover of environmental public goods makes local governments form a “free-riding” phenomenon, which leads to the absence of government pollution control work and the lack of supply capacity of air pollution control, resulting in the aggravation of air pollution (Levinson 2003; Konisky 2007; Zheng et al. 2014).

Column (4) shows that the coefficient of $SPR \bullet FD$ is significantly positive at the level of 1%, indicating that the moderating term for fiscal decentralization and urban sprawl exacerbates air pollution, i.e., fiscal decentralization aggravates the impact of urban sprawl on air pollution. It is not hard to understand that under the system of fiscal decentralization, the motivation of the local government is mainly to expand the area of land and the scale of manufacturing industry by the policy of low cost of land use, thus resulting in forming the phenomenon of urban sprawl (Tang et al. 2019). Additionally, to increase local fiscal revenue, local governments will lower the threshold of enterprises' pollution emission and attract non-local enterprises to move in and a large number of low-quality FDI to flow into their jurisdiction, which will not only cause a large number of industries to gather in the outskirts of cities but also promote the accelerated expansion of urban area (Liu et al. 2018). Finally, because the real estate industry brings huge benefits to the local government, the local government tends to accelerate the housing expansion by land development and farmland destruction (Tao et al. 2010). In the above-mentioned case of fiscal decentralization, local governments not only expand the size of the city, reduce the concentration of urban economic resources, but also cause more air pollution by blindly increasing the land supply area and developing industrial production.

From the spatial perspective, the spatial correlation coefficients (ρ) are all significantly positive at the 1% level, which again proves that there is an obvious spatial agglomeration characteristic of air pollution in China, i.e., the increase in local air pollution will aggravate the air pollution in the surrounding areas. In columns (1) and (3), the coefficient of $W \cdot SPR$ is significantly positive at the 1% level, indicating that urban sprawl has a positive spillover effect, i.e., increased local urban sprawl will promote air pollution in the surrounding areas. In columns (2) and (3), the coefficients of $W \cdot FD$ are significantly positive at the 1% level, which indicates that increased local fiscal decentralization will promote air pollution in the surrounding areas. The above results are only preliminary confirmation that urban sprawl and fiscal decentralization have positive spillover effects on air pollution, and their specific spatial spillover effects will be further explored in later sections.

4.4 Analysis of spatial spillover decomposition effect results

When spatial coefficients are introduced in the spatial panel model, we cannot focus only on the direct effect of the explanatory variables on the explained variable, but should also comprehensively consider the spatial effects and the time effects of the explanatory variables on the explained variable. To analyze the spatial effect results

more accurately, the partial differential decomposition method of the spatial regression model proposed by LeSage and Pace (2009) is employed to decompose the spatial spillover effects into direct effects and indirect effects to further explain the impacts of fiscal decentralization and urban sprawl on air pollution.⁶ The above spatial spillover decomposition effect is thus calculated as:

$$\text{Short - term direct effect} = \left[(I - \rho W)^{-1} (\alpha_{2k} I_N) \right]^{\bar{d}} \quad (6)$$

$$\text{Short - term indirect effect} = \left[(I - \rho W)^{-1} (\alpha_{2k} I_N) \right]^{\overline{rsum}} \quad (7)$$

$$\text{Long - term direct effect} = \left\{ [(1 - \alpha_1)I - (\rho W)]^{-1} (\alpha_{2k} I_N) \right\}^{\bar{d}} \quad (8)$$

$$\text{Long - term indirect effect} = \left\{ [(1 - \alpha_1)I - (\rho W)]^{-1} (\alpha_{2k} I_N) \right\}^{\overline{rsum}} \quad (9)$$

where I is the unit matrix. \bar{d} and \overline{rsum} denote the operators for calculating the mean of the diagonal elements of the matrix and the operators for calculating the row and mean of the non-diagonal elements of the matrix, respectively. The definitions of other parameters are the same as above.

