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Urban Sprawl and Haze Pollution: Based on Raster Data of Haze PM2.5 Concentrations in 283 Cities in Mainland China

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Incorporating the urban sprawl and its quadratic term into the analytical framework of the environmental Kuznets curve and considers the spatial and threshold effects of pollution, this paper used the raster data of haze PM2.5 concentrations in 283 cities in mainland China to verify the non-linear effects of urban sprawl on urban haze pollution. It finds that: the inter-city spillover effect of haze pollution is significant, and the environmental Kuznets curve holds on haze pollution; there is an inversed "U" relationship between urban population size and haze pollution; the enlarge of the urban built-up area of city would increase haze pollution significantly; the impact of urban population size on haze pollution has a threshold effect that it would decline with the urban built-up area expansion; the coordination between population urbanization and land urbanization has an notable effect on haze pollution that its incoordination in China's urbanization has aggravated haze pollution in city and this impact would lagged 1–2 period in time.

Keywords: urban sprawl, haze pollution, population urbanization, land urbanization, spatial Durbin model, coordination

1 INTRODUCTION

In recent years, haze pollution has been a prominent environmental problem in mainland China (Li et al., 2021). Haze pollution is not only the greatest public health risk, but also has serious negative impacts on economic and social development (Huang and Chew, 2021). Therefore, it is worthy to deeply discuss the economic and social determinants of haze pollution.

Haze pollution is coupled with human economic activities (Liao et al., 2020). A major economic phenomenon in mainland China in recent years is continued urbanization, mainly in the form of expanding urban population size and urbanized built-up area. (Li et al., 2022). So, the relationship of urbanization and haze pollution has triggered many theoretical and empirical discussions. Some studies have shown that this is a complex causal relationship between urbanization and haze pollution (Yang and Yan, 2021), that it would vary by region, economic stage and scale (Feng and Wang, 2020; Yang et al., 2020). For this, we consider that there may be a threshold effect of urban sprawl on hazy pollution, and then we deduce a nonlinear causality of urbanization and hazy pollution. However, this nonlinear relationship is hardly investigated in a linear analysis framework in the existing literature. Consequently, we introduce a quadratic term of urbanization to explore it. In addition, the Chinses urbanization is characterized by lagging population urbanization, over-

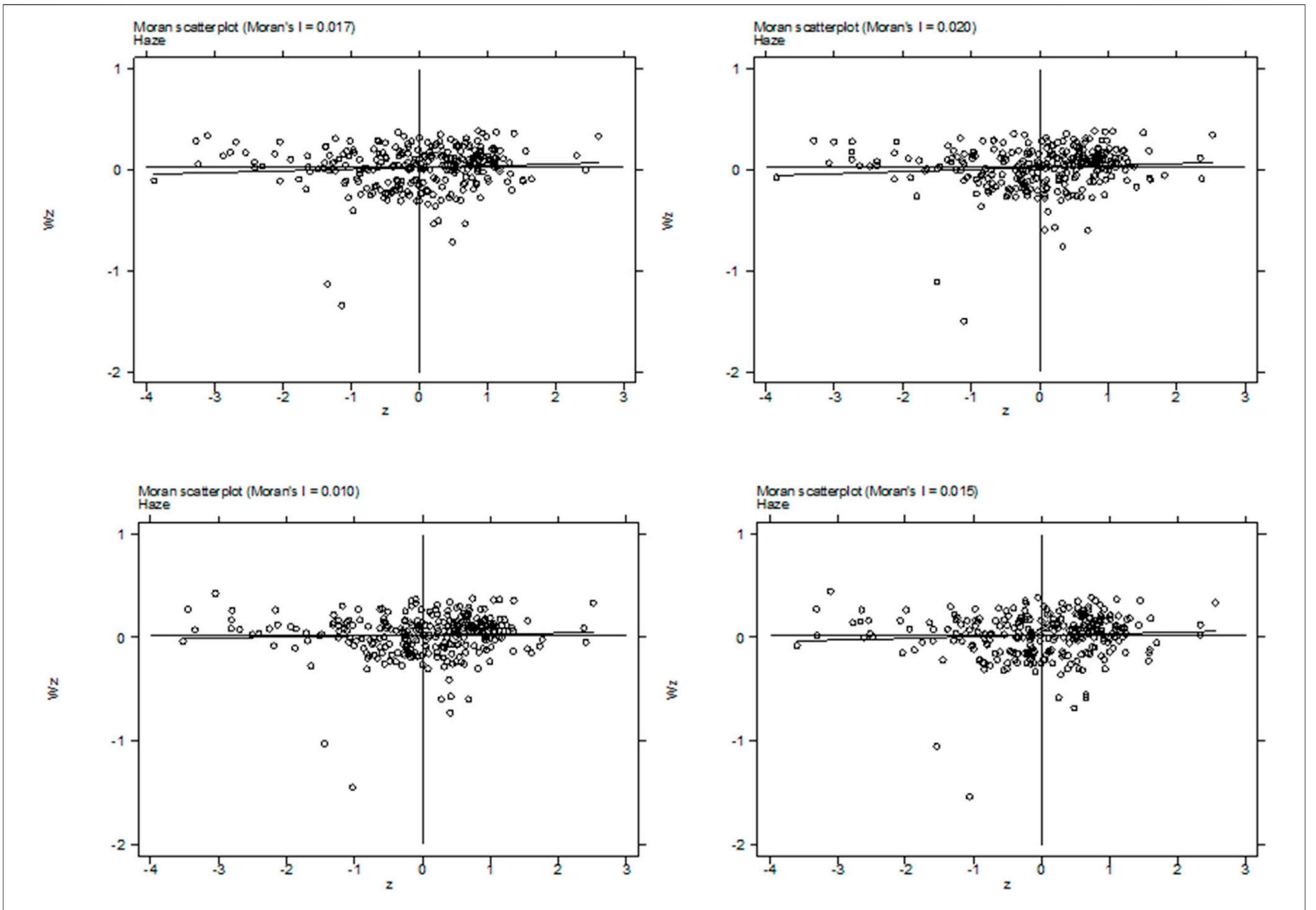

FIGURE 1 | Moran scatter plot of haze pollution.

urbanization of land, and an incoordination between population and land in urbanization (Zhang et al., 2022). And this incoordination would even affect the relationship of urbanization and pollution.

Therefore, the questions concerned in this paper are whether there is a significant causal relationship between urban expansion and haze pollution? Is there a threshold effect of urban sprawl on haze pollution? Does the incoordination of population urbanization and land urbanization significantly affect the relationship between urbanization and haze pollution?

The possible contributions of this paper are: firstly, using a prefectural city-level raster data of PM2.5 concentrations in 283 cities in mainland China and establishing a spatial econometric model based on the environmental Kuznets curve to discuss the influence of urban expansion on haze pollution from the two perspectives of population and land, and also analyzing the spatial effects of haze pollution; secondly, constructing threshold models with population and urban built-up area as threshold variable respectively to discuss the non-linear effect of urbanization on haze pollution; Third, a greater contribution of this article is to include coordination between population urbanization and land urbanization in the study to investigate whether the incompatibility between these two has an impact on haze pollution, and analyze its impact mechanism.

2 LITERATURE REVIEW AND THEORETICAL ANALYSIS

2.1 Literature Review

The experience of economic development and environmental pollution in various countries shows that developed economies have experienced serious environmental pollution, including haze pollution, in the early stages of industrialization, such as the United Kingdom, Germany, the US and Japan (Jungwook K. and Jinkyeong K., 2021). Scholars have summarized this experience as a general economic law between economic development and environmental pollution: the environmental Kuznets curve (Maddison D, 2006; Müller-Fürstenberger and Wagner, 2007). The environmental Kuznets curve points to an inverted “U" relationship between economic development and environmental pollution: in the early stages of rapid economic development, environmental pollution in an economy will gradually increase as resource inputs increase; as the economy develops further, the level of technology improves and the quality of economic growth increases, environmental pollution will gradually decrease (Song et al., 2021). Under this rule, other economic variables will also affect environmental pollution, including government regulation, foreign investment, urbanization development, etc. The impact of these variables on environmental pollution will eventually manifest as changes in the slope and inflection point of the inverted "U" curve (Wang and Padmanabhan P, 2021; Song and Ye, 2021).

Among the existing empirical studies, scholars have also explored other factors influencing environmental problems. Some studies have found that renewable energy, biomass energy and per capita income are closely related to environmental pollution, and that the use of renewable energy is not only beneficial to environmental protection but also promotes economic recovery and sustainable development (C. Magazzino et al., 2022 and M. Mele et al., 2021; H. Altintas and Kassouri, 2020; M. Mele et al., 2021), in addition, C. Magazzino and M. Mele et al. (2021) suggest that fossil fuel combustion and economic growth have a significant impact on atmospheric pollutants such as PM2.5, PM10 and CO_2. It has also been found that the penetration of information and communication technologies accelerates electricity consumption while promoting economic growth, which in turn leads to higher CO_2 emissions and environmental pollution, in which urbanization development has played an important role (C. Magazzino, M. Mele et al., 2021). S. Katircioglu et al. (2018) suggest that the environmental Kuznets curve is characterised by an inverted "U" shape with increasing urbanisation and population. In addition, Y. Kassouri (2021) argues that urbanisation has significant direct or indirect spatial spillover effects on the ecological and water footprints. In the face of the serious situation of environmental pollution, it is also crucial to identify the factors influencing haze as one of the primary pollutants. Scholars have explained the influencing factors of haze pollution in terms of economic development, industrial upgrading, foreign investment, government regulation, and transportation (Lan and Pan, 2019). Yang and Yan (2021) measured the impact of urban sprawl on haze pollution in terms of urban built-up area and urban utility occupancy and found a non-linear relationship between the two. Scholars have also found that population concentration has a spatial impact on haze pollution through scale and intensification effects, and that the expansion of urban population size exacerbates haze pollution (Li and Zhou et al.,2012), including both direct and indirect effects (Feng and Wang, 2020), at the same time, China's rapid urbanisation has brought not only economic and population agglomeration, but also serious haze pollution, but the haze also had a significant impact on the level of urbanisation ((Fan et al., 2019; Liu et al., 2021a). In addition, the development of land urbanization also increases haze pollution, but this effect is only manifested as an indirect effect (Yu X. et al., 2020).

Further research by scholars found inter-regional and inter-city differences in the relationship between city size and haze pollution, with the expansion of city size helping to suppress haze pollution in megacities and first-tier cities (Fan et al., 2019), and scale heterogeneity being significantly present in the results of tests of the effect of urbanization on haze pollution (Liu and Ragusa, 2019).

There are several points to add to the existing literature: firstly, the spatial effects of haze pollution are ignored in the literature discussing urban expansion-related elements on haze pollution, which may lead to unreliable conclusions of existing studies. The spatial mobility of haze pollution determines its possible spatial correlation, as confirmed by many scholars (Hao and Liu, 2016; Fan et al., 2019). Secondly, the findings of existing studies imply that there may be a threshold effect of variables such as city size on haze pollution, i.e. the relevant variables may have a non-linear effect on haze pollution (Yu X. et al., 2020), but the existing literature only artificially divides the sample for testing and does not use a threshold model to discuss this issue objectively. Thirdly, haze pollution is a matter of economic development stage (Zhang et al., 2021), and the theory behind it lies in the environmental Kuznets curve, which is confirmed by scholars to exist in haze pollution (Maddison D, 2006; Müller-Fürstenberger and Wagner, 2007). Relevant studies therefore need to build models in this theoretical framework, which corroborates existing studies that have found different effects of urbanization development-related indicators on haze pollution in different cities, regions and stages. Finally, the urbanization in mainland China is characterized by a lag in population urbanization and a lack of coordination between the two, which has led to many problems in the economic development of mainland China (Liu et al., 2021b), and therefore the impact of the lack of coordination between population urbanization and land urbanization on haze pollution needs to be discussed, which has not been analyzed in depth in the literature.

This paper precisely attempts to start from the shortcomings of the above-mentioned several existing studies, based on the theoretical framework of environmental Kuznets curve, the impact of urban expansion on haze pollution is systematically discussed.

2.2 Theoretical Analysis

The mechanism of haze formation is complicated, but briefly three conditions are required: a certain concentration of pollutants, static atmospheric conditions, and a certain humidity of air. Among these, human economic activity mostly influences the concentration of the pollutants which mainly are aerosols. The secondary aerosols are formed largely by human economic activity, and particles include SO_X, NO_X, $SVOC_X$, CO_X, organic compounds containing halogens, etc. And these particles can attached toxic heavy metals and other toxic, which then form haze in stationary weather and high humidity (Yu J. et al., 2020).