Table 5 shows the results of the decomposition of spatial spillover effects. From the short-term decomposition effect, the coefficients of the total effect, direct spillover effect, and indirect spillover effect of urban sprawl and fiscal decentralization on air pollution are significantly positive, which indicates that urban sprawl can significantly promote air pollution, and there is a significant positive spatial spillover effect. From the long-term effect, the total effect of urban sprawl and fiscal decentralization on air pollution is significantly negative, but the direct and indirect effects are negative but not significant. In terms of urban sprawl, the local government will reduce the environmental threshold and attract the population and low-quality enterprises in the adjacent areas to recover the economic benefits of urban construction losses in the short term. Furthermore, the concentration of the population has increased the pressure on transportation and housing in the region and increased the vehicle exhaust emissions and industry construction, resulting in air pollution. Besides, low-quality enterprises often have the characteristics of “high energy consumption, high emission and high pollution,” which causes the aggravation of local air pollution. The above state will not last for a long time. As the matching of the speed of urban sprawl and the size of the urban population in this region, as well as the gradual improvement in the emission threshold of enterprises, the large-scale inflow of population and productive enterprises in the adjacent areas is restricted. And the promotion effect of urban sprawl in adjacent areas on air pollution in the region is alleviated.

⁶ Because we use a dynamic spatial panel data model, we further divide the direct and indirect effects into long-term (LR_Effect) and short-term (SR_Effect) effects in the time dimension to reflect the short-term immediate effects of the explanatory variables on the explanatory variables and the long-term effects considering the time-lagged effects, respectively (Chen et al., 2017; Elhorst, 2014; Feng and Wang, 2020).

Table 5 Decomposition results of spatial spillover effect

Variables	SR_Effect			LR_Effect		
	Direct	Indirect	Total	Direct	Indirect	Total
<i>SPR</i>	0.1492*** (7.81)	0.2514*** (8.40)	0.4006*** (8.92)	- 0.3143 (- 0.23)	- 1.0006 (- 0.74)	- 1.3149*** (- 8.15)
<i>FD</i>	0.4605*** (13.38)	0.9563*** (17.41)	1.4167*** (17.86)	- 1.2466 (- 0.27)	- 3.4069 (- 0.74)	- 4.6535*** (- 11.86)
<i>ROA</i>	0.0331*** (2.87)	0.0536*** (3.05)	0.0867*** (3.28)	- 0.0722 (- 0.17)	- 0.2128 (- 0.50)	- 0.2849*** (- 3.18)
<i>BUS</i>	- 0.0015 (- 1.11)	- 0.0037* (- 1.92)	- 0.0052* (- 1.74)	0.0051 (0.47)	0.0120 (0.88)	0.0170* (1.71)
<i>FIN</i>	0.0253*** (3.76)	0.0254** (2.54)	0.0507*** (3.41)	- 0.0266 (- 0.11)	- 0.1401 (- 0.60)	- 0.1667*** (- 3.30)
<i>POP</i>	0.0070 (1.31)	0.0200*** (2.71)	0.0271** (2.40)	- 0.0280 (- 0.27)	- 0.0610 (- 0.57)	- 0.0890** (- 2.36)

***, **, and * indicate that the estimated coefficients are significant at 1%, 5%, and 10% levels, respectively. The value in parentheses () represents the value of Z

In terms of fiscal decentralization, in the short term, the adjacent areas will accelerate economic development through “bottom-to-bottom competition” to catch up with the economic growth of the surrounding economically developed areas. For instance, most of the financial funds in the adjacent areas are used for production and construction rather than environmental protection expenditure, which makes the local government’s “free-riding” behavior impossible to achieve, limiting the formation of the pattern of air pollution control. As a result, the fiscal decentralization of the adjacent areas not only promotes air pollution in the adjacent areas, but also significantly aggravates the local air pollution. In the long term, with the gradual coverage of inter-regional coordinated pollution control measures, local governments also gradually tend financial funds to environmental protection departments, support the development of the environmental protection industry, and subsidize enterprises to carry out cleaner production, thus weakening the role of fiscal decentralization in promoting air pollution.

4.5 Analysis of regional heterogeneity results

Owing to the great differences in the level of economic development among regions, this paper divides the whole sample into eastern, central, and western regions for classification and discussion. The regression results are shown in Table 6. In columns (1)—(4), the first lag terms of air pollution are still significantly positive, indicating that the “snowball” effect of air pollution in the overall space–time is still significant. From the regression results of eastern China, the direct and moderating effects of urban sprawl and fiscal decentralization on air pollution are not significant in columns

(1) and (2). On the one hand, urban sprawl in the eastern region tends to be high-density and orderly expansion, which alleviates the air pollution caused by urban disorderly expansion (Li and Li 2019). On the other hand, the eastern region has a high threshold for the performance appraisal standards of government departments. While expanding its urban development, the eastern region places more emphasis on high-quality economic development, and its competition mode has been transformed from “bottom-by-bottom competition” to “top-by-top competition” (Wu et al. 2020a,b,c). In addition, the eastern region has a high financial level and more advantages in terms of resources, and financial funds can be used to offset the cost of pollution control and emission reduction (Hua et al. 2018). Therefore, the promotion effect of urban sprawl and fiscal decentralization on air pollution is not significant in the eastern region.