Urban population expansion will affect haze pollution in three ways: the first is that population expansion would increase material and resource consumption and then result in increased pollutants emission and bring about environmental pollution such as haze. And meanwhile, population urbanization could also change the consumption structure, resulting in more domestic and production waste emissions and deteriorating environmental quality (Feng and Wang, 2020). For example, urban population expansion increases housing demand. And this boosting housing demand would raise construction dust and then promote primary aerosol particle concentrations. It also increases the organic matter volatilized from painting materials, which increases secondary aerosol particle concentrations. All of these would increase haze pollution. The second is that urbanized mode of production and living would increase energy and consumer goods consumption per capita and then leads more industrial and domestic waste, which would increase environmental and haze pollution. In here, the urban waste disposal and incineration and the winter heating all would increase sulphur oxide and nitrogen oxide emission, leading to an increase in secondary aerosol particle concentrations and causing haze pollution (Wang et al., 2021). The third is the expansion of urban population will increase the government's ability to govern environmental pollution and the productivity of the urban economy and then reduce pollution levels per unit of output and haze pollution (Sun et al., 2020; Jiang et al., 2021). Moreover, urban population expansion will increase the people's opportunity for better education, increase the utilization of public transport and then reduce environmental pollution. In addition, the concentration of population in cities would promote the development of service industries, squeeze out industries with high pollution emission intensity, and even could reduce haze pollution. At the early stage of urbanization, the first two ways play the major role, and urban population expansion will increase haze pollution; as urbanization further developed, the third way will dominate and haze pollution gradually be reduced (Sun et al., 2020; Jiang et al., 2021; Wang et al., 2021). Therefore, Hypothesis 1 proposed as:

Hypothesis 1: There is a non-linear effect of urban population expansion on haze pollution that it will increase haze pollution at first and then decrease haze pollution.

Previous studies have confirmed that urban land expansion increases environmental pollution (Zhang et al., 2020), and this even true for haze pollution (Yang and Yan, 2021). Firstly, the process of urban built-up area expansion, initial building construction, later infrastructure support and continued construction of residential areas will increase dust emissions, which in turn increase the concentration of primary aerosol particles and secondary aerosol particles and then haze pollution. In addition, the renovation materials used in the construction process will increase VOCs, which also increase the concentration of secondary aerosol particles and increase haze pollution (Yang and Yan, 2021). Secondly, the expansion of urban areas will lift the amount of motor vehicles and traffic distances, which in turn increase the nitrogen oxides caused by motor vehicle emissions, and therefore also increase haze pollution by the higher concentration of secondary aerosol particles. Thirdly, it has been suggested that the expansion of built-up areas will lead to a decrease in wind speed over a certain area of the city center, which in turn increase the probability of stationary weather and increase haze pollution (Yang and Yan, 2021). Finally, the natural boundaries of cities usually have ecological green areas such as forests, wetlands, parks and grasslands that have a haze dissipating effect, and therefore, haze pollution is lower in suburban areas compared to urban areas. However, as urban land continues to expand it will destroy the green areas in the suburbs, leading to a decrease in the haze dissipating function of the city and exacerbating haze pollution (Zhang et al., 2020). Of course, in the process of urban land expansion, haze pollution will be mitigated by reducing the density of pollutant emissions per unit area, but in terms of the combined effect, the extensive land expansion in the current would increase haze pollutant emission, reduce the haze dissipation capacity of cities, and may exacerbate haze pollution. Then Hypothesis 2 put forward as:

Hypothesis 2: The extensive urbanization which mainly in form of land expansion would increase haze pollution significantly.

The inconsistency between population urbanization and land urbanization is essentially the unreasonable structure and allocation of factors (Lei et al., 2022). And in China, this inconsistency is particularly evident in the rapid urbanization of the land (Liu et al., 2021b), that land are over-allocated to cities and labour become relatively scarce. This distorted allocation of factors has led to extensive land use, which is useless for economic efficiency and environmental protection. In population's effects on environmental pollution like haze, built-up area expansion would play a role. In here, the expansion of built-up areas would lead to the extension of urban space, leading to an increase in the spatial distance between the workforce and enterprises. This would strengthen the impact of population expansion in city on haze pollution. And more, emissions from pollutants brought about by population urbanization may be dissipated or weakened by nature's air purification system. But urban land expansion would lead to the destruction of ecosystems such as forests around urban areas, that indirectly amplify the haze pollution from population urbanization (Li et al., 2022; Yang and Yan, 2021). Therefore, we put forward the Hypothesis 3:

Hypothesis 3: The effect of urban population expansion on haze pollution is influenced by land expansion, and the incoordination of land urbanization and population urbanization would enlarge the negative effect of urbanization on haze pollution.

3 MODEL AND DATA

3.1 Model

Considering the possible spatial correlation of haze pollution brought about by the regional correlation of stationary weather and moisture conditions, the mobility of haze pollution, and the correlation of economic activities between neighbouring cities and regions in the haze generation process, a spatial econometric model will be developed in this paper to test the correlation hypothesis. The general form of the spatial econometric model is the spatial Durbin model (SDM).

The PM2.5 concentration of city i in period t is $Haze_{i,t}$ and X is the correlation factor affecting urban haze pollution, so the SDM model for urban haze pollution is:

$$Haze_{i,t} = \rho WY_{i,t} + \beta X_{it} + \theta WX_{i,t} + \mu_{i,t}\mu = \lambda W\mu + \varepsilon \quad (1)$$

In **Eq. 1**, $Haze_{i,t}$ is the explanatory variable and X is the explanatory variable of interest, W is the spatial weight matrix, μ is the random error term, WY is the spatial dependence of the dependent variable, and WX is the spatial dependence of the independent variable, ρ is the spatial autoregressive coefficient and λ is the residual autoregressive coefficient.

In addition, considering the possible existence of "time inertia" of haze pollution, this paper will also introduce the lag term of haze pollution in the spatial Durbin model and construct a dynamic spatial Durbin model as follows:

$$Haze_{i,t} = \alpha Haze_{i,t-1} + \rho WY_{i,t} + \beta X_{it} + \theta WX_{i,t} + \mu_{i,t} \tag{2}$$

In **Eq. 2**, $Haze_{i,t-1}$ is the haze pollution of city i in period $t-1$, α is the regression coefficient of variable $Haze_{i,t-1}$, and other variables and correlation coefficients have the same meaning as in **Eq. 1**.

Equations 1, **2** are further expanded based on the environmental Kuznets curve to build the final SDM model for this paper:

$$\begin{aligned} Haze_{i,t} &= \alpha Haze_{i,t-1} + \beta_1 gdp_{it} + \beta_2 gdp_{it}^2 + \beta_3 popu_{it} + \beta_4 bua_{it} + \beta_5 fdi_{it} + \\ &\beta_6 energy_{it} + \beta_7 greenland_{it} + \beta_8 infor + \beta_9 fininc_{it} + \beta_{10} fin_{it} + \beta_{11} bank_{it} + \\ &\beta_{12} tbd_{it} + \beta_{13} gov_{it} + \beta_{14} is_{it} + \rho WY_{i,t} + \theta WX_{i,t} + \mu_{i,t} \end{aligned} \tag{3}$$

In **Eq. 3**, $Haze_{i,t-1}$ is the lagged term of the explanatory variable, the core explanatory variables are population size (*popu*), built-up area (*bua*), primary (*gdp*) and secondary (*gdp²*) indicators of economic development. The control variables added include: level of foreign direct investment (*fdi*), energy intensity (*energy*), greenland coverage (*greenland*), level of information technology development (*infor*), size of government (fiscal revenue *fininc* and fiscal expenditure share *gov*), level of financial development (savings *fin*, deposit balance *bank*), level of industrial structure (non-agricultural industry share *is* and service industry development level *tbd*) etc (Feng and Wang, 2020), When $\alpha = 0$, it is a static spatial panel model and when $\rho = \theta = 0$, it is a dynamic spatial panel model.