Table 6 Analysis of the results of regional heterogeneity

Variables	Eastern regions		Central and western regions	
	(1)	(2)	(3)	(4)
<i>L.Air</i>	0.4265*** (18.15)	0.3772*** (17.66)	0.8343*** (45.49)	0.6564*** (39.75)
<i>SPR</i>	- 0.0123 (- 0.74)	- 0.0544 (- 0.97)	0.2193*** (8.39)	- 0.3660*** (- 8.14)
<i>FD</i>	- 0.0723 (- 1.60)	- 0.0728 (- 1.48)	0.4115*** (10.24)	0.1977*** (4.36)
<i>SPR × FD</i>		0.0429 (0.65)		1.4542*** (14.81)
<i>ROA</i>	0.0057 (0.46)	0.0003 (0.02)	0.0289** (2.13)	- 0.0207 (- 1.49)
<i>BUS</i>	- 0.0004 (- 0.40)	- 0.0008 (- 0.67)	- 0.0032 (- 1.59)	- 0.0062*** (- 2.92)
<i>FIN</i>	- 0.0058 (- 0.77)	- 0.0070 (- 0.94)	0.0424*** (5.28)	0.0428*** (5.46)
<i>POP</i>	- 0.0071 (- 0.86)	- 0.0063 (- 0.78)	0.0004 (0.08)	- 0.0137** (- 2.44)
ρ	0.3789*** (19.72)	0.4458*** (24.51)	0.5142*** (42.40)	0.6427*** (57.48)
σ^2	0.0082*** (26.88)	0.0088*** (26.51)	0.0175*** (35.24)	0.0188*** (33.23)
Individual effect	Yes	Yes	Yes	Yes
Year effect	Yes	Yes	Yes	Yes
N	1344	1344	2422	2422
R^2	0.8713	0.8594	0.6509	0.5195

***, **, and * indicate that the estimated coefficients are significant at 1%, 5%, and 10% levels, respectively. The value in parentheses () represents the value of Z

In columns (3) and (4), urban sprawl and fiscal decentralization and their moderating term significantly promoted air pollution in the central and western regions. In the first place, urban sprawl is in the stage of low-density expansion. This low-density trend makes the transportation network and service facilities relatively scattered, and residential areas are separated from other functional areas. The increasing distance of residents' travel activities such as working, going to school, and shopping makes them more dependent on private cars, which leads to the continuous increase in vehicle ownership and thus the increase in exhaust emissions (Iyigun 2006; Bento et al. 2006). Secondly, the ecological environment in the central and western regions is relatively fragile, while urban sprawl engulfs the green open space, which causes a large number of marshes, beaches, and wetlands to be filled up, forests and deserts to be destroyed, and directly reduces the pollution carrying capacity of the ecosystem (Feng and Wang 2020). Eventually, the fragile ecosystem will become worse and its self-regulation ability will be weakened, which will aggravate air pollution (Navamuel et al. 2018). Meanwhile, the financial capacity of the central and western regions is relatively weak, which makes it difficult to support such a heavy burden of pollution control costs. To obtain fiscal revenue and develop the regional economy, the central and western regions have gradually become a refuge for industrial transfer of some foreign-funded polluters in the eastern region of China, which leads to the worsening trend of air pollution.

4.6 Analysis of robustness test results

To analyze the accuracy of the conclusion under the above full sample condition, the robustness test is carried out from the following two aspects. Firstly, the core explanatory variables are replaced to verify the robustness of the results. Following Zhu (2016), the ratio of general budget revenue of prefecture-level cities to GDP has been used to re-measure the fiscal decentralization index. The dynamic space Durbin model is used to re-test and regress the results. The relevant results are shown in column (1) and column (2) (see Table 7). Secondly, robustness examinations are performed by alternative estimation methods. The spatial autoregressive model is used to test the results, which are shown in columns (3) and (4) (see Table 7). Furthermore, because of the diverse construction and definition of the spatial weight matrix, the inverse distance matrix is further built in this paper to verify the robustness of the previous results. The related estimation results are shown in columns 5 and 6 of Table 7. Table 7 indicates that the directionality of the regression coefficient of the core explanatory variables is consistent with that of the above findings, which implies that the regression results are robust and reliable.

5 Conclusions and policy recommendations

New urbanization and green development are the two major themes of current economic and social development. Environmental quality is the basis of a city's sustainable development, and urban environmental quality mainly reflects the efficacy of environmental governance by the government. In this context, this paper empirically tests the

Table 7 Robustness test

Variables	Robustness test 1		Robustness test 2		Robustness test 3	
	(1)	(2)	(3)	(4)	(5)	(6)
<i>L.Air</i>	0.7017*** (49.60)	0.7398*** (52.31)	0.6834*** (48.42)	0.6831*** (48.39)	0.5479*** (35.31)	0.6558*** (45.51)
<i>SPR</i>	0.1740*** (10.82)	- 2.6885*** (- 88.28)	0.1004*** (6.26)	0.0072 (0.23)	0.0661*** (3.65)	- 0.0352 (- 0.93)
<i>FD</i>	9.6830*** (55.06)	- 1.0585*** (- 5.19)	0.3640*** (12.34)	0.3336*** (10.83)	1.0835*** (30.16)	- 0.1634*** (- 4.30)
<i>SPR × FD</i>		45.1142*** (111.94)		0.1507*** (3.43)		0.0900* (1.69)
<i>ROA</i>	0.0089 (0.90)	- 0.0407*** (- 4.13)	0.0207** (2.12)	0.0249** (2.53)	0.0318*** (2.88)	0.0128 (1.11)
<i>BUS</i>	- 0.0001 (- 0.04)	- 0.0118*** (- 10.30)	- 0.0014 (- 1.25)	- 0.0018 (- 1.60)	- 0.0040*** (- 3.12)	- 0.0037*** (- 2.77)
<i>FIN</i>	- 0.0419*** (- 7.08)	- 0.0861*** (- 14.53)	0.0140** (2.52)	0.0130** (2.33)	- 0.0109 (- 1.61)	- 0.0120* (- 1.74)
<i>POP</i>	0.0134*** (3.00)	0.0576*** (12.85)	0.0052 (1.20)	0.0052 (1.21)	- 0.0320*** (- 6.26)	0.0009 (0.17)
ρ	0.5010*** (51.69)	0.4800*** (49.52)	0.5186*** (53.61)	0.5179*** (53.52)	1.0011*** (138.02)	1.0487*** (171.53)

Table 7 (continued)

Variables	Robustness test 1		Robustness test 2		Robustness test 3	
	(1)	(2)	(3)	(4)	(5)	(6)
σ^2	0.0147*** (44.23)	0.0149*** (44.80)	0.0146*** (43.76)	0.0146*** (43.78)	0.0188*** (46.17)	0.0198*** (45.43)
Individual effect	Yes	Yes	Yes	Yes	Yes	Yes
Year effect	Yes	Yes	Yes	Yes	Yes	Yes
N	3766	3766	3766	3766	3766	3766
R^2	0.2511	0.2219	0.7764	0.7776	0.2239	0.7092

***, **, and * indicate that the estimated coefficients are significant at 1%, 5%, and 10% levels, respectively. The value in parentheses () represents the value of Z

impact of urban sprawl and fiscal decentralization on air pollution by constructing the economic geography matrix and using the dynamic spatial Durbin model based on the urban panel data of 269 prefecture-level cities in China from 2004 to 2018. Our study contributes to the literature on air pollution (He et al. 2012; Cheng and Zhu 2021; Feng and Wang 2020; Stone 2008), which applies a new framework on the relationship between fiscal decentralization, urban sprawl, and air pollution based on a dynamic spatial Durbin model. In particular, differently from previous studies that limited the analysis to merely local effects of the estimated results, we examined the spatial spillover effects (direct, indirect, and total effects) of fiscal decentralization and urban sprawl on air pollution. Given the regional heterogeneity of the sample, we add to the existing literature by forming two subgroups: the Eastern region and the Central and Western regions. Doing so will enable our study to provide additional in-depth insights and an empirical basis for implementing regionally differentiated environmental governance policies for policymakers in China and developing countries with similar economic development to China.