Newer literature has proposed models that can consider both the spatial error term and the spatial lag term, i.e. the spatial lag model with a spatial lag error term (SARAR), and to verify the robustness of the spatial Durbin model conclusions, the estimation results of the SARAR model are also presented in this paper.

In addition, this paper will also develop a threshold model to test the threshold effect of urban sprawl on haze pollution. The threshold estimation method was proposed by Hansen B E (1999) and has been widely accepted by scholars to date. The basic form of the single threshold model is:

$$Y = \mu + \beta_1' XI(q \le \gamma) + \beta_2' XI(q > \gamma) + \varepsilon \tag{4}$$

In **Eq. 4**, Y is the dependent variable, which in this paper is urban haze pollution, X is the independent variable, β' is the value of the coefficient corresponding to the independent variable, q represents the threshold variable, γ is the threshold value, ε is the random disturbance term, $I(\cdot)$ is the indicator functions. The determination of the number of threshold values and the test principles are not repeated.

The threshold model developed for this study (a single threshold model with built-up area as the threshold variable) is:

$$\begin{aligned} Haze_{it} &= \mu_i + \beta_1 popu_{it} I(bua_{it} \le \gamma) + \beta_2 popu_{it}^2 I(bua_{it} > \gamma) \\ &+ \varphi_1 gdp_{it} + \varphi_2 gdp_{it}^2 + \cdots\cdots + \varepsilon_{it} \end{aligned} \tag{5}$$

The threshold model is consistent with the control variables of the spatial econometric model.

3.2 Data

3.2.1 The Data for This Paper are Derived From Two Sources

The first is haze data. The haze data in this paper come from the Center for International Earth Science Information Network (CIESIN) at Columbia University, United States CIESIN at Columbia University relies on the Socio-Economic Data and Applications Center (SEDAC) to publish satellite-borne Moderate Resolution Imaging Spectrometer (MODIS) and Multi-angle Imaging Spectrometer (MISR) measurements to obtain aerosol optical thickness images, which can be transformed to obtain raster data of PM2.5 concentrations, which are widely used in haze pollution studies (Peter, 2008; Chen and Han, 2021) In this paper, ArcGIS 10.2 software was used to parse this data into PM2.5 concentration data for the corresponding year for sample cities above the prefecture level in mainland China.

This is followed by urban expansion indicators and other related variables measuring economic development. The original data for urban expansion and other indicators were obtained from the *China Urban Statistical Yearbook* and the *China Regional Economic Statistical Yearbook* during the sample period, and the data for each price deflator were obtained from the publicly available provincial and municipal statistical yearbooks of each province in the corresponding year.

In the process of data collection and collation, the balanced panel data of 283 mainland Chinese cities from 2010 to 2016 were finally collated in order to obtain balanced panel data, taking into account the availability of data. In the data quantification process. the explanatory variable haze pollution is selected as the annual average value of PM2.5 concentration; the core explanatory variables are selected as the population size, built-up area, economic development primary and secondary terms. The population size is taken from the total population of the municipal district at the end of the year, and the economic development index is taken as the logarithmic value of GDP per capita; other control variables include: foreign direct investment level, energy intensity, green space coverage, information development level, government size, financial development level and the industry structure level. Among them, the energy intensity indicators used the quantification of GDP output per unit of industrial electricity consumption (10,000RMB/10,000 kWh); the information development level was quantified by quantifying international internet users (household); the government size is quantified using the ratio of municipal revenues to fiscal expenditures; the consumption level indicators used the total retail sales of social consumer goods per capita in each city (10,000RMB/Per); the financial development level is quantified by the amount of savings and the balance of deposits; the industry structure level is quantified by the proportion of non-agricultural industries and the proportion of services. The capital stock indicator is obtained using the perpetual inventory method. The other variables are quantified by taking the original meaning of the indicator and are not repeated. All physical capital variables are taken as logarithmic values. The data are described in **Table 1**.

4 ANALYSIS OF THE EMPIRICAL RESULTS

4.1 Impact of Land Expansion and Population Expansion on Urban Haze Pollution

Before analyzing the impact of land expansion and population expansion on urban haze pollution, it is necessary to examine the spatial correlation between urban haze pollution. In this paper, As shown in **Figure 1**, this paper gives Moran scatter plots for 2010, 2012, 2014, and 2016.

From the Moran's I index, haze pollution among Chinese cities shows a significant spatial correlation with a positive coefficient proving the existence of spatial spillover effects of haze pollution among cities, which is consistent with the findings of existing studies (Hao and Liu, 2016). The existence of strong spatial mobility of haze pollution, the existence of spatial clustering of economic activities in the haze generation process, and the existence of spatial similarity of climate in the haze generation process all contribute to the spatial correlation of haze pollution between cities.

In this paper, the results of the spatial SARAR model and the spatial SDM model are presented, as well as the results of the models with and without control variables respectively, and the four sets of estimation results are given in **Table 2**. In the process of analysis, Stata 14.0 software was used.

From the model estimation results of the spatial SARAR and SDM, the spatial coefficients passed the significance test, further indicating that there is a spatial spillover effect of haze pollution, and the haze pollution in this region will have an impact on the haze pollution in neighboring regions, corroborating the results of the Moran scatter plot and confirming the spatial correlation of urban haze pollution. From the model estimation results, the population expansion and built-up area expansion of cities will significantly increase haze pollution (1% significance level), and this conclusion holds in all four models with strong robustness. The expansion of urban population will cause the concentration of economic activities in urban areas, which will increase haze pollution; at the same time, an increase in urban population will also lead to an increase in related consumption in terms of clothing, food, housing and transport, which will easily cause traffic congestion and generate more household waste, speed up energy consumption and thus increase haze pollution.The expansion of the built-up area will firstly cause an increase in the sources of haze pollution due to construction and building, etc. In addition, the expansion of the built-up area will increase the mileage of urban traffic and the probability of congestion, which will also increase the sources of haze pollution.

The primary indicator of economic development has a significant positive effect on haze pollution (1% level of significance), indicating that economic development exacerbates haze pollution, but the secondary indicator of economic development has a significant negative effect on haze pollution (1% level of significance), indicating that there is an inverted "U" shaped relationship between economic development and haze pollution, confirming the existence of an environmental Kuznets curve in urban pollution in mainland China. This is consistent with the findings in the literature (Maddison, 2006; Müller-Fürstenberger and Wagner, 2007; Song et al., 2021). The reason for this phenomenon is that in the early stage of economic development, the economic activities are mainly industrial, and the government also relaxes the environmental control to attract more enterprises to invest, which causes a large amount of polluting gas and waste emissions, and thus aggravates the haze pollution. When the economic development enters the mature stage, the economy of scale has been formed, and it is no longer necessary to sacrifice the environment to promote development, instead, environmental protection should be the top priority to achieve sustainable development, so the economic development and haze pollution show an inverted "U" shape relationship.

Considering the "temporal inertia" of haze pollution, this paper also presents the results of dynamic spatial Durbin model estimation.

As shown in **Table 3**: Haze pollution in the lagged period has a significant effect on haze pollution in the current period (1% significant level), indicating that haze pollution has a significant time dependence, and haze pollution in the previous period will aggravate haze pollution in the current period. The other variables estimated are consistent with the baseline regression, the relationship between economic development and haze pollution still shows an inverted "U" shape feature, the expansion of population size and built-up area will increase haze pollution (1% significant level), and the spatial coefficient is still significant, which further confirms the robustness of the results of this paper.

This paper focuses on the mechanisms involved, firstly, population expansion will increase resource consumption, change the consumption structure, create more pollution sources, and lead to haze pollution (Feng and Wang, 2020), secondly, population urbanization will inevitably increase housing demand, and construction will lead to an increase in solid pollutants such as dust and generate haze, and again, domestic waste disposal and winter heating will lead to pollutant gas emissions and intensify haze pollution (Wang et al., 2021).However, there may be a non-linear relationship between population size and haze pollution, as the government will continue to increase environmental management as urbanisation grows, while increased access to education will increase people's environmental literacy and thus reduce haze pollution (Sun et al., 2020; Jiang et al., 2021), as will be further confirmed below. Land expansion will generate more solid particulate matter due to the continued construction of buildings and infrastructure, secondly, increased transport

TABLE 1 | Description of data.

Time	Population size (10,000 people)		Area of built-up area (sq km)		Haze (PM2.5) concentration	
	Mean	Std.Dev.	Mean	Std.Dev.	Mean	Std.Dev
2010	95.22	168.30	91.94	130.45	5700.78	4313.33
2011	95.66	172.43	96.82	136.85	5944.32	4473.94
2012	95.05	172.94	103.02	143.34	6395.50	4804.16
2013	96.58	176.20	105.94	146.74	6481.29	4942.68
2014	100.65	199.26	111.67	148.24	6383.56	4806.35
2015	103.32	202.97	130.62	248.67	6218.93	4659.43
2016	105.54	206.72	124.77	160.75	6327.04	4710.50

Data source: Compilation and calculation of original data by the author.

TABLE 2 | Impact of urban sprawl on haze pollution.

Variables	With control variables		Without control variables	
	SARAR	SDM	SARAR	SDM
gdp	1,498***	1,846***	2,320***	2,185***
	(386.4)	(435.0)	(372.3)	(377.8)
gdp^2	−67.38***	−82.90***	−102.1***	−98.82***
	(19.75)	(21.59)	(18.10)	(18.30)
popu	1.215***	1.235***	1.032***	0.923***
	(0.457)	(0.459)	(0.345)	(0.351)
bua	0.374***	0.401***	0.398***	0.371***
	(0.117)	(0.117)	(0.115)	(0.117)
fdi	−187.2	−247.6		
	(207.0)	(207.9)		
energy	−0.000467	−0.000429		
	(0.00199)	(0.00199)		
greenland	1.646	1.461		
	(1.074)	(1.093)		
infor	−0.149	−0.148		
	(0.0924)	(0.0924)		
fininc	1.46e−05	1.79e−05		
	(2.15e−05)	(2.16e−05)		
fin	−100.5***	−61.24		
	(28.41)	(50.12)		
bank	65.89	83.90*		
	(42.57)	(45.79)		
tbd	−5.93e−05	−6.76e−05		
	(4.41e−05)	(4.41e−05)		
gov	990.6	946.5		
	(696.8)	(790.1)		
is	713.7***	659.0**		
	(259.6)	(263.6)		
rho	0.759***	0.638***	−0.269**	0.749***
	(0.0451)	(0.0442)	(0.124)	(0.0333)
lambda	−0.162		0.849***	
	(0.130)		(0.0340)	
sigma2_e	159,491***	136,114***	159,808***	138,947***
	(4,422)	(4,346)	(4,471)	(4,442)
Observations	1,981	1,981	1,981	1,981
Number of cities	283	283	283	283

*Data source: Stata 14.0 software output. ***, **, * represent significance levels at 1, 5, 10% respectively. ()Within are standard errors.*

distances will lead to more vehicle emissions, and thirdly, the expansion of built-up areas will reduce wind speeds in city centres, which is detrimental to air movement, all of which will contribute to haze pollution (Yang and Yan, 2021).

TABLE 3 | Impact of urban sprawl on haze pollution based on dynamic SDM.

Variables	Dynamic SDM
$haze_{t-1}$	1.122***
	(0.00745)
gdp	232.4***
	(3.040)
gdp2	-7.774***
	(0.101)
popu	0.00484***
	(0.00135)
bua	0.0548***
	(0.00211)
Control variables	Control
Spatial	
rho	0.785***
	(0.0391)
Variance	
sigma2_e	44.16***
	(0.834)
Observations	1698
Number of cities	283

*Data source: Stata 14.0 software output. ***, **, * represent significance levels at 1, 5, 10% respectively. ()Within are standard errors.*

Some studies have pointed out that there may be inter-sample and inter-scale heterogeneity in the effect of expanding city size on haze pollution (Fan et al., 2019), suggesting that variables such as city size may have a non-linear effect on haze pollution, so this paper further adds the quadratic term of the city population size variable and the quadratic term of the built-up area of the city to the benchmark model for testing. The estimation results of the SARAR model and SDM model are also presented in this section.

With the inclusion of the quadratic term, the spatial coefficients are still estimated to be significant (1% level of significance). From the results, the primary term of population size still has a significant positive effect on haze pollution, but its quadratic term is significantly negative, indicating that urban haze pollution will gradually increase as the population size increases, but after reaching a certain size, the increase in urban population will help to reduce urban haze pollution, i.e. there is also a significant inverse "U" shaped relationship between population size and urban haze pollution. The effect of population size on urban haze confirms the hypothesis of this paper.

TABLE 4 | Non-linear effects of urban sprawl on haze pollution.