The results from the dynamic spatial Durbin model show that air pollution has a significant positive spatial correlation in China. Urban sprawl and fiscal decentralization significantly promote air pollution, respectively. At the same time, the moderating term for urban expansion and fiscal decentralization is significantly positive, indicating that fiscal decentralization strengthens the promotion effect of urban sprawl on air pollution. Further research shows that the impact of urban sprawl and fiscal decentralization on air pollution is regionally heterogeneous due to the differences of economic development level and urban expansion degree among regions. Specifically, urban sprawl and fiscal decentralization and the moderating terms of fiscal decentralization and urban sprawl have no significant impact on air pollution in the eastern region, while urban sprawl and fiscal decentralization and the moderating terms of fiscal decentralization and urban sprawl significantly promote air pollution in central and western regions. Therefore, to win the battle to “defend the blue sky” and realize sustainable economic development, the following work needs to be performed.

Firstly, from the perspective of the local government, policymakers should remove the obstacles of pollution control, strengthen the joint prevention and control of air pollution and policy coordination among local governments, and promote the breadth and depth of regional cooperation of air pollution among governments at all levels. From the perspective of the central government, it is necessary to coordinate the objective functions and strengthen the supervision functions of local governments, clarify the rights and responsibilities of governments for environmental pollution, optimize the top-level design of the environmental system, standardize the requirements of joint prevention and control policies, strengthen the binding force of environmental regulations and the punishment of high pollution discharge enterprises, and avoid the “tragedy of the commons” caused by the transfer of air pollution.

Secondly, city boundaries should be scientifically defined to promote reasonable urban expansion and prevent disorderly urban sprawl. Policymakers should firmly grasp the urban land space planning concept of “safety, efficiency, ecology, and quality” and take a people-oriented approach, which does not take the land as the priority based on accelerating the process of demarcating urban boundaries. Besides, policymakers should seek to coordinate the coupling of urban economic development and

the ecosystem. In terms of urban development strategy, the traditional thinking pattern of urban spatial planning is broken, urban development needs more clarification, and planning techniques and methods need to be innovated to prevent urban sprawl.

Thirdly, the central government should further optimize the performance evaluation system and fiscal decentralization mechanism. In recent years, although local governments have included the supply of public goods such as environmental quality and investment in environmental governance into the performance goal assessment system, it is difficult to eliminate the long-formed idea of “emphasizing economic development over environmental governance.” Therefore, policymakers should appropriately increase the proportion of environmental governance and ecological protection in the performance assessment indicators. At the same time, policymakers should also strengthen the reforms to the accountability mechanism of environmental governance, encourage local governments to change the structure of fiscal expenditure, and finally complete the transformation from desalination speed to strengthening quality. Finally, while delegating financial power, the central government should combine “decentralization” and “management,” focusing on the rational distribution of central authority and local fiscal power.

Fourth, policymakers should adjust the proportion of fiscal decentralization. Local financial and administrative rights should be balanced to reduce incentives to “make money from the land” and prevent urban sprawl. At the same time, in terms of the land use system, policymakers should further clarify the boundaries of land use types and improve the power-constraint mechanism. For land revenue system management, due to the past one-time large-scale land transfer mode, it is easy to lead to the shortsighted behavior of local governments. Therefore, policymakers can establish corresponding land transfer funds, allow local governments to withdraw land transfer fees in stages, and reserve a part of the funds as the urban development and construction funds of the later government, so as to promote the sustainable development of the urban economy and gradually realize the gradual urban expansion.

Finally, policymakers should give full consideration to the actual situation and laws governing local economic development and promulgate air pollution policies according to local conditions. Facing regional air pollution differentiation, policymakers also should formulate reasonable environmental protection policies and regional policies to avoid urban sprawl caused by fiscal decentralization. For example, for different regional cities, the government should formulate the control index of urbanization spread according to local conditions and adjust the local fiscal decentralization index accordingly. For the large cities in the eastern part of China, policymakers should reduce the fiscal transfer payment and expand the local tax sources to control the city size. For central and western cities, policymakers should improve the degree of fiscal decentralization, promote urban industrial agglomeration, and further curb urban sprawl to achieve air pollution control by means of centrally directed fund allocation and other means.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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