Variables	SARAR	SDM
gdp	2,332***	2,200***
	(386.6)	(396.1)
gdp^2	-102.4***	-99.29***
	(18.93)	(19.30)
popu	2.222***	1.870***
	(0.661)	(0.669)
popu^2	-0.000507**	-0.000389*
	(0.000229)	(0.000233)
bua	1.132*	1.172*
	(0.615)	(0.632)
bua^2	-0.000230	-0.000247
	(0.000185)	(0.000190)
rho	-0.250**	0.703***
	(0.124)	(0.0369)
lambda	0.844***	
	(0.0350)	
sigma2_e	159,335***	137,669***
	(4,455)	(4,398)
Observations	1,981	1,981
Number of cities	283	283

*Data source: Stata 14.0 software output. ***, **, * represent significance levels at 1, 5, 10% respectively. ()Within are standard errors.*

The positive effect of population size on haze pollution is easy to understand, and the explanation for the reduction in pollution brought about by further population size is that, firstly, the concentration of population in cities will improve the technical efficiency of cities through scale effects, etc., improving the quality of economic growth and reducing haze pollution; secondly, the expansion of city size will reduce the unit cost of the government to combat pollution such as haze, and will also improve the government's ability to combat pollution; Thirdly, the concentration of population in the city will promote the development of the service industry on both the supply and demand sides, thus having a crowding-out effect on industries with high pollution emission intensity, which in turn will reduce haze pollution.

The expansion of built-up area has a significant positive effect on urban haze pollution, but unlike population size, the secondary indicator of built-up area does not have a significant effect on haze pollution, indicating that the impact of urban area expansion on haze pollution is mainly monotonic and increasing. Possible reasons are that, on the one hand, the expansion of built-up areas will generate a large number of pollution sources, and also crowd the surrounding agricultural land, wetlands and woodlands, etc., breaking the ecological balance and reducing the ability of the environment to recover itself, on the other hand, the urbanization of people in China obviously lags behind the urbanization of land, and the continuous expansion of built-up areas further increases the problem of incompatible development between the two, indirectly aggravating haze pollution (Li et al., 2021; Zhang et al., 2022).

Table 4 confirms that there is a non-linear effect of increasing population size on urban haze pollution, which suggests that there may be a threshold effect of population size indicators on urban haze pollution, and this paper will further construct a threshold model to test whether this threshold effect exists. In the process of analysis, this paper uses population size and built-up area as threshold variables respectively, and population size and its quadratic term as the core explanatory variables to test their effects on urban haze pollution.

TABLE 5 | Threshold effects of urban sprawl on haze pollution.

Variables	Land expansion as a threshold variable	Population expansion as a threshold variable
gdp	2,922***	3,071***
	(445.5)	(449.0)
gdp^2	−109.6***	−118.6***
	(23.36)	(23.51)
bua	0.324**	0.325**
	(0.139)	(0.140)
fdi	−75.71	−99.52
	(245.5)	(246.6)
energy	0.000677	0.000756
	(0.00236)	(0.00237)
greenland	0.773	1.643
	(1.300)	(1.298)
infor	−0.210*	−0.158
	(0.112)	(0.112)
fininc	−3.29e–06	4.85e–05*
	(2.93e–05)	(2.74e–05)
fin	−274.1***	−261.9***
	(33.97)	(34.07)
bank	98.17*	123.8**
	(50.73)	(50.84)
tbd	6.15e–06	8.58e–06
	(5.22e–05)	(5.25e–05)
gov	1,455*	1,405
	(858.7)	(860.3)
is	601.5*	651.2**
	(309.0)	(310.2)
Popu(Zone 1)	7.742***	4.335
	(1.927)	(5.047)
Popu(Zone 2)	4.789***	1.998**
	(0.957)	(0.810)
popu^2 (Zone 1)	−0.00834***	−0.0415
	(0.00230)	(0.0349)
popu^2 (Zone 2)	−0.000869***	−0.000452
	(0.000315)	(0.000308)
Constant	−12,912***	−13,224***
	(2,112)	(2,115)
Observations	1,981	1,981
R-squared	0.257	0.251
Number of cities	283	283

*Data source: Stata 14.0 software output. ***, **, * represent significance levels at 1, 5, 10% respectively. ()Within are standard errors.*

4.2 Threshold Effects of Land Expansion and Population Expansion on Urban Haze Pollution

This paper uses Hansen's (1999) method of minimizing the sum of squared residuals to test the number of thresholds. The test procedure used the Bootstrap Method to draw samples 300 times for significance testing of the threshold effect. From the test results in **Table 5**, the F-statistic of the single threshold with built-

TABLE 6 | Impact of land expansion and population expansion coordination on urban haze pollution.

Variables	Current period		Lag 1 period		Lag 2 period		Lag 3 period	
	SARAR	**SDM**	**SARAR**	**SDM**	**SARAR**	**SDM**	**SARAR**	**SDM**
gdp	1,550***	1,929***	2,535***	2,413***	3,239***	3,415***	3,223***	3,416***
	(389.3)	(435.7)	(475.9)	(486.0)	(526.0)	(537.2)	(563.2)	(625.1)
gdp²	−70.77***	−88.27***	−111.9***	−109.7***	-154.6***	-164.8***	-160.0***	-171.7***
	(19.92)	(21.63)	(23.86)	(24.36)	(26.76)	(27.21)	(29.66)	(31.86)
popu	2.243***	2.485***	2.762***	2.556***	3.457***	3.352***	5.546***	6.049***
	(0.679)	(0.681)	(0.802)	(0.803)	(0.963)	(0.948)	(1.805)	(1.817)
bua	0.344***	0.378***	0.408***	0.394***	1.592**	1.715**	2.975***	2.886***
	(0.118)	(0.118)	(0.118)	(0.119)	(0.758)	(0.757)	(1.024)	(1.025)
popu²	−0.000521**	−0.000634**	−0.000313	−0.000256	-0.000736*	-0.000694*	-0.00235	-0.00295
	(0.000258)	(0.000259)	(0.000344)	(0.000345)	(0.000396)	(0.000391)	(0.00186)	(0.00188)
coode	45.11	26.67	−246.8***	−259.0***	-337.6***	-333.9***	53.01	27.48
	(74.52)	(75.04)	(87.91)	(89.88)	(99.94)	(99.47)	(117.0)	(118.1)
fdi	−170.6	−225.8	−185.0	−264.0	92.29	47.24	92.54	72.90
	(207.0)	(207.5)	(215.0)	(218.3)	(234.4)	(233.5)	(233.2)	(233.8)
energy	−0.000500	−0.000647	−0.000871	−0.000706	-0.000799	-0.000844	-0.486	-0.547
	(0.00199)	(0.00199)	(0.00199)	(0.00200)	(0.00197)	(0.00195)	(0.490)	(0.491)
greenland	2.058*	1.940*	4.009***	4.441***	5.775***	6.081***	7.406***	7.905***
	(1.092)	(1.105)	(1.430)	(1.439)	(1.806)	(1.820)	(2.060)	(2.118)
infor	−0.111	−0.0962	−0.227*	−0.256**	0.280	0.313	0.732	0.597
	(0.0942)	(0.0942)	(0.117)	(0.118)	(0.527)	(0.529)	(0.710)	(0.713)
fininc	3.12e-05	4.10e-05*	6.07e-05*	8.11e-05**	0.000108**	0.000110**	0.000139*	0.000157**
	(2.31e-05)	(2.32e-05)	(3.41e-05)	(3.49e-05)	(4.67e-05)	(4.65e-05)	(7.64e-05)	(7.65e-05)
fin	−100.2***	−39.12	−46.74	−45.23	−94.60**	−94.03	−166.5	−196.8*
	(28.56)	(50.44)	(51.90)	(55.52)	(43.91)	(66.58)	(110.8)	(112.0)
bank	71.90*	92.20**	69.36	66.08	69.50	65.44	98.75	79.95
	(42.87)	(45.78)	(48.94)	(48.83)	(56.44)	(56.76)	(97.05)	(99.61)
tbd	−5.26e−05	−6.28e−05	−0.000159***	−0.000166***	−0.000246***	−0.000253***	−0.000229***	−0.000230***
	(4.42e-05)	(4.42e-05)	(6.07e-05)	(6.11e-05)	(7.15e-05)	(7.09e-05)	(8.58e-05)	(8.55e-05)
gov	796.5	581.9	1,280	1,078	1,266	537.4	1,079	433.6
	(706.7)	(796.7)	(877.7)	(884.7)	(934.2)	(951.5)	(1,022)	(1,054)
is	697.6***	653.2**	591.0**	606.1**	404.6	317.5	77.08	−24.26
	(259.7)	(263.0)	(269.6)	(269.6)	(270.1)	(268.2)	(268.1)	(268.4)
rho	0.753***	0.620***	−0.101	0.622***	0.605***	0.528***	0.699***	0.559***
	(0.0467)	(0.0455)	(0.165)	(0.0485)	(0.0920)	(0.0663)	(0.0735)	(0.0700)
lambda	−0.141		0.823***		0.260		0.154	
	(0.133)		(0.0539)		(0.164)		(0.166)	
sigma2_e	159,271***	135,310***	160,899***	132,771***	155,607***	120,905***	147,731***	108,075***
	(4,415)	(4,319)	(4,751)	(4,578)	(4,702)	(4,564)	(4,693)	(4,562)
Observations	1,981	1,981	1,698	1,698	1,415	1,415	1,132	1,132
Number of cities	283	283	283	283	283	283	283	283

*Data source: Stata 14.0 software output. ***, **, * represent significance levels at 1, 5, 10% respectively. ()Within are standard errors.*

up area as the threshold variable was the largest and the most significant (5% significance level), indicating the existence of a significant threshold effect. In contrast, the test with population size as the threshold variable fails the significance test from the single threshold to all three thresholds, indicating that there is no threshold effect. This paper gives the estimation results of the two models, mainly based on the former analysis.

Using the built-up area as the threshold variable, according to the test and estimation results of the threshold model, the primary and secondary terms of population size have significant effects on urban haze pollution in both intervals, with positive and negative effects respectively, which is consistent with the results of the spatial econometric model, indicating an inverted "U" shape relationship between population size and urban haze pollution.

It is further observed that with the expansion of built-up area, the absolute values of the coefficients of the primary and secondary terms of population size on urban haze pollution are decreasing in different two threshold intervals, indicating that the impact of population expansion on haze pollution will be affected by the built-up area, and the joint effect of land urbanization and population urbanization will affect haze pollution. The impact of population size on haze pollution differs at different levels of land urbanization and built-up area size, and the impact of population size on haze pollution decreases with the expansion of built-up area, which is in line with our expectation. As the built-up area expands, urban space rises, population density decreases and therefore the concentration of haze pollution decreases. Of course, this conclusion does not mean that to reduce urban haze pollution and the impact of population expansion on haze pollution we need to increase the size of built-up areas. On the contrary, a prominent problem in the process of urban expansion in China is the incompatibility between population urbanization and land urbanization, which is manifested in the rapid urbanization of land (Liu et al., 2021), and it has been demonstrated in this paper and related literature that the expansion of urban built-up area can lead to increased haze pollution, the ideal scenario would be a coordinated expansion of population size and built-up area.

Therefore, considering that the estimation results of the threshold model have demonstrated a causal relationship between population expansion, land expansion and haze pollution, and that the effect of population expansion on haze pollution varies with land expansion, this paper further incorporates the coordination of population urbanization and land urbanization into the analytical framework of this paper to verify its effect on urban haze pollution.

4.3 The Impact of Coordination Between Land Expansion and Population Expansion on Urban Haze Pollution

This paper draws on the study of (Liao et al., 2020), where the coordination index of land urbanization and population urbanization is formulated as:

$$C_{LT} = \left| \frac{L + T}{\sqrt{2}} \right| \sqrt{L^2 + T^2} \tag{6}$$

In **Eq. 6**, L is the growth rate of urban population, T is the growth rate of built-up area, C_{LT} representing the degree of coordination between the two. In terms of criteria, $C_{LT} < 0.8$ means that land urbanization and population urbanization are not coordinated; $0.8 < C_{LT} < 0.9$ means that they are basically coordinated; $0.9 < C_{LT} < 1$ means that they are coordinated. From the results of this paper, the average value of the coordination index between population urbanization and land urbanization in the sample cities is 0.7676, and since $L<T$, the urbanization of the sample cities has the incoherent problem of over-urbanization of land. This tendency of urbanization in favor of land rather than population leads to a series of problems, including inefficient land use, sloppy economic development and high urban transport costs (Liao et al., 2020).

In this paper, both the SARAR model and the SDM model were constructed to test the effects of population urbanization and land urbanization coordination on urban haze pollution. The results are shown in **Table 6**, from the estimation results of the two models, the effect of coordination between population urbanization and land urbanization on urban haze pollution is not significant. Could it be that there is no effect of coordination between population urbanization and land urbanization on urban haze? It has been pointed out in the literature that the pattern of over-urbanization of land can lead to problems such as a sloppy economic development pattern, therefore it also leads to increased pollution such as haze, which is inconsistent with the present findings. The explanation given in this paper is that there may be a lagged effect of the coordinated degree of population urbanization and land urbanization on pollution such as haze. Therefore, this paper develops models with lag 1, lag 2 and lag 3 respectively to further test the effect of coordinated degree of population urbanization and land urbanization on urban haze pollution.

TABLE 7 | Sensitivity analysis.

Parameter	Delta	delta_conf	s1	s1_conf
gdp	0.080841	0.013410	0.048416	0.017703
gdp2	0.081188	0.012921	0.048416	0.016137
popu	0.172066	0.017002	0.210166	0.036700
bua	0.114475	0.015190	0.128831	0.027231
coode	0.069441	0.013320	0.038278	0.014312

Data source: python 3.10 software output.

From the estimation results of the SARAR model and SDM model, the effect of coordination between population urbanization and land urbanization on urban haze pollution is significantly negative (1% significance level) in the lag 1 model, the estimation result of the lag 2 model is also significantly negative (1% significance level), and the estimation result of the lag 3 model is not significant, indicating that the lagged effect of population urbanization and land urbanization coordination on urban haze pollution is shown to be period 1 and period 2.

In terms of specific impact mechanisms, the main reason for the uncoordinated development of population urbanization and land urbanization is that government-led land urbanization distorts the allocation of land factors, while unequal urban public services inhibit the development of population urbanization (Lei et al., 2022; Liao and; Wu et al., 2022), both of which manifest as inefficient factor allocation. The distortion of factor allocation will lead to a sloppy and inefficient way of economic development, with large-scale overbuilding such as industrial parks increasing haze pollution, while the low rate of allocation of factors such as labour to the urban sector will cause industrial parks to be idle. Empirical analyses have shown that the inconsistency between population urbanization and land urbanization due to rapid land urbanization increases haze pollution, which may be related to the sprawl of urban space due to the expansion of built-up areas and the consequent reduction in inter-city accessibility, or to the destruction of peri-urban ecosystems due to urban expansion and the consequent reduction in the ability of cities to dissipate haze (Yang and Yan, 2021), but these related effects do not manifest immediately in the current period and there is a significant lag period.

4.4 Sensitivity Analysis

In order to better ensure the stability of the estimation results, a sensitivity analysis of the main explanatory variables was conducted in this paper based on the Delta Moment-Independent Analysis algorithm (E. Borgonovo, 2007). The variables selected are economic development, the secondary term of economic development, population size, built-up area and the urbanisation of population towns and land coordination. The final output parameters are shown in **Table 7**.

The results report the sensitivity coefficients of the parameters, and the sobol first-order sensitivity coefficients based on variance, respectively, the sensitivity coefficients of each variable are positive and pass the 95% confidence test, which says that haze pollution has a certain sensitivity to each variable. As can be seen from **Table 7**, population is the most influential parameter on haze pollution, and its sensitivity coefficient is about 0.172, followed by built-up area with a sensitivity coefficient of 0.114, and again, are economic development and its secondary term, with the lowest sensitivity coefficient for the coordination of population urbanization and land urbanization. The sensitivity coefficients calculated based on the variance are basically consistent with the results of the total sensitivity coefficient. In general, all of the above variables have significant effects on haze pollution, which indicates that the results of this paper are robust.

5 CONCLUSION AND DISCUSSION

China's urbanization has achieved tremendous success with the expansion of urban scale, but it has also led to a series of economic, social and environmental problems (Fan and Zhao, 2012), among which there is a significant effect of population scale expansion and built-up area expansion and their coordination on urban haze pollution. Based on raster data of urban haze PM2.5 concentrations, this paper incorporates urban expansion and its quadratic term into the analytical framework of the environmental Kuznets curve and considers spatial effects to verify the influence of variables related to urban expansion on urban haze. The study finds that there is a significant spatial spillover effect on urban haze pollution, and the environmental Kuznets curve holds for urban haze pollution; there is an inverted "U" relationship between urban population size and urban haze pollution; the increase in built-up area significantly increases haze pollution; there is a threshold effect of population size on urban haze pollution, and as the built-up area increases, the effect of population size on haze pollution decreases; the coordination between population urbanization and land urbanization has a significant effect on haze pollution, and the incompatibility between population and land in China's urbanization process exacerbates haze pollution, with a 1-2 period lag effect.

While there is much debate in China about the optimal size of cities, this paper provides a new perspective on the consideration of haze pollution. Leaving aside the debate on city size, one point to note is that the coordinated development of land urbanization and population urbanization should be incorporated into the relevant discussion and analytical framework of urban environmental pollution. The policy implications of this paper include the following:

Firstly, in addition to strengthening enforcement and supervision of haze pollution, the government should also work on strengthening spatial planning and implementation of urban development guidelines to curb "pie-spreading" urban development. First of all, the government should carry out scientific and reasonable urban development planning, and should develop the concept of spatial conservation, smart growth and compact city development to avoid unnecessary encroachment and over-exploitation of the space around the city, which will help reduce haze pollutant emissions and maintain haze dissipation capacity. In this process, the government should change the spatial structure of the land offered for sale, reduce the proportion of land on the urban fringe therein, and increase efforts to vacate and optimize the allocation of land in the city again to promote three-dimensional urban development. Secondly, the government should formulate corresponding implementation guidelines for development plans and strengthen the supervision of the implementation of the relevant guidelines to ensure that the corresponding plans are implemented. For example, the government can build a system of ecological isolation at the edge of the city, as a rigid bottom line for urban land expansion, to ensure that it is not breached.

Secondly, the high quality and rapid development of population urbanization can help to cross the threshold value of its impact on urban environmental pollution and release the intensive effect of population concentration on environmental pollution. Therefore, the government should promote the high-quality development of population urbanization through initiatives such as promoting the equalization of public services in cities and towns and the orderly coniferization of the agricultural transfer population. Firstly, it should further deepen reforms to mend the shortcomings in the high-quality development of urbanization, break through the institutional and institutional barriers that restrict the development of population urbanization, achieve equalization in public services such as education, healthcare and pensions, and at the same time promote the work of settlement and the rational and orderly promotion of the citizenship of the agricultural professional population. Secondly, in response to the growing number of depopulated cities, reasonable and scientific analysis and planning should be carried out, and efforts should be made to promote the redevelopment of depopulated cities in terms of industrial cultivation and the introduction of talents.

Thirdly, the government should base on the long term and strengthen the coordinated and balanced level of development of population urbanization and land urbanization to release their lagging effect on reducing pollution such as haze. The main characteristic of uncoordinated urbanization in cities is that land urbanization is ahead of its time while population urbanization is lagging behind. Therefore, promoting rapid population urbanization and curbing excessive land expansion is a feasible option to enhance the coordinated development of population urbanization and land urbanization. In addition, cities should determine their own urbanization development path based on their factor endowment advantages. Some cities should develop land-scarce and labour-intensive industries to absorb the employed population, correct the degree of coordinated development of population and land, optimise the level of factor allocation, improve efficiency and reduce pollution.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

JJ and ZW conceptualized and designed the study, revising it critically for important intellectual content. JY coordinated and supervised data collection, carried out the initial analyses, and reviewed and revised the manuscript. ZW corrected the data analyses, drafted the manuscript, and critically reviewed the manuscript. All authors read and approved the final manuscript.

